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Can the crowdsourcing data paradigm take atmospheric science to a new level? A case study of the Urban Heat Island of London quantified using Netatmo weather stations.

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Abstract

Crowdsourcing techniques are frequently used across science to supplement traditional means of data collection. Although, atmospheric science has so far been slow to harness the technology, developments have now reached the point where the benefits of the approaches simply cannot be ignored: crowdsourcing has potentially far-reaching consequences for the way in which measurements are collected and used in the discipline. To illustrate this point, this paper uses air temperature data from the prolific, low-cost, Netatmo weather station to quantify the urban heat island of London over the summer of 2015. The results are broadly comparable with previous studies, and indeed standard observations (albeit with a warm bias, a likely consequence of non-standard site exposure), showing a range of magnitudes of between 1 and 6°C across the city depending on atmospheric stability. However, not all the results can be easily explained by physical processes and therefore highlight quality issues with crowdsourced data that need to be resolved. This paper aims to kickstart a step-change in the use of crowdsourcing in urban meteorology by encouraging atmospheric scientists to more positively engage with the new generation of manufacturers producing mass market sensors.

1. Background

1.1 Crowdsourcing

Crowdsourcing was first termed by Howe (2006) referring to the idea of outsourcing to the crowd. Linked with public engagement activities via citizen science, crowdsourcing is now increasingly finding itself as an established technique for collecting mass data in many scientific disciplines. For example, as part of a comprehensive review on the use of the technique in the atmospheric sciences, Muller, et al. (2015) discusses how the term has moved on from just sourcing services from the public to utilising sensors via internet platforms to gather meteorological data or information. Examples of studies in the discipline include collecting air temperatures from smartphones (Overeem et al, 2013), temperature and precipitation data from vehicles (Mahony & O’Sullivan, 2012) as well as supplementing traditional networks with amateur weather stations (Bell et al, 2013) and other smart devices.

However, with these few notable exceptions, the use of crowdsourced data in the atmospheric sciences is actually very limited when compared to other areas of scientific study (Muller et al, 2015). The reasons for this are deep rooted in the discipline, which has spent over 150 years investigating how to obtain a precise and representative observation. However, this has ultimately resulted in limited measurement coverage, mostly due to the high associated costs of deploying weather monitoring equipment. It means that many cities often only have a single weather station which is insufficient to resolve the heterogeneous urban climate (Chapman et al, 2015). Hence, the existing measurement paradigm, despite delivering high quality meteorological data, is presently at odds with the crowdsourcing concept where absolute accuracy is sacrificed in pursuit of increased coverage. Almost by definition, crowdsourced atmospheric data lack the calibration, quality assurance and control of traditional data (Muller, et al., 2015), yet the advantages of higher resolution measurements (or observations where there are presently no measurements at all) cannot be ignored.

1.2 The Urban Heat Island Effect

Urbanisation has dramatically shaped the environment that we see today (Chandler, 1965), with the Urban Heat Island (UHI) effect being one of the greatest problems associated with urban growth (Tan et al. 2010). UHI are a weather phenomenon measured in the urban canopy layer (Oke, 1981) and caused by anthropogenic alterations to the environment such as urban geometry, building density, anthropogenic heat release and land cover. The effect has been quantified in numerous studies around the world (see Stewart 2011 for a systematic review) and in particular, London’s UHI has been studied in detail for nearly two centuries (see the seminal work of Howard, 1833 and Chandler, 1965).

With 54% of the world’s population living in urbanised areas, and this set to rise to 66.4% by 2050, the UHI effect is becoming an increasing concern because of the effects it has on thermal comfort, energy and human health (Mavrogianni, et al., 2011; United Nations, 2014). Health impacts extend beyond heat stress and include respiratory problems and eye irritants particularly amongst vulnerable members of the population such as the elderly (Tomlinson et al, 2011). Furthermore, a major concern for researchers and practitioners in the field is the compound effect of UHI and climate change (Watkins, et al., 2007). Heatwaves, such as the 2003 European heatwave event provides a good example of how the impacts of UHI will increase in a changing climate (GLA, 2006). During this event, there was a 42% increase in the number of deaths in London, when compared with the number of deaths for the same period in the previous five years (Watkins, et al., 2007). Under climate change, there is an increasing probability of more frequent and intense heatwaves (Tan, et al. 2010) and the impacts will be most acutely felt in cities.

1.3. Quantifying the UHI

There are numerous approaches available to quantify the UHI effect. Many of these have already been applied in London and report magnitudes typically in the range of 6 - 9°C (e.g. Watkins et al, 2002a; Mavrogianni, et al. 2011). Such wide variations can be attributed to subtle differences between methodologies and study periods and is unsurprising, given no agreed standardised approach to measuring UHI actually exists (Stewart, 2011). The canopy UHI is traditionally measured using station pairs (e.g. Wilby, 2003) or transect approaches (e.g. Smith et al, 2013). However, neither are ideal as station pairs offer limited spatial information, where as transects often lack a temporal component. As an alternative, many studies have attempted to quantify the UHI using remote sensing (e.g. Schwarz et al, 2011; Tomlinson et al, 2012). This provides spatial data at a daily resolution, but is limited as it observes land surface temperatures as opposed to canopy air temperatures. Given these restrictions, numerical models are frequently used instead to quantify the UHI (e.g. Grimmond et al, 2010). However, numerical models presently can’t resolve all the processes needed to produce accurate city-scale UHI simulations

(Bohnenstengel, et al. 2011) and a lack of observation data prevents adequate initialisation and validation. This is evidenced by the typically lower maximum UHI magnitudes (when compared to observations) predicted by numerical models for London, which produce a lower range of values of 2 - 5°C (e.g. Grawe et al, 2013; Bohnenstengel, et al. 2011).

Fortunately, a recent trend in urban climatology has seen a growing number of high resolution urban meteorological networks brought about by the decreasing costs of instrumentation (see Muller et al, 2013 for a comprehensive review, but notable examples include the Birmingham Urban Climate Laboratory: Chapman et al., 2015; Oklahoma City Micronet: Basara et al., 2010; the Helsinki Testbed: Koskinen et al. 2011). The advantage of such dense networks is clear, but very few cities are fortunate enough to have a deployment. Furthermore, the networks that do exist are proving to be unsustainable given the high costs of maintaining, and managing, large amounts of equipment and data (Chapman et al, 2015). The result is networks are often used for short-term measurement campaigns and are decommissioned before the real benefits associated with long term monitoring become realised.

These issues with sustainability are central to the conclusion that urban meteorological networks are not actually the panacea needed for measuring the UHI (Chapman, 2015), hence there still exists a growing need to investigate other means to supplement existing data channels. Amateur weather stations provide a means of doing this (Bell et al, 2013) and indeed, have already been used to quantify the UHI. For example, Wolters and Brandsma (2012) and Steeneveld, et al. (2011) both gathered automatic temperature data from amateur weather stations to estimate the magnitude of the canopy UHI in urban areas in the Netherlands by utilising small networks of amateur weather stations. Such studies highlight the potential of supplementing traditional measurements with a limited number of amateur measurements, but that there remains a considerable scientific challenge in scaling up the measurements to the point where they are genuinely high resolution, and above all, of sufficient quality to be accepted by the atmospheric science community. However, given the spatial limitations of traditional approaches, crowdsourcing of amateur observations offers perhaps the only viable option to further improve the resolution of measurements, at least in the short term. Fortunately, new opportunities have recently emerged in this area in the form of low cost, citizen science weather stations that connect to smartphones and local Wi-Fi networks to relay data in real time to the cloud. Such units have become mainstream consumer peripherals in recent years with tens of thousands now deployed in cities across the world. For the first time, this study explores the use of air temperature data from one such weather station, the Netatmo - to monitor the London UHI.

2. Methods

2.1 Study Area

London, UK, has a population of 8.2 million people living in an area of 1,572km^2 (Office for National Statistics, 2011, Watkins, et al., 2007). This study uses the M25 orbital motorway as an approximate boundary in order to define a sample area used for data collection and analysis, although for easy comparison with other studies, results will be presented for the Greater London area within the city boundaries (Figure 1).

2.2 The Netatmo Weather Station

The amateur weather station chosen to be utilised in this study is the Netatmo weather station, which is easily configured and controlled by a smartphone (or tablet) to monitor and record the local environment. The involvement of the public in this approach is that they are the gatekeeper, or regulator, of their weather station as they install the device and ensure ongoing operational running. It is therefore considered to be a passive crowdsourcing method (Muller, et al., 2015). Whilst there are a large number of similar citizen science weather stations available (see Bell et al 2013; 2015), none have proven to be as prolific in adoption as the Netatmo, particularly in urban settings.

Netatmo weather stations consist of a number of sensors, which monitor inside and outside air temperature (specified manufacturers accuracy: ±0.3°C) and relative humidity (±3%) as well as indoor barometric pressure (±1mb), carbon dioxide concentration and noise pollution. Optional additional measurements include precipitation and wind, although these modules are less frequently purchased and therefore data are less available. Data is transmitted wirelessly, using a combination of Bluetooth and Wi-Fi, to the cloud where it can be accessed via a smart device, as well as being made available online via a ‘weathermap’ on the Netatmo website with observations updated every five minutes (Netatmo, 2015). The accuracy of the Netatmo weather station in controlled climatic conditions, and against standard outdoor apparatus, has been assessed by Meier et al (2015) where a sample of eight outdoor modules was tested and found to be mostly within the manufacturers specifications for between 0-30°C. However, a cold bias (of up to 1°C) was identified at higher temperatures.

2.3 Data Extraction

Data can be freely extracted from the Netatmo database using a specialist API. In this study, data requests were sent to the API using Javascript code run using the Node.js framework. The code extracted station ID, date & time stamp, latitude, longitude, altitude and air temperature for all 287 Netatmo stations located within the study area (Figure 1). Data was extracted to study the night-time UHI at 01:00BST ± 5 minutes over the study period of May and June 2015, several hours after sunset to ensure near-maximum UHI magnitude (Mavrogianni, et al. 2011). Stations which were not available for the entire study period were removed from the analysis.

Additional surface observation data from the British Atmospheric Data Centre was also used. London has seven traditional weather stations within the city boundaries (Figure 1) and this data serves two purposes in this study. Firstly, to provide an initial quantitative validation of the Netatmo data and secondly, to approximate the atmospheric stability for each night. As per Jones & Lister (2009), data from Heathrow (lat: 51.4787; long: -0.44904; elevation: 25m) and Kew Gardens (lat: 51.4813; long: -0.29276; elevation: 6m) was used to supplement Netatmo temperature readings with regional observations of cloud (Heathrow) and wind (Kew Gardens) to allow a classification of atmospheric stability over the study period via the Pasquill-Gifford approach (Table 1). Class E was the most common during the study, with the fewest number of days falling into class G. The lack of the ‘extremely stable’ class G days (especially in May) can be explained by the north-westerly air flow that brought wet and windy conditions with the UK receiving above average rainfall during the study period (157%). Increasingly stable conditions began to dominate in June due to a high pressure system after the first week with parts of London receiving only one third of its average rainfall along with sunnier than average conditions (117%) seen over the UK (Met. Office, 2015).

2.4 Data Processing & Quality Control

Data quality control is notoriously difficult with crowdsourced data (Muller et al, 2015), but a basic check is always recommended to remove any obviously erroneous values (caused by the poor siting of apparatus i.e. indoors or even in a greenhouse). Although, it cannot be determined with total confidence that data are actually erroneous, this is handled in this study by removing any observations that were found to be more than three standard deviations from the all station mean. Whilst just 5 sites were removed as a result of this process (~1.5%), this step would have been more important during a daytime study given the unshielded design of the Netatmo unit.

UHI magnitude was then calculated for each site by subtracting values from a rural reference site (Figure 2). The selection of a rural site is often difficult and care is needed to avoid unwanted biases from surface effects such as nearby water bodies or significant elevation differences (Stewart, 2011). Also given the small biases identified with the Netatmo unit by Meier et al (2015), it is important for consistency that the reference site is also a Netatmo station rather than a standard site. The site chosen was at Hildenborough, Tunbridge Wells (Lat: 51.216995; long: 0.243991; elevation: 47m). This was selected as it was consistently one of the coldest sites in the sample downloaded and was located at an elevation close to the average of London of 35m.

Indeed, the Tunbridge Wells area also has a history of being used as a rural reference site (see Chandler, 1965; Watkins, et al. 2002b).

Finally, average UHI maps per stability class were then produced using ordinary kriging in ArcGIS to spatially interpolate the Netatmo point data across the study area (Figure 3). For the validation exercise, comparisons were made per stability class using standard weather station data, averaged across the study period at 01:00 BST with the nearest Netatmo station (Table 2) and the spatially interpolated data (Table 3).

3. Results & Discussion

3.1. Characterising the London UHI

Figures 2 and 3 show that, as expected, there is a general increase in magnitude in the intensity of the UHI in line with atmospheric stability. Note that class F has a greater UHI magnitude than stability class G, but this is a likely consequence of the small sample size for class G. The differences between stability classes are significant as confirmed by a Friedman ANOVA and post-hoc Wilcoxon signed rank test (p=0.000).

These results also demonstrate that a UHI was consistently present during the study in London, with a baseline of around 1-2°C during periods of low atmospheric stability, rising to a maximum of 5.5°C in more stable conditions. However, as expected in a megacity such as London, there is no single urban heat core as is more commonly found in smaller urban areas.

Instead, the UHI in London manifests as a series of localised hot and cold anomalies (Kalnay and Cai, 2003; Tomlinson, et al., 2012; Grawe et al., 2013).

Three significant areas of urban heat can be found. As would be expected, there is a concentration in the urban core (i.e. the City of London) and central West London (just west of the City of Westminster) but also in the area surrounding Heathrow airport; a feature frequently mentioned in UHI studies of London (e.g. Jones & Lister, 2009). Indeed, Virk, et al. (2015) discuss how the building design of Heathrow airport causes overheating and localised warming. Similarly, localised cold anomalies correspond well with urban greenspace, for example the effect of Richmond Park can clearly be identified in the south west (as per Bohnenstengel et al. 2011), whilst the heat of the urban core is effectively split into two by the combined effect of Hyde Park, St James Park, Regents Park and Hampstead Heath (as per Wolf & McGregor, 2013). Similar smaller-scale features can also be seen across the study area, the majority of which can be explained by localised centres of population and greenspace (Figure 1). It is important to highlight that the potentially significant anomalies caused by Heathrow and London Parks will not be fully captured in this study given the absence of Netatmo units in these localities. Instead, the results show the more generalised impact of such features on the surrounding area (see Stewart & Oke, 2012). This is particularly highlighted in the validation exercise where the Netatmo weather sites are consistently warmer than the standard sites which are more typically located in areas of greenspace (Tables 1 and 2: discussed in detail in the next section). Finally, the location of the highlighted features appears consistent regardless of atmospheric stability with little evidence of larger scale advective effects in unstable conditions.

As the true magnitude of the UHI can be hidden by averaging (Tomlinson, et al. (2012), a single extreme event was also investigated. The UK was subject to a heatwave event in early July 2015 caused by a warm southerly flow that brought hot air from continental Europe over the study area. To investigate, temperature data was obtained for 01:00BST ± 5 minutes on 2nd July. The proceeding day saw 36.7℃ recorded at Heathrow Airport which was the highest temperature recorded anywhere in the UK since the heatwave event of August 2003 (Met Office, 2015b). These conditions led to a significant UHI on the evening of the 1st July with a magnitude of nearly 6°C (Figure 3). The general trend is that the localised hot and cold anomalies become more pronounced in heatwave conditions although relative positions varied little. For example, a significant intensification of heat is evident in the docklands east of the city, a landuse often associated with increased temperatures (Oke, 1997; Grimmond, 2007). However, the highest temperatures are actually found within the Waltham Forest area of the city. This is not evident in the previous analyses and is most likely an outlier, perhaps best explained by the limitations of using crowdsourced data. However, inspection of Figure 2 does indicate that three stations were recording a heat anomaly in the area which does increase confidence in the legitimacy of the localised effect on this night.

3.2 Data Validation & Limitations

As the validation exercise has shown (Tables 2 & 3), for six of the seven standard sites there appears to be a consistent warm bias in the Netatmo data, increasing in line with atmospheric stability. This is particularly evident during the heatwave event (Table 4), where a warm bias of up to 3.1°C is evident in the interpolated data (3.6°C in the nearest station analysis). City

Airport, which itself exhibits a consistently warm bias, is the main anomaly in this exercise, but this can be explained by its location directly adjacent to the large thermal mass of the Thames Estuary. The observed biases of the other sites appear to contradict the cold bias of the Netatmo unit previously identified by Meier et al (2015), but it is important to highlight that this is unlikely to be an instrumentation bias, but a siting bias. Instead, the results emphasise the 'warming' effect of the increased data coverage in less well exposed residential areas (Bell, et al. 2013), as opposed to areas of greenspace (e.g. Richmond Park, Waltham Forest) or highly industrialised or commercial landuses (e.g. London Docklands). This effect is to some degree confirmed by the increase in bias in line with atmospheric stability and underlines the difference in climate experienced by individuals compared to standard observation sites. Whilst it is clearly useful to measure at a higher resolution in residential areas, this siting bias needs addressing, particularly as the sample can be further biased as such weather stations could be considered to be a 'luxury' item resulting in increased coverage in the more affluent areas of the city. Such problems could be overcome by researchers by purchasing additional units for field campaigns to fill such gaps.

Linked to this, quality assurance and control represents the biggest challenge when using crowdsourcing techniques (Bell, et al. 2013; Muller, et al. 2015). Metadata is traditionally used to improve understanding of the limitations of data (i.e. site exposure, calibration and instrumentation quality and history), but given the nature of the deployment, such data is not readily available. Limited verification is possible using tools such as Google Earth, but this is insufficient to fully determine data representativity (i.e. consistent sensor height and exposure: the WMO (2008) state that air temperature should be measured between 1.25-2.0m - the reality is that this will be measured at a range of different heights in this study). This limitation can only realistically be overcome by including a voluntary metadata section online for end-users to document, with images, the siting and exposure of their instruments. An alternative approach is to purchase and deploy additional Netatmo units to act as ‘gatekeepers’ complying as close as possible to WMO guidelines for quality control purposes (Goodchild and Li, 2012)

These limitations can be clearly seen in this study in the form of a localised heat island in the area around Biggin Hill in the southeast of the study area during the heatwave event. Closer inspection of the data shows that this is actually the result of a single weather station with what appears to be a warm bias (Figure 2). Without more stations or improved metadata, it is impossible to determine exactly whether this is an outlier (e.g. unit located in a greenhouse), although the presence of a localised heat island at this location is certainly not highlighted in previous studies.

Other sources of uncertainty linked with utilising data from amateur weather stations include ongoing calibration by users (or a lack of) and general design flaws (Bell, et al. 2015). For example, a particular design concern with the Netatmo unit is the fact it is an unventilated sealed unit. The problem is further compounded by the lack of a radiation shield which would be particularly problematic if the data was used for daytime studies. Longer term issues could also be a problem as it is well documented that lower cost sensors require more frequent calibration due to a greater tendency for drift (Young et al, 2014), emphasising the need for regular calibration which is particularly challenging in a citizen science setting. However, despite these concerns, the results from the validation exercise in the paper along with previous comparisons of the Netatmo with standard measurements have proved promising (see Meier et al, 2015), although extended records and larger scale studies are required before any significant conclusions can be drawn.

4. Conclusions

Overall, this study has shown the potential of using crowdsourced data for meteorological studies from a new generation of internet-connected weather stations. The results are encouraging and highlight increases in overall magnitude of the UHI in line with atmospheric stability as well as similar localised cold and heat anomalies to previous studies in London. However, differences were also noted in the distribution of urban heat from previous studies and it is these local anomalies, along with instrumentation and siting biases when compared with standard instrumentation, that highlight the limitations of the technique and the need for improved data quality control measures when using crowdsourced data.

There is much that could be done to improve the quality of measurements and this now needs to be the priority for further research and development in the area. For example, online data hubs could play an increasingly important role in standardising observations. Hubs such as WOW (wow.metoffice.gov.uk) and Weather Underground (wunderground.com) already receive daily observations from tens of thousands of automatic weather stations. As each hub dictates the format of observations, the data naturally inherits a degree of uniformity (e.g. same units). This can also be taken a step further, encouraging station owners to provide additional metadata about their new station. Weather Underground already requires users to list the station model, height above ground, and surface type (e.g. grass) to be noted. WOW allows users to grade their sites based upon schemes from the Climatological Observers Link and the WMO. It focuses on attributes that affect the accuracy and spatial representativity of a site such as its exposure, degree of surrounding urbanisation and the instrumentation in use. Unfortunately, a consequence of the ‘plug and play’ nature of Netatmo stations is that virtually no metadata is available, but this could be addressed by asking users for details during the registration process.

Increased metadata will not only increase user confidence with the data, but will also ensure that contributors think more about the quality of data that they are producing. As suggested, this would be further aided by the provision of detailed guidance from the manufacturer. Indeed, the manufacturers of smart devices could greatly improve the product offering by working more closely with meteorology experts to advise on not only metadata, but product design (i.e. improved shielding and ventiliation) and automated quality control such as bias correction online (whilst maintaining the availability of raw data). Further detailed testing of apparatus in the laboratory would also be advantageous (e.g. Meier et al, 2015), and there is a need for long term assessments against traditional techniques and a pressing need to devise strategies which enable in-situ calibrations of multiple units in the field to ascertain errors associated with relying on the crowd. The use of gatekeepers has already been mentioned, and indeed the sparse network of existing standard weather stations as in this paper, but it is here where high resolution Urban Meteorological Networks (in different climates around the world) can play an increasingly important role to improve end-user confidence in the data in highly instrumented cities and thus permitting the expansion of global studies that rely on crowdsourcing data alone (Chapman et al, 2015). However, a key question remains whether a large number of less accurate observations can give better results than a low number of accurate observations.

Overall, this study has clearly highlighted the potential of crowdsourcing data to rapidly provide a high resolution air temperature dataset. However, the potential is not limited to air temperature and many other meteorological parameters can be sensed using this approach. It is clear that a new generation of manufacturers such as Netatmo have achieved, over a very short timescale, a resolution of data that has previously been impossible in atmospheric science. This feat, along with the desire to share real-time data so easily via online maps and APIs is not to be underestimated and should be highly commended. Whilst the approach should not be seen as a cheap replacement for long established techniques, it appears a complementary means to expand our capabilities in all areas of the atmospheric sciences (e.g. Mass & Madaus, 2014). It is for this reason why it is now time for the atmospheric science community to embrace these new approaches and to work together with emerging, somewhat untraditional, technology companies to ensure that this extremely powerful approach is fit for purpose to meet the needs of all.

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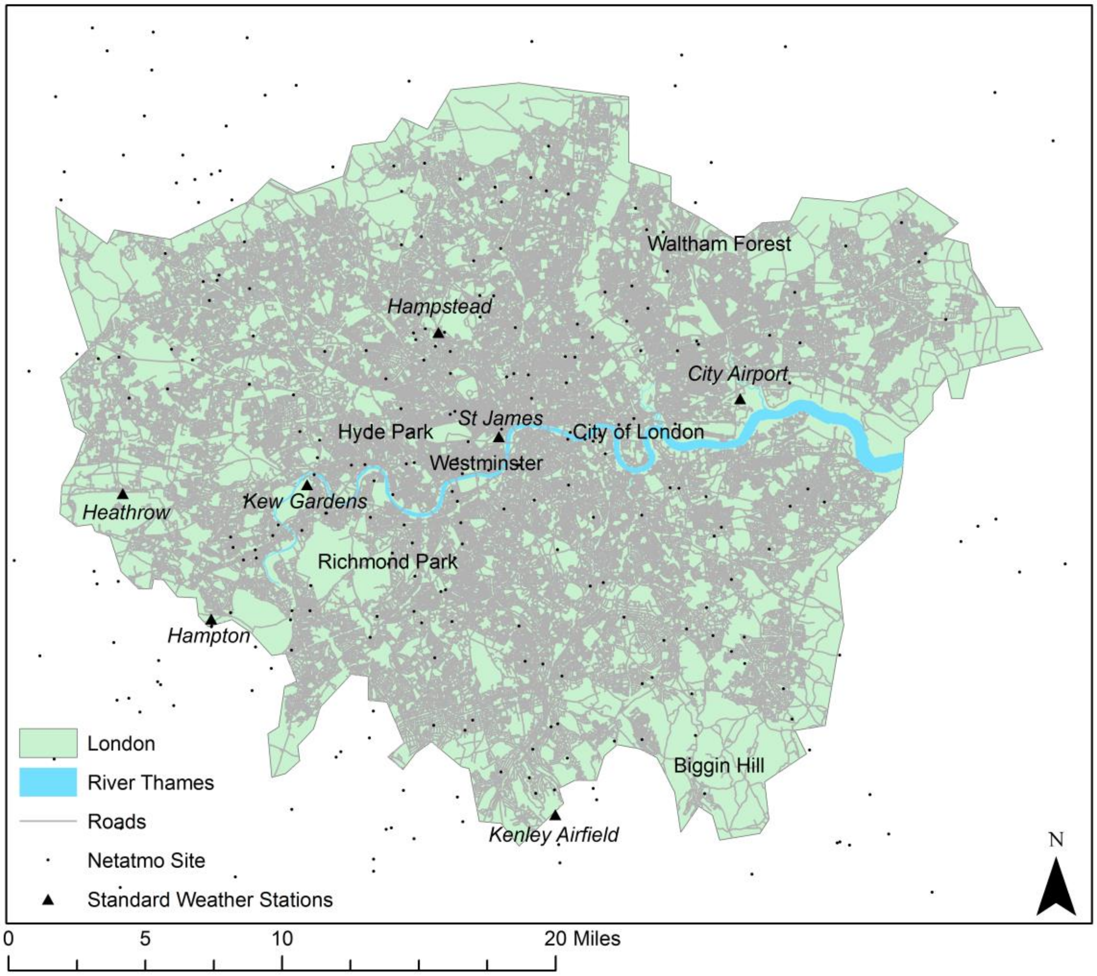
List of Figure Captions

Figure 1: Study area highlighting locations of Netatmo and standard weather stations as well as other locations discussed in text.

Figure 2: Urban heat island maps based on site specific values for each Pasquill Gifford stability class (D,E,F,G) and a heatwave event.

Figure 3: Spatially interpolated urban heat island of maps for each Pasquill Gifford stability class (D,E,F,G) and a heatwave event.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City Airport
St James
Hyde Park
City of London
Westminster
Kew Gardens
Heathrow
Richmond Park
Hampton
Biggin Hill
Kenley Airfield
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London
River Thames
Roads
Netatmo Site
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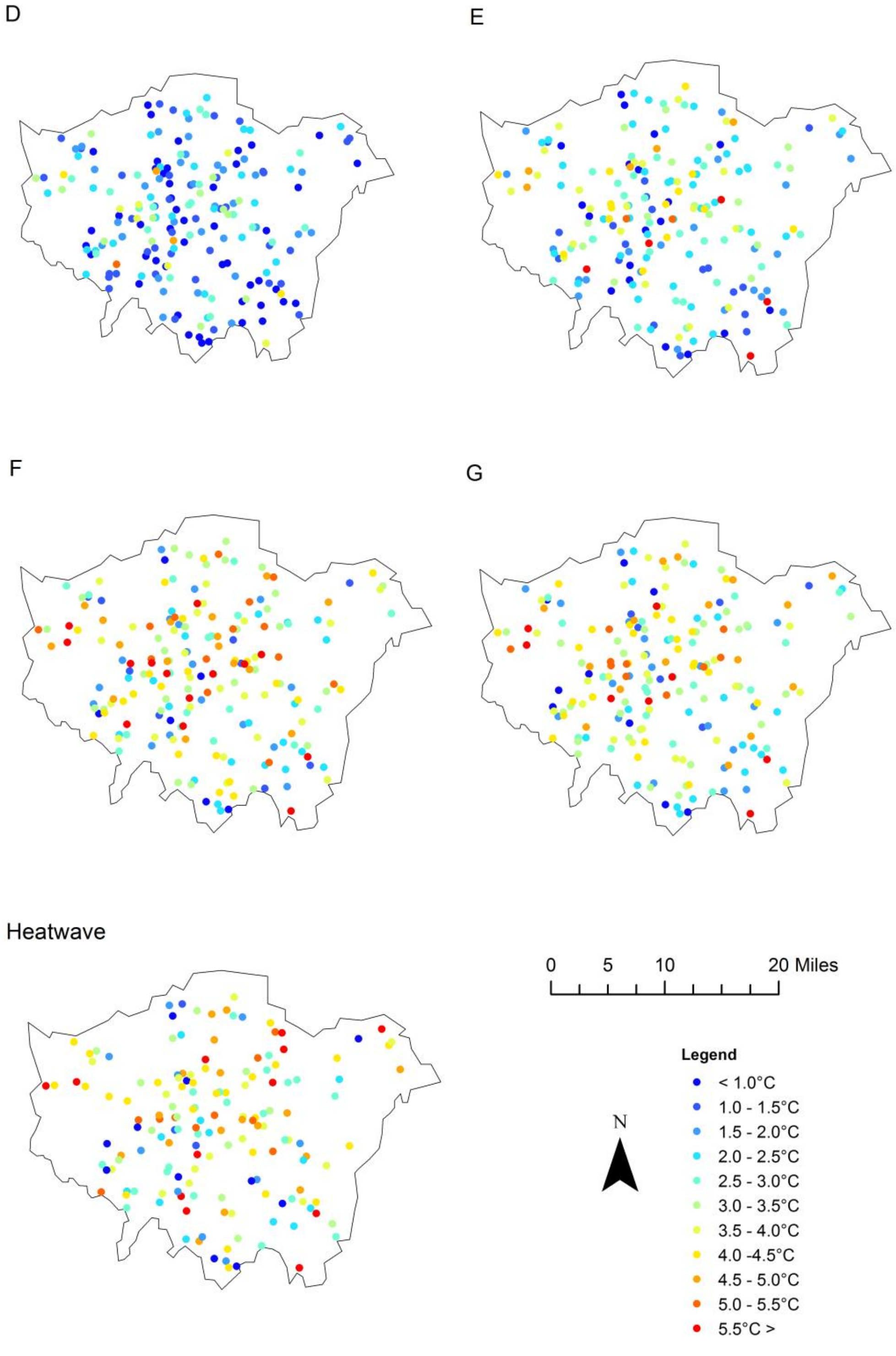
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2.0 - 2.5°C
2.5 - 3.0°C
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4.5 - 5.0°C
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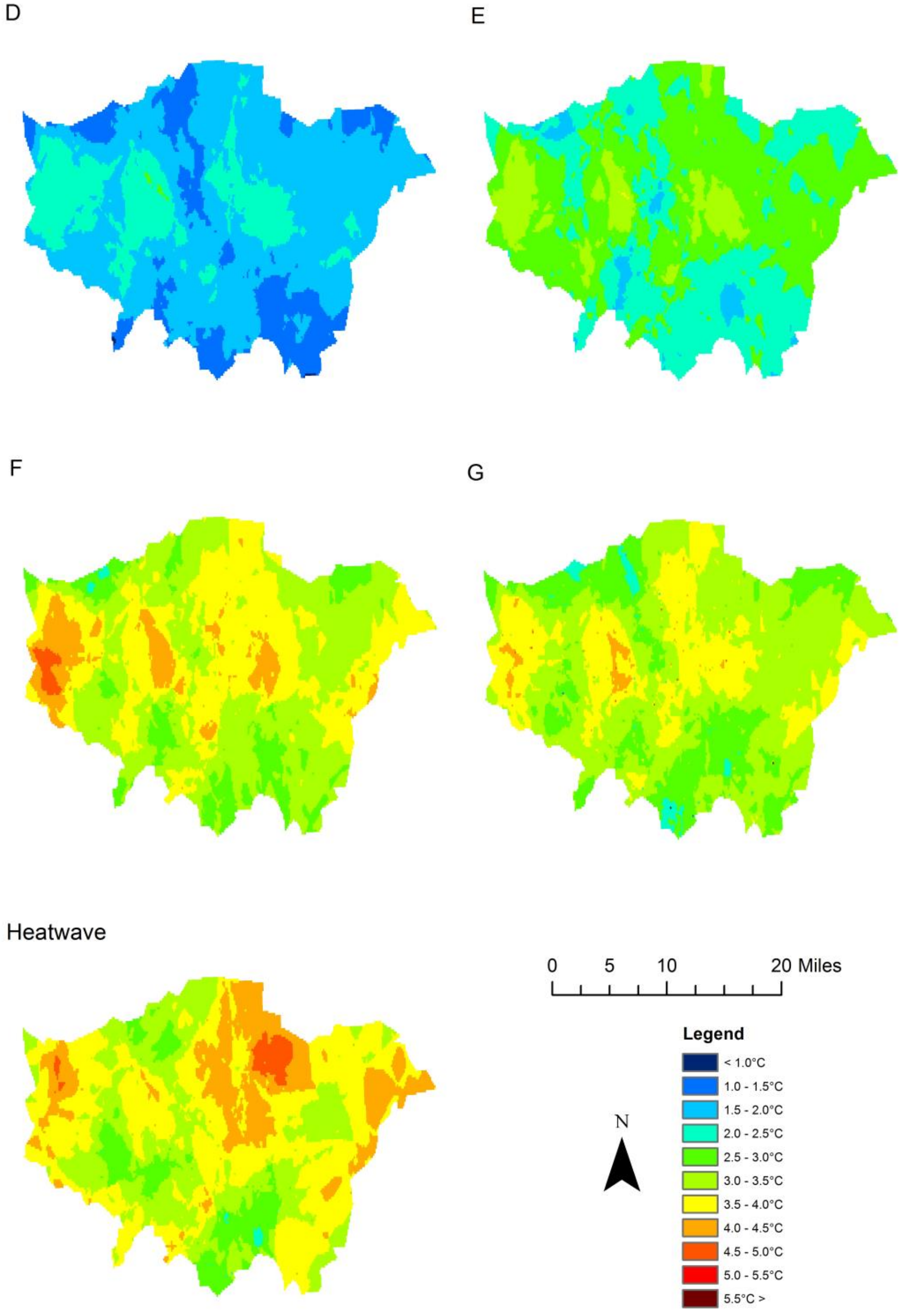
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5.0 - 5.5°C
5.5°C >
N

Table 1: Pasquill-Gifford stability classes (Pasquill & Smith, 1983)

Surface Wind Speed (m/s)	Pasquill-Gifford Stability Class	
	≥ 4/8 oktas cloud	< 4/8 oktas cloud
<2	G	G
2 - 3	E	F
3 - 5	D	E
5>	D	D

Table 2: Biases between Netatmo weather sites and official weather stations using averaged data from 01:00BST over the study period.

Station Name	Distance between observations	Bias (°C)			
		Class D	Class E	Class F	Class G
Hampstead	362m	0.9	2.9	3.4	2.1
St James	471m	1.2	1.9	2.6	2.5
Heathrow	7175m	1.3	1.9	2.9	3.5
Hampton	1200m	0.8	1.0	1.9	2.2
Kew Gardens	1686m	0.4	2.2	0.8	2.7
Kenley Airfield	1460m	0.3	0.1	0.5	0.6
City Airport	3065m	-1.1	-1.4	-1.3	-0.2
Average Bias		0.5	1.2	1.6	1.9

Table 3: Biases between spatially interpolated Netatmo data and official weather stations using averaged data from 01:00BST over the study period.

	Bias (°C)			
Station Name	Class D	Class E	Class F	Class G
Hampstead	1.6	1.9	2.6	2.4
St James	0.1	0.3	0.9	1.0
Heathrow	1.3	1.6	2.6	2.2
Hampton	0.4	0.8	1.1	1.3
Kew Gardens	0.8	1.5	2.2	2.3
Kenley Airfield	1.8	1.9	2.6	2.6
City Airport	-0.2	-0.3	-0.2	0.4
Average Bias	0.8	1.1	1.7	1.7

Table 4: Quantitative validation between Netatmo weather sites and official weather stations on the 02/07/2015 01:00BST.

Station Name	Air Temperature (°C)		Distance between observations	Bias (°C)	Spatially Interpolated Temperature (°C)	Bias (°C)
	Weather Station	Netatmo				
Hampstead	21.7	23.8	362m	2.1	23.7	2.0
St James	23.0	25.5	471m	2.5	23.6	0.6
Heathrow	21.4	19.8	7175m	-1.6	24.2	2.8
Hampton	21.7	25.3	1200m	3.6	23.8	2.1
Kew Gardens	21.3	20.3	1686m	-1.0	23.1	1.8
Kenley Airfield	19.6	20.1	1460m	0.5	22.7	3.1
City Airport	24.0	23.0	3065m	-1.0	23.3	-0.7
Average Bias				0.73		1.67