Observations of urban heat island advection from a high-density monitoring network

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With 69% of the world's population predicted to live in cities by 2050, modification to local climates, in particular Urban Heat Islands (UHIs), have become a well studied phenomenon. However, few studies have considered how horizontal winds modify the spatial pattern in a process named Urban Heat Advection (UHA) and this is most likely due to a lack of highly spatially resolved observational data. For the first time, this study separates the two-dimensional advection-induced UHI component, including its pattern and magnitude, from the locally heated UHI component using a unique dataset of urban canopy temperatures from 29 weather stations (3 km resolution) recorded over 20 months in Birmingham, United Kingdom. The results show that the mean contribution of UHA to the warming of areas downwind of the city can be up to 1.2 °C. Using the inverse Normalized Difference Vegetation Index as a proxy for urban fraction, an upwind distance at which the urban fraction has the strongest correlation with UHA was demonstrated to be between 4 and 12 km. Overall, these findings suggest that urban planning and risk management needs to additionally consider UHA. However, more fundamentally, it highlights the importance of careful interpretation of long-term meteorological records taken near cities when they are used to assess global warming.

Key Words: advection; heat; sensors; temperature; urban; urban heat advection; urban heat island; wind

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1. Introduction

It is well documented that urban conurbations are warmer than their rural surroundings (Arnfield, 2003; Stewart, 2011). The resulting phenomenon, known as the urban heat island (UHI), develops through the absorption of energy within the built environment during the day, and subsequent release at night. The structure and intensity of the UHI are controlled by the city form and are a direct result of anthropogenic modifications to the surface energy balance (Oke, 1973, 1982). These changes include: reduced sky view factor (fraction of visible sky from the ground); restricting long-wave radiation loss at night; different thermal and reflective properties from construction materials; reduced evaportranspiration due to less vegetation; lower wind speeds (increased surface roughness); and anthropogenic heat from buildings, people and vehicles. Cities typically exhibit spatial variations in UHI intensity that can be broadly classified into Local Climate Zones (LCZ), which are effectively determined by land use (Stewart and Oke, 2012). Alternatively, land cover products, for example vegetation indices derived from remote sensing, can used to assess UHI intensity (Chen et al., 2006).

The largest UHI intensities are generally found in the central business districts under clear skies and calm winds, whereas more turbulent conditions increase mixing and weaken UHIs.

The significance of the UHI effect becomes increasingly apparent by studying interactions with the health and well-being of the local population. For example, in England and Wales, 81.5% of the population are urbanised (ONS, 2013) and with cities unable to cool down as efficiently as their surroundings, there is a growing heat-health and infrastructure risk (Grimmond et al., 2010; Thornes, 2015). UHI impacts are further compounded during heatwave events. It is estimated that the 2003 summer heatwave led to as many as 70 000 excess deaths throughout Europe (Robine et al., 2008), 2000 of which were in England (Johnson et al., 2005). Climate projections (e.g. UKCP09: http://ukclimateprojections.metoffice.gov.uk/) indicate that heatwaves will become an increasingly regular feature of the UK climate before the end of the century, underlining the need for increased mitigatory action to protect vulnerable populations and critical infrastructure (Chapman et al., 2013). Until recently, a lack of external influence has left urban planning to habitually follow historical architecture, based on local climate and culture.
For example, the METROMEX campaign demonstrated that advection modulates downwind sensible heat fluxes (Ching et al., 1983; Godowitch et al., 1987) and urban plumes were shown to typically extend 10–15 km downwind (Dirks, 1974; Wong and Dirks, 1978). Between the neighbourhood and city scales, the heterogeneous nature of urban environments acts to create a series of overlapping local internal boundary layers (Garratt, 1990; Barlow, 2014). Over a warmer UCL, heat will be transferred upward from the UCL to the UBL (from neighbourhood- to city-scale). Heat released from the UCL becomes vertically mixed and subsequently advected downwind (Clarke, 1969; Oke, 1982). Observations during the METROMEX field campaign indicated that advection modulates downwind sensible heat fluxes (Ching et al., 1983; Godowitch et al., 1987) and urban plumes were shown to typically extend 10–15 km downwind (Dirks, 1974; Wong and Dirks, 1978). Between the neighbourhood and city scales, the heterogeneous nature of urban environments acts to create a series of overlapping local internal boundary layers (Garratt, 1990; Barlow, 2014). Over a warmer UCL, heat will be transferred upward from the UCL to the UBL, whereas over a cooler UCL, downward heat flux is likely to occur. However, little is known about the mechanisms of the two processes, particularly the latter, i.e. how much heat from these urban plumes is mixed downwards into the UCL to warm the air underneath. Furthermore, the vertical scale of the UBL varies diurnally. A well-developed UBL during the day (1–2 km) will allow plumes to spread high into the UBL. However, at night the UBL becomes typically limited to a few hundred metres at night, capped by stable air above. On this basis, heat will not be dispersed vertically as far from the UCL at night as is possible during the day.

Prior investigations into UHA have been attempted using temperature data collected from two related methodologies: (i) mobile sensors based on a traverse (Brandsma and Wolters, 2012; Unger et al., 2010) and (ii) fixed sensors at weather stations in the region (Chandler, 1965; Brandsma et al., 2003; Haeger-Eugensson and Holmer, 1999; Gedzelman, 2003; Takane et al., 2013). In addition to presenting the spatial patterns of UHI, not UHA, a limitation of these methodologies is a general inability to demonstrate the high-resolution two-dimensional structure of UHI with any statistical confidence due to either temporal or spatial limitations of the chosen approach. Typically, the method of using mobile sensors along transects suffers from short duration of measurement, whereas the method of using fixed sensors at stations is constrained by the small number of stations. For example, the METROMEX campaign demonstrated wind modifications to the UHI (Ackerman et al., 1978); however, the UHA signals were weak due to the coarse spatial resolution (horizontal resolution of about 13 km) and because not all observations were within the UCL. Given these constraints, recent attempts to quantify UHA have focussed on modelling approaches to enable the simulation of spatial dimensions that observations have, to date, been unable to capture (e.g. Zhang et al., 2009; Bohnenstengel et al., 2011; Chemel and Sokhi, 2012; Heaviside et al., 2015). Remote-sensing techniques have also been increasingly used to capture the spatial nature of surface UHI (Tomlinson et al., 2012, 2013). However, satellite-derived surface UHI are not always directly comparable with UCL UHI (air temperature). It is hypothesised that advection is a key cause for this difference because the surface UHI remains static (i.e. linked to underlying land use), whereas the UCL UHI is much more dynamic due to wind effects (Azevedo et al., 2016).

Fundamentally, a lack of high-quality dense urban networks has restricted the study of UHA features (Muller et al., 2013), largely due to the difficulty and cost of siting and maintaining urban networks (Chapman et al., 2014). This paucity of data has resulted in previous observational studies relying on a transect approach and modelling approaches limited by a lack of evaluation data. To overcome this challenge this article presents the two-dimensional pattern and magnitude of the advection-induced UHI component, UHA, under various wind speeds and directions at the city scale using a new high-resolution urban meteorological observational dataset. In doing so, a quantification of UHA is achieved which can be used strategically to mitigate heat impacts of upwind local climate on downwind populations. It also enables a critical view of whether rural reference stations commonly used in UHI studies are truly representative of the background climate due to possible contamination by UHA, which has potential implications on the accuracy of temperature records used for analyses of global warming.

2. Methods and background

2.1. Study area and data

A new network of automatic weather stations – the Birmingham Urban Climate Laboratory (BUCL) has been installed across Birmingham (52.5°N, 1.9°W, Figure 1), the United Kingdom’s second largest city with 1.1 million inhabitants, specifically to...
study city-scale weather processes using stations within the UCL. The BUCL network consists of two arrays of weather monitoring equipment and this study utilises data from the coarse array of 25 automatic weather stations (Vaisala WXT520, accurate to ±0.3 °C at 20 °C; Vaisala, 2012) that records minute averages of air temperature, relative humidity, atmospheric pressure, wind speed and direction, and precipitation at 3 m above ground. Guidelines on siting instruments in urban areas (Oke, 2006) were adhered to where possible when the network was installed with most stations sited within school grounds. A full description of the network can be found in Chapman et al. (2014) and is further documented via a new urban metadata protocol devised during the deployment (Muller et al., 2013). Observations are also taken from four UK Met Office weather stations accessed through the British Atmospheric Data Centre: Paradise Circus, Winterbourne, Elmdon and Coleshill. In total 29 stations provide coverage across Birmingham at approximately 3 km resolution (Table 1; Figure 1). To represent an unobstructed synoptic flow, wind data are taken from Coleshill, at approximately 3 km resolution (Table 1; Figure 1). To represent an unobstructed synoptic flow, wind data are taken from Coleshill, at a height of 10 m, due to its location outside the city. Data for this study were obtained from 1 January 2013 to 1 September 2014. The network and data undergo a rigorous process of quality assurance and control. Full descriptors of the data quality assurance procedures are documented in Warren et al. (2016) complete with repository links directly to the data and associated metadata.

In addition to the meteorological data, the normalized difference vegetation index (NDVI), a readily available MODerate-resolution Imaging Spectroradiometer (MODIS) product already used in UHI studies (e.g. Chen et al., 2006), is used to indicate urban fraction across Birmingham. The mean NDVI is calculated from averaging a 250 m resolution January and July 2014 (16-day composite) image to account for seasonality in leaf coverage. From herein the NDVI data, normalised to between 0 (rural) and 1 (urban), is referred to as urban fraction (Ufrac).

2.2. Urban heat island

UHI intensity is traditionally calculated by taking the temperature difference between an urban and a rural reference station (Arnfield, 2003; Stewart, 2011). However, this approach is challenged by the fact that rural reference stations near cities may be influenced by UHA if they are located within the urban envir as demonstrated conceptually by Lowry (1977) and directly in the region of study through modelling (Heaviside et al., 2015). To minimise this influence by UHA, a new concept of ‘inverse UHI’ is introduced, which adopts temperatures at a central urban station ($T_u$) as reference. The Met Office station at Paradise Circus is chosen to represent the central urban station ($T_u$) due to its location within the centre of Birmingham and is the station where the highest temperatures have been identified in previous studies (Tomlinson et al., 2012, 2013; Heaviside et al., 2015). The hourly temperature difference ($\Delta T_{u-i}$) between each station in the network ($T_i$, where $i$ denotes the ith station) and the central urban station ($T_u$) is calculated for the data period (Eq. (1)):

$$\Delta T_{u-i} = T_i - T_u.$$  

The value of this temperature difference ($\Delta T_{u-i}$) is mostly negative as the central urban station ($T_u$) is likely to be higher than other stations in the network ($T_i$). Temperature data are split equally into three wind-speed groups, WG1 (<2 m s$^{-1}$), WG2 (2–3 m s$^{-1}$) and WG3 (>3 m s$^{-1}$). Only night-time observations (based on daily sunset and sunrise times) with low cloud cover (<4/8 oktas) are included, to focus on conditions most favourable for strong UHI development. Classifying by wind speed, cloud cover and night-time, groups the data into conditions of similar stability (neutral and stable) as per Pasquill–Gifford stability classes (Pasquill and Smith, 1983; Tomlinson et al., 2012). The mean temperature difference within each wind speed group is taken ($\bar{\Delta T}_{u-i}$).

The assumption is made that the mean temperature difference between the ith station and central urban station ($T_u$) remains constant within these stability classifications, thereby compensating for some stations not being temporally homogeneous. In order to interpret the magnitude of the mean temperature difference ($\bar{\Delta T}_{u-i}$) as the positive UHI intensity, the minimum temperature difference in each wind speed group is

| Station | Network | Latitude | Longitude | Altitude (m) | Urban fraction (1 km radius) | LCZ |
|---------|---------|----------|-----------|-------------|-----------------------------|-----|
| W001    | BUCL    | 52.57    | −1.84     | 119         | 0.36                        | Scattered trees |
| W002    | BUCL    | 52.39    | −2.06     | 187         | 0.23                        | Scattered trees |
| W003    | BUCL    | 52.54    | −1.96     | 104         | 0.38                        | Scattered trees |
| W004    | BUCL    | 52.37    | −1.92     | 202         | 0.16                        | Scattered trees |
| W005    | BUCL    | 52.44    | −1.86     | 158         | 0.49                        | Open low rise  |
| W006    | BUCL    | 52.5    | −1.92     | 132         | 0.6                         | Open low rise  |
| W007    | BUCL    | 52.49    | −1.90     | 134         | 0.83                        | Compact mid rise |
| W008    | BUCL    | 52.44    | −1.97     | 168         | 0.45                        | Open low rise  |
| W009    | BUCL    | 52.47    | −1.86     | 123         | 0.7                         | Compact mid rise |
| W010    | BUCL    | 52.48    | −1.93     | 157         | 0.61                        | Open low rise  |
| W011    | BUCL    | 52.39    | −2.00     | 190         | 0.51                        | Open low rise  |
| W012    | BUCL    | 52.42    | −1.91     | 134         | 0.5                         | Open low rise  |
| W013    | BUCL    | 52.47    | −1.90     | 125         | 0.82                        | Compact mid rise |
| W014    | BUCL    | 52.42    | −1.84     | 141         | 0.5                         | Open low rise  |
| W015    | BUCL    | 52.51    | −1.83     | 98          | 0.68                        | Heavy industry |
| W016    | BUCL    | 52.45    | −1.82     | 130         | 0.53                        | Open low rise  |
| W017    | BUCL    | 52.48    | −1.79     | 101         | 0.52                        | Open low rise  |
| W018    | BUCL    | 52.49    | −1.81     | 100         | 0.48                        | Open low rise  |
| W019    | BUCL    | 52.50    | −1.87     | 110         | 0.74                        | Open mid rise  |
| W020    | BUCL    | 52.53    | −1.85     | 140         | 0.55                        | Open low rise  |
| W021    | BUCL    | 52.56    | −1.89     | 173         | 0.51                        | Open low rise  |
| W022    | BUCL    | 52.41    | −1.95     | 150         | 0.47                        | Open low rise  |
| W023    | BUCL    | 52.56    | −1.79     | 122         | 0.32                        | Open low rise  |
| W026    | BUCL    | 52.46    | −1.93     | 150         | 0.41                        | Open low rise  |
| W027    | BUCL    | 52.44    | −1.89     | 158         | 0.49                        | Open low rise  |
| Coleshill | Met Office | 52.48  | −1.69     | 96          | 0.39                        | Scattered trees |
| Elmdon  | Met Office | 52.45  | −1.74     | 96          | 0.61                        | Open mid rise  |
| Paradise Circus | Met Office | 52.48  | −1.90     | 139         | 0.9                         | Compact high rise |
| Winterbourne | Met Office | 52.46  | −1.93     | 140         | 0.4                         | Open low rise  |

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subtracted from each station. The resulting positive UHI intensity
is denoted by $\Delta T^+$.

2.3. Urban heat advection

As discussed in section 1, the environment (or area) of influence exerted by a city on its surrounds varies dimensionally. Lowry’s (1977) working model (Eq. (2)) states the temperature ($T_i$, or other element) at a given station $i$, time $t$, and weather type $x$ is a sum of the background temperature ($B$), and deviation caused by landscape ($L$, e.g. relief) and urban effects ($U$). If landscape effects are comparable at two given stations (rural and urban), any temperature difference can be attributed to urban effects. However, in practice, a given rural station may be influenced by the urban environ under particular weather type (or wind direction), and therefore the temperature difference is not an accurate reflection on UHI intensity. Lowry’s (1977) model is therefore unable to distinguish between urban effects, i.e. heat created locally or advected from upwind. As such, Lowry’s (1977) concept should be enhanced through separating urban effects (U) at a given location into contributing terms: local UHI, and additional UHA (Eq. (3)). Separating these terms however is complicated by the fact that observed data combines information on both processes.

$$T_{i,t,x} = B_{i,t,x} + L_{i,t,x} + U_{i,t,x}$$  \hspace{1cm} (2)

$$T_{i,t,x} = B_{i,t,x} + L_{i,t,x} + (UHI_{i,t,x} + UHA_{i,t,x})$$  \hspace{1cm} (3)

In order to separate UHA from UHI, a methodology used in Weather Research and Forecasting (WRF) modelling of the August 2003 heatwave (Heaviside et al., 2015) is adapted for the BUCL observation network. Here, the time-mean temperature field is subtracted from the averaged modelled field for each of four specified wind directions at 90° intervals ($\theta$: northeast (NE), southeast (SE), southwest (SW) and northwest (NW)). A hypothetical example is presented in Figure 2, whereby this methodology decomposes the UHI into the time-mean component (predominantly dependent of local land surface) and a horizontally advected component. To calculate the mean UHI at the $i$th station in the BUCL network, $(T_{i,u}^{(\theta)})_{UHA (i)}$, the temperature field ($\Delta T_{i,u}$) across all wind directions is subtracted from the mean temperature difference for a given wind direction sector ($\theta$), $(\Delta T_{i,u}^{(\theta)}$), shown in Eq. (2). An example calculation is presented in Figure 3(a). To account for any directional biases within the data, the temperature field across all wind directions ($\Delta T_{i,u}^{(\theta)}$) used in Eq. (4) is calculated by taking the mean of the mean temperature difference of each wind sector, $(\Delta T_{i,u}^{(\theta)})$, Eq. (5).

$$T_{i,u}^{(\theta)} = \frac{\Delta T_{i,u}^{(\theta)} - \Delta T_{i,u}}{4}$$  \hspace{1cm} (4)

$$\frac{\Delta T_{i,u}}{4} = \frac{(\Delta T_{i,u}^{(NE)} + \Delta T_{i,u}^{(SE)} + \Delta T_{i,u}^{(NW)} + \Delta T_{i,u}^{(SW)})}{4}$$  \hspace{1cm} (5)

By calculating the mean UHA for a given wind sector, $(T_{i,u}^{(\theta)})_{UHA (i)}$, the positive value is interpreted as half the advection-induced UHI component and the negative value is half the advection-induced UHI component from the opposing wind direction (Figure 2(c)). As such, UHA can be interpreted as the difference between these two values (n.b. upwind and downwind values will swap with opposing wind directions), and free from background, landscape and UHI effects. Whilst this approach distinguishes between each component in Lowry’s (1977) model, it is unable to determine the process and scale at which UHA occurs (i.e. horizontally through the UCL or downwards mixing from the thermal plume), as vertical observations are not available.

2.4. Urban heat advection distance

To investigate the spatial scale at which UHA occurs, concentric annuli (ann) at 3 km intervals extending 0–3, 4–6, 7–9, 10–12 and 13–15 km from each station ($i$) are overlaid onto the Ufrac data (Figure 3). Within each of the five annuli, the mean urban fraction is calculated, referred to as $Ufrac_{i,d}^{(ann)}$, where $d$ is the index of the annuli (i.e. $d = 1$: 0–3 km; $d = 2$: 4–6 km; ... $d = 5$: 13–15 km). Each annulus is further split by the four wind direction sectors ($\theta$) to create four arcs, and for each $\theta$, the mean urban fraction is calculated, referred to as $Ufrac_{i,d}^{(\theta)}$. A similar methodology used to calculate the mean UHA for a given wind sector $(T_{i,u}^{(\theta)})_{UHA (i)}$ is then applied to the Ufrac data. Namely, at a given station $i$ and distance $d$, the Ufrac annuli $Ufrac_{i,d}^{(\theta)}$ is subtracted from the Ufrac arc $Ufrac_{i,d}^{(\theta)}$ (Eq. (6)).

$$\frac{\Delta Ufrac_{i,d}^{(\theta)}}{4} = \frac{Ufrac_{i,d}^{(\theta)} - Ufrac_{i,d}^{(\theta)}}{4}$$  \hspace{1cm} (6)

This quantity, $\Delta Ufrac_{i,d}^{(\theta)}$, reflects the directional inhomogeneity, or variability of urban land use, of the $d$th annulus, i.e. whether the urban fraction value in a given direction is higher or
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Figure 3. Hypothetical explanation of how (a) UHA ($T^{\text{UHA}}_{\text{ann}}$) and (b) Ufrac difference from the mean ($\overline{\text{Ufrac}}_{\text{ann}}^{(d)}$) are calculated under a NE wind for a given station (i) located in the centre of the crosshairs. The temperature difference ($\overline{\Delta T}_{i\text{-}u}$) has a smaller magnitude from the NE (more urbanised sector), i.e. the actual temperature is closer to the urban reference than SW (less urbanised sector).

Figure 4. Spatial interpolation (kriging) of the nocturnal positive UHI intensity ($\Delta T_{i\text{-}u}^{\text{UHI}}$) under low cloud cover in three wind-speed groups: (a) WG1 (<2 m s$^{-1}$), (b) WG2 (2–3 m s$^{-1}$) and (c) WG3 (>3 m s$^{-1}$). The analysis is limited to the outer boundary of observations.

lower than the mean of all directions. A hypothetical calculation is shown in Figure 3(b). In order to generate statistically meaningful correlations between UHA and directional variability of upwind urban fractions, stations in the network with little Ufrac variation between arcs (<0.1 range) are excluded from the analysis. Whilst the station data are grouped for similar stability, there are still differences in the mean UHI and UHA for each wind direction explained by meteorological differences within wind groups that cannot be accounted for. For example the data are categorised into less than 4/8 oktas; however, within this group winds from the SE may have a higher percentage of completely clear skies. Finally, to account for directional differences, normalised UHI and UHA values for each wind direction are taken.

3. Results and discussion

3.1. Urban heat island

Ordinary kriging (R ‘kriging’ package version 1.1) is used to interpolate the positive UHI intensity ($\Delta T_{i\text{-}u}^{\text{UHI}}$) for each wind speed group (Figure 4). Interpolation predicts temperatures at unmeasured locations using weighted averages from surrounding stations. Kriging-based approaches to spatial interpolation have been used in several UHI studies (e.g. Szymanskowski and Krzyza, 2009; Knight et al., 2010; Unger et al., 2010; Azevedo et al., 2016). As per Knight et al. (2010) the analysis is confined to the outer boundary of observations and only used for visualisation. A large mean night-time UHI intensity under low cloud cover up to 4.3°C is observed across the region in WG1. Cool spots are found to the north of the city in Sutton Park and directly to the south in notably green urban areas within the city. Both areas are approximately 2°C cooler and are marked by ‘temperature cliffs’: a sharp change in temperature over short distances. A decrease in the maximum UHI intensity is found when wind speed increases (WG2: 3.0°C and WG3: 1.3°C) and spatially the heat becomes more confined to the city centre. The observed UHI spatial pattern is found to be similar to satellite and modelling research in Birmingham (Tomlinson et al., 2012, 2013; Heaviside et al., 2015). However, UHI intensities vary between these methodologies due to inherent differences between surface and UCL temperatures.

3.2. Urban heat advection

The resulting mean UHA ($T^{\text{UHA}}_{\text{ann}}$) is shown spatially for each wind speed group and sector in Figure 5. The results show that a significant upwind, downwind temperature difference of up to 1.2°C exists across Birmingham (WG2). The NE and SW cases show a clear downwind warming, present in each wind group, with a transition from a positive to negative warming located over the city centre. The NW case has warming and SE cooling present over the whole domain, in all wind groups. Whilst warming is still more pronounced downwind in the NW case, the cross-domain warming could be accounted for by urbanisation northwest of Birmingham (see Ufrac in Figure 1). Additionally as the analysis is...
In order to show the relationship between urban fraction the two urban effects UHI and UHA, Pearson's correlation coefficient is firstly conducted across all stations between the Ufrac annuli confined around the city, there are limitations with kriging or any spatial interpolation technique at the edge of a domain. Spatially the results have demonstrated the urban influence, through UHA, to extend outside the city limits. In effect the observed UHA patterns match the hypothetical calculation (Figure 2) and substantiate Lowry’s (1977) dynamic urban environ zone.

In order to quantify the mean UHA across all stations, the data are split into two groups of stations that are considered to be upwind or downwind of the city centre. The SW and NE wind sectors, as indicated in Figure 1, are used for this analysis due to the increased number of stations in this direction across the city. The calculated mean UHA \( T_{UHA}^{(θ_i)} \) at each station in the SW and NE groups are combined (i.e. both groups show positive UHA downwind) for each wind speed group (Figure 6). For WG1 a mean UHA across all stations of 0.2° C is observed. As wind speeds increase (WG2) the mean UHA rises to 0.4° C. A further increase in wind speed (WG3) reduces mean UHA to 0.3° C. It is also found that for WG2, UHA reaches 0.5° C or higher at 25% of stations, up to a maximum of 1.2° C. A maximum UHA occurring in WG2 could be explained by a reduced capability to advect heat with lower wind speeds, and less heat to advect from a smaller UHI at high wind speeds. This finding is similar to Brandsma et al. (2003) who found peak UHA to occur at medium wind speeds between 2.2 and 3.9 m s\(^{-1}\).

The results show that UHA is a significant phenomenon present in the UCL and is not limited to a thermal plume in the UBL (Clarke, 1969; Dirks, 1974; Wong and Dirks, 1978; Oke, 1982). As such this analysis shows that the temperature of a given location is significantly affected by adjacent urban fraction. Additionally, because the UHA components presented in Figures 5 and 6 are temporally averaged over 20 months, it is suggested that UHA could be higher under certain meteorological conditions, for example a heatwave (Heaviside et al., 2015). To place this additional downwind warming in context, a degree temperature difference has the potential to increase mortality by 2% for every degree rise over 17.7° C in the West Midlands (Hajat et al., 2014; Heaviside et al., 2016).

However whilst UHA is successfully separated from the UHI signal and quantified for Birmingham, these observations are unable to differentiate UHA processes. Further work is needed to explore whether winds move heat horizontally through the UCL, or if urban heat is mixed into the UBL, and then a proportion brought back to the UCL downwind.

3.3. Urban heat advection distance

In order to show the relationship between urban fraction the two urban effects UHI and UHA, Pearson’s correlation coefficient is firstly conducted across all stations between the Ufrac annuli.
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4. Conclusions

The complex nature of urban environments provides intrinsic challenges in quantifying UHI. To address this, a new high-density network of urban weather stations (BUCL) in Birmingham has been used to quantify both UHI and UHA at a sub-city scale. The unique spatial and temporal aspects of this dataset has shown Birmingham to exhibit a large mean nocturnal UHI intensity of up to 4.3 ℃ under low wind speeds and clear skies over 20 consecutive months.

Overall, using the novel methodology outlined, a clear spatial pattern of long-term averaged UHAI (the advection-induced UHI component separated from the locally heated UHI component) is found across the city, with a maximum magnitude of 1.18 ℃. The peak UHI influence is found under the medium-wind group (WG2), with a mean UHA signal of 0.4 ℃, and with 25% of stations experiencing between 0.5 and 1.2 ℃. The maximum UHI found in WG2 rather than WG1 (the low-wind group) could be explained by a reduced capacity to advect heat for WG1. For the high-wind group (WG3), however, UHI intensities are vastly reduced due to increased atmospheric mixing, thus leaving little heat for advection. Whilst these observations establish that UHA in the UCL is a significant phenomenon, the processes at which heat is transported (i.e. horizontally through the UCL or mixed downwards from the urban plume) cannot be identified in this study. However the correlation methodology based on urban fraction data is able to show that the total UHI component at a given location is a construct of the urban heat created by local land use and heat advected from upstream sources, with distance dependent on wind speed. With distances over 10 km at which the advection signal is still present, this has considerable implications not only for long-term climate records taken near cities, but for adapting cities and protecting vulnerable citizens in a changing climate.

Although UHI has previously been difficult to quantify and is not always considered in UHI studies due to the lack of urban meteorological observations, this article has successfully demonstrated UHA to be a substantial and noteworthy urban climate process. The unique methodology developed in this article (i.e. use of urban reference temperatures and techniques to isolate UHA only previously used in mesoscale modelling approaches) can be readily adapted to other urban networks worldwide.

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