TITLE: **London's urban climate: historical and contemporary perspectives**

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Introduction

The history of urban climatology is linked in many ways to London. The origin of the field is widely attributed to Luke Howard[1] and his influential book 'The Climate of London'; London was the first global megacity and for hundreds of years has experienced many of the 'issues' that are now the stimulus for urban climate research – emissions, air quality, heat stress, sustainable development; and influential climatologists, Gordon Manley, Tony Chandler and Bruce Atkinson, for example, have worked in and on the city advancing how we measure, analyse and model urban climate. Here a brief overview is presented, structured around the issues that provided the rationale for the studies – all of which persist today.

At the outset it is important to note two caveats. First, while examples of earlier work are presented these are not in any way exhaustive[2] nor intended to be. Second, the focus here is on the physical nature of the urban atmosphere, particularly temperature, not its chemical composition; though the two are of course not independent, especially in the context of air quality

Earliest concerns remain those of today - Urban Air Quality

Although human activities, most notably fire, have affected air quality for thousands of years, Helmut Landsberg (1981[3]) in his book cites Neumann (1979[4]) as identifying odes of Quintus Horatius Flaccus about 24 B.C. as the earliest reference. Landsberg's (1981) subsequent descriptions of air pollution all focus on London and attempts to ban coal burning in 1273, 1306 (King Edward I), by Queen Elizabeth I (1533-1603) for periods when Parliament was sitting, and John Evelyn (1661[5], *The Rota* 1976[6]) attempts to influence Charles II.

John Evelyn was not successful in getting coal burning banned, but his 1661 publication provides an early description of air pollution in London (Chandler 1962[7], Land berg 1981, Atkinson 1985[8]). Describing London as a '*city consisting of a wooden, northern, and inartificial congestion of houses; some of the principal streets so narrow, as there is nothing more deformed and unlike than the prospect of it at a distance, and its asymmetrie within the walls' (The Rota 1976 citing Everlyn 1659, p1).* Evelyn recognised the link between urban air quality and urban form. He also became a Commissioner for the improvement of the City streets and through this encouraged planting of trees in the Royal Parks (The Rota 1976). Following the Great Fire in September 1666 (when ca. 13,200 houses and a large number of churches and City of London buildings were destroyed), he again made recommendations about tree planting, again without success (The Rota 1976).

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[1] Howard L 2007. The Climate of London. IAUC edition available at www.lulu.com in two volumes
[2] I would welcome suggestions of other sources to consult.
[3] Landsberg H (1981) The Urban Climate. Academic Press.
[4] Neumann J (1979) Air pollution in Ancient Rome. Bull Amer. Meteorol. Soc, 60,1097
[5] Evelyn J (1661) Fumifumigium or The Inconveniencie of the AER and SMOAK of LONDON DISSIPATED. With fome Remedies humbly proposed available: http://ia600204.us.archive.org/6/items/fumifugium00eveluoft/fumifugium00eveluoft.pdf
[6] The Rota (1976) Front pages in Evelyn (1661[5])
[7] Chandler TJ (1962) London's Urban Climate, The Geographical Journal 128, 279-98
[8] Atkinson BW (1985) The Urban Atmosphere. Cambridge University Press, 85 pp

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These themes of urban morphology and the planting of trees both remain at the fore of urban air quality and health studies today. For example, a large research project funded by EPSRC and then the Home-Office, DAPPLE[9] (Dispersion of Air Pollution and its Penetration into the Local Environment) led by Alan Robbins, used a variety of techniques to study in detail 'the most polluted street in Europe' (Marylebone Road in London). Data were collected about the physical state of the atmosphere, exposure and ambient air quality, in conjunction with information on traffic (Arnold et al. 2004[10], Dobre et al. 2005[11], Tomlin et al. 2009[12], Wood et al. 2009[13]). These field measurements have been complemented with wind tunnel (hardware) and numerical modelling. Results show clearly that the dispersal of pollutants is highly dependent on the meteorological conditions (stability, and variability of the 3-d wind field) and morphology of the urban surface.

Tree planting is part of the current London Climate Change Adaption Strategy (GLA 2010a[14]) and the latest GLA (2010b[15]) air quality strategy for London 'Cleaning the Air'. Air quality is a major issue; the 2008 annual limit value of NO_2 (40 µg m^{-3}) was exceeded by 1287 km of road in 2008 in London (in 2010 947 km). Despite improvements it is anticipated it may take almost to 2025 to bring this to 0 km (Defra 2011[16]). As road traffic is the dominant source, London has introduced a low emission zone to reduce emissions; however, this remains highly contentious. Mayor Boris Johnson has removed the western extension of the congestion charging zone.

Development and Deployment of Instruments

Before measurements of urban climates could begin instruments had to be developed and procedures for deployment were needed. Much of this was communicated through The Royal Society which was officially established in 1660[17]. In 1665 Hooke's Micrographia[18] included descriptions of his thermometer, a modified design of an Italian one, which included a scale. His thermometer was to act as a standard until 1709 with numerous developments during this period (Patterson 1951[19], Quinn and Compton 1975[20]). New instrumentation continues to be developed and used today; As in the past new instruments allow new variables to be observed and new sites to be instrumented. Today in London Large Aperture Scintillometry (Gouvea et al. 2011[21]) and

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[9] http://www.dapple.org.uk/

[10] Arnold SJ, H ApSimon, J Barlow, S Belcher, M Bell, JW Boddy, R Britter, H Cheng, R Clark, RN Colvile, S Dimitroulopoulou, A Dobre, B Greally, S Kaur, A Knights, T Lawton, A Makepeace, D Martin, M Neophytou, S Neville, M Nieuwenhuijsen, G Nickless, C Price, A Robins, D Shallcross, P Simmonds, RJ Smalley, J Tate, AS Tomlin, H Wang, P Walsh (2004) Introduction to the DAPPLE Air Pollution Project. *Science of the Total Environment* 332:139-153.

[11] Dobre, A., Arnold, S. J., Smalley, R. J., Boddy, J. W. D., Barlow, J. F., Tomlin, A. S. and Belcher, S. E. (2005) *Flow field measurements in the proximity of an urban intersection in London, UK.* Atmospheric Environment, 39 (26). pp. 4647-4657.

[12] Tomlin, A. S., Smalley , R. J., Tate, J. E., Arnold, S. J., Dobre, A., Barlow, J. F., Belcher, S. E. and Robins, A. (2009) A field study of factors influencing the concentrations of a traffic-related pollutant in the vicinity of a complex urban junction. Atmospheric Environment, 43 (32). pp. 5027-5037

[13] Wood, C. R., Arnold, S. J., Balogun, A. A., Barlow, J. F., Belcher, S. E., Britter, R. E., Cheng, H., Dobre, A., Lingard, J. J. N., Martin, D., Neophytou, M. K., Petersson, F. K., Robins, A. G., Shallcross, D. E., Smalley, R. J., Tate, J. E., Tomlin, A. S. and White, I. R. (2009) Dispersion Experiments in Central London: The 2007 DAPPLE project. Bulletin of the American Meteorological Society, 90 (7). pp. 955-970. ISSN 1520-0477

[14] GLA (2010b)http://legacy.london.gov.uk/mayor/priorities/docs/Climate_change_adaptation_080210.pdf

[15] GLA (2010a) Cleaning the Air: The Mayor's Air Quality Strategy http://www.london.gov.uk/sites/default/files/Air%20Quality%20Strategy%20v3.pdf

[16] http://uk-air.defra.gov.uk/library/no2ten/documents/110609_UK_overview_document_FINAL.pdf

[17] http://royalsociety.org/about-us/history/

[18] Hooke R (1665) Micrographia. http://www.gutenberg.org/ebooks/15491

[19] Patterson LD (1951) Thermometers of the Royal Society, 1663–1768, American J. of Physics 19, 523 -535

[20] Quinn TP, J P Compton (1975) The foundations of thermometry *Rep. Prog. Phys*. 38, 151-239

[21] Gouvea M, L Pauscher L, S Kotthaus, H Ward, F Lindberg, J Evans, C Wood, J Barlow, J Salmond, T Foken, S Grimmond (2011) Initial results from scintillometer measurements at different scales in central London, 3rd Scintillometer Workshop, Wageningen, The Netherlands, 18-19 April 2011

Ceilometry (Loridan et al. 2011[22]) is being used, along with multiple sensors that can now be relatively cheaply produced because of new technology (Watkins et al. 2002[23]; Mavrogianni et al. 2011[24], Ryder and Toumi, 2011[25]).

Early attention in London was also directed to the siting of instruments, again through initiatives from the Royal Society. In the 1660s Robert Hooke made recommendations on how to observe (Kingston 1997). In 1723 there was a second attempt to establish an International meteorological network which was led by the Royal Society (Jurin 1723[26], Camuffo 2002[27]). Recommendations were made for sensor location (inside a North facing room with infrequent fire) and measurement procedures based on John Locke[28] of London (Camuffo 2002) and Robert Hooke (Kington 1997[29]).

The appropriate siting of instrumentation continues to be an issue. This is partly because instruments are deployed for multiple purposes and because of the need to ensure that instrumentation is not stolen or vandalized. Meta data about sites and instruments are critical. Robinson (2010[30]) recently completed a detailed survey of a large number of the climate stations located within London. This follows an earlier study of some of the stations by Nuffield Students while at KCL[31]. These reveal marked differences between networks and sites.

The Study of London as part of studies of Regional Climate

The first sets of analyses of meteorological data observed in London were concerned not with the urban aspects of London but rather its general, regional location.

Long term rainfall records for London extend back to 1727 (Nicholas and Glasspoole 1931[32] cited by Jones et al. 1997[33]) and for temperature[34] back to 1659 (Manley 1974[35]), with daily data from 1772

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[22] Loridan T, CSB Grimmond, BD Offerle, DT Young, T Smith, L Jarvi, F Lindberg. Local-Scale Urban Meteorological Parameterization Scheme (LUMPS): longwave radiation parameterization & seasonality related developments Journal of Applied Meteorology & Climatology. **50**: 185-202 doi: 10.1175/2010JAMC2474.1

[23] Watkins R, J Palmer, M Kolokotroni, P Littlefair (2002), The London Heat Island—surface and air temperature measurements in summer 2000, *ASHRAE Trans 2002* **108** (2002) (Pt1).

[24] Mavrogianni A, M Davies, M Batty, SE Belcher, SI Bohnenstengel, D Carruthers, Z Chalabi, B Croxford, C Demanuele, S Evans, R Giridharan, JN Hacker, I Hamilton, C Hogg, J Hunt, M Kolokotroni, C Martin, J Milner, I Rajapaksha, I Ridley, JP Steadman, J Stocker, P Wilkinson, Z Ye (2011) The comfort, energy and health implications of London's urban heat island Building Serv. Eng. Res. Technol. 32, 35–52

[25] Ryder CL, R Toumi (2011) An urban solar flux island: Measurements from London, Atmospheric Environment 45, 3414-3423

[26] Jurin AJ (1723) Invitatio ad Observationes Meteorologicas Communi Consilio Instituendas, *Philosophical Transactions,* 32, 422-427 (in Latin)

[27] Camuffo D (2002) History of the long series of daily air temperature in Padova (1725–1998) *Climatic Change* 53: 7–75,

[28] No reference is given by Camuffo (2002) for this. But there is a paper: Locke J (1704-1705) A Register of the Weather for the Year 1692, Kept at Oates in Essex. *Philosophical Transactions*, 24, 1917-1937 which has data observed by day and hour.

[29] Kington J (1997) Observing and measuring the weather: a brief history, in Hulme and Barrow (ed) 'Climate of the British Isles: present, past and future' Rouledge, London, 137-152.

[30] Robinson P. (2010) *The London Meteorological Monitoring Network.* MSc in EMMM, King's College London.

[31] http://geography.kcl.ac.uk/micromet/

[32] Nicholas FJ and Glasspoole J (1931) General monthly rainfall over England and Wales 1727 to 1931*, British Rainfall* 1931,299-306.

[33] Jones PD, D Conway, K Briffa(1997) Precipitation variability and drought. in Hulme and Barrow (ed) 'Climate of the British Isles: present, past and future' Rouledge, London, 196-219.

[34] This is referred to as the Central England Temperature data set as not all data are actually for London for a variety of reasons (Manley 1974). The data are presented in a number of papers and summarized in Hulme and Barrow (1997, Appendix D)

[35] Manley G (1974), Central England temperatures: Monthly means 1659 to 1973. Quarterly Journal of the Royal Meteorological Society, 100: 389–405. doi: 10.1002/qj.49710042511

(Parker et al. 1992[36]). Routine collection of temperature data in the vicinity of London appear to have begun around 1763[37] at a time when a number other cities in Europe began to collect similar observations (Brunt 1926[38]). Hourly air temperatures were collected in London at the Greenwich Observatory from 1814. Rainfall was measured from 1813 and at Camden Square from 1858 (Brunt 1926). Unfortunately, there is one gap in the data (January 1707-October 1722), which seems to stem from the fact that the data were destroyed by the Royal Society as they were perceived ofbeing of no further use (Manley 1974, p391[39]).

By 1800 London was the first megacity in the world (Molina and Molina 2004[40]) with a population of 1 million people. This grew to 1.45 million by 1821 (Figure 1). It was in this period that Luke Howard initiated his observations which resulted in his books 'The Climate of London', editions of which were published in 1818, 1820 and 1833[41]. This seminal work, which formally recognises human effects on climates in cities, is commonly regarded as establishing the foundations of the urban climate field (Chandler 1962, Landsberg 1981, Lee 1984[42], Mills 2008[43]).

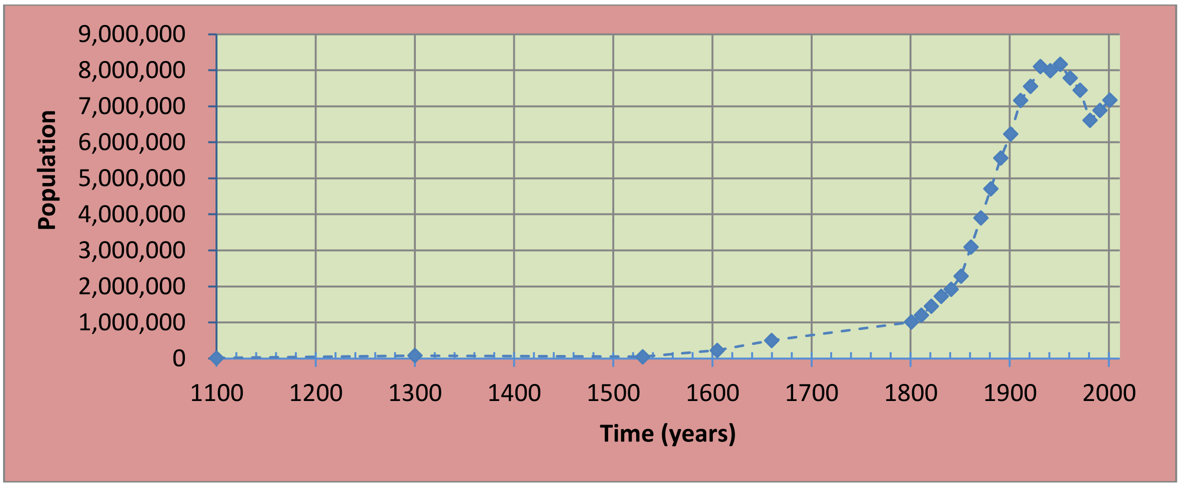

Figure 1: Population of London since 1100. Data sources: http://www.visionofbritain.org.uk/; http://www.londononline.co.uk/factfile/historical/; http://en.wikipedia.org/wiki/History_of_London

Luke Howard conducted observations of air temperature in a variety of different locations around London over a period of 25 years (Chandler 1962, Mills 2008, his Table 1). He analysed this data in conjunction with measurements established at Somerset House in 1806[44] (Chandler 1962). Although the exposure of the instrument varied between the sites, and was not always known[45] (Chandler 1962, Mills 2008), the daily data allowed him to draw conclusions that identified what we would now refer to as the 'urban canopy air temperature urban heat island (UHI)'. Luke Howard also

[36] Parker D E, Legg TP, Folland C . (1992), A new daily central England temperature series, 1772–1991. International Journal of Climatology, 12: 317–342. doi: 10.1002/joc.3370120402
[37] January 1764 is first monthly data reported by Brunt (1925) but he indicates there is annual data for 1763
[38] Brunt D (1926) Periodicities in European Weather *Philosophical Transactions of the Royal Society of London. Series A,* 225, 247-302
[39] Manley (1974) cites Philos. Trans., 24, 1707, p. 347; Symons Magazine, 59, 1924, pp. 183-184.
[40] Molina MJ, LT Molina (2004) Megacities and atmospheric pollution *Air & Waste Manage. Assoc.* 54:644-680.
[41] Howard L (1818) The Climate of London; Howard L (1820) The Climate of London, Vol 2; Howard L (1833) The Climate of London, 2nd Edition
[42] Lee DO 1984 Urban climates *Progress in Physical Geography 8: 1-31*
[43] Mills G (2008) Luke Howard and The Climate of London. *Weather*, 63,153-157.
[44] The Royal Society moved in to Somerset House in 1780 and given the long connection already with the thermometer, the 1806 date may refer to Howard's initial measurements rather than the Royal Society's.
[45] The Royal Society was located to the East of the Strand Entrance where the Courtauld Institute of Art now occupies (http://royalsociety.org/about-us/history/somerset-house/). Some probable location could be possibly determined.

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observed other variables including rainfall, pressure, and clouds. Through careful analyses of these data, and consideration of measurement issues, he identified the controls on a number of variables. As Mills (2008) notes, Howard's interest was regional so it was the careful data collection that allowed him to identify that he had observations that were being affected by more than the regional influences. Through consideration of the impact of sites, instrumentation and exposure, he was able to conclude that London, specifically the urban emissions; e.g. anthropogenic heat (fires, metabolism of people), urban morphology (influencing wind and radiation), and differences (in evaporation rates) influenced the observations.

Many authors since Howard have analysed data collected in London. Many, like him, have been concerned with the London data for its meso-scale features or regional location (e.g Brunt 1926). However, Bilham (1938[46]) in his book 'The Climate of the British Isles' includes an eight page section on 'Town Climates' (p303-311). Although initially concerned with air quality ('smoke pall') and the 'sordid' surroundings of the town, Bilham provides a climatology of sunshine hours comparing the London Central area and the suburbs. Recently, Ryder and Toumi (2011) had a similar focus, using low cost incoming shortwave radiation sensors located across the 33 Boroughs of London to identify what they term a 'solar flux island' which like Bilham (1938, his Figure 99) shows the radiation deficit in the central area of London (Ryder and Toumi 2011, their Figure 3).

Bilham (1938) also conducted two paired comparisons of air temperature for two periods: 1906-1935 between Westminster (also known as St James's Park) and Wisley, and 1921-1935 for Kensington and Croydon, with a mean monthly analysis based on the mean, maximum and minimum temperatures. He notes that the town has higher temperatures by night and day in almost all months. The mean difference is 1°F in Kensington (1.5 °F summer, 0.6 °F winter). Following a detailed analysis of the relative elevation of the sites, he rejects that as the explanation, rather invoking 'retention of heat by the brickwork' and reduced nocturnal radiation loss. Recent studies have calculated and mapped the sky view factor, which has a high correlation with the UHI (Oke 1981) for the whole of London (Lindberg and Grimmond 2010[47], Figure 2).

Bilham (1938) also analysed wind data observed at South Kensington (30' above roof, 110' above ground level, Science Museum), Kew Observatory and Croydon (105' above ground level, most open). The latter was regarded as being of the outskirts of London. The role of buildings reducing wind speeds is clear from his analyses.

Three books published in 1950's focused on regional climate (Manley 1952, Meteorological Office 1952[48], Brooks 1954[49]). Although '*The Climatological Atlas of the British Isles'* identified 13 weather stations for London, the only maps of London are for rainfall (1881-1915, June 16 1917) and fog (visibility < 1100 yards Sept 1 1936 to March 1937 at 9h). There is also little in Brooks' (1954) book despite three potentially relevant chapters ('Fog and Soot', 'Local climate' and 'Where to live; Where to holiday'). Not unexpectedly, air pollution receives the most analysis with relations between coal consumption, soot deposition and visibility. Additionally, the micro-scale impact of the surface on air temperature[50] (including tarmac and brick rubble) and the influence on frost dates (but for a Midlands city) are addressed. Manley's (1954) book 'Climate and the British Scene' mentions London

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46 Bilham EG (1938) The Climate of the British Isles, Macmillian and Co Ltd, London, 347pp
47 Lindberg F & CSB Grimmond, Continuous sky view factor from high resolution urban digital elevation models, *Climate Research* 42: 177-183 doi:10.3354/cr00882
48 Meteorological Office (1952) The Climatological Atlas of the British Isles, M.O. 488, HMSO
49 Brooks' (1954) 'The English Climate'
50 This may have been influenced by the 1953 publication of 'Micrometeorology' by O.G. Sutton. This book has no reference to urban climate.

but does not address London's urban climate. Interestingly though, his 1944[51] paper which has a number of figures that appear in his later book, does have a section about urban climates. However, there he notes that Bilham (1938) has addressed London so he turns his attention to Manchester.

In 1976 another book with a similar title was edited by Chandler and Gregory (1976[52]) 'The Climate of the British Isles'. This, not unsurprisingly, does have a chapter by Chandler on 'The Climate of Towns'. Whereas later books, such as Wheeler and Mayes (1997[53]), just has a focus box on the London's UHI (p72, Mayes 1997[54]).

The Great Smog

In terms of air pollution, little changed from the conditions that stimulated Evelyn's (1661) writings for another 300 years. A series of "killer smog" events in the 1940s and 1950s related to exposure to sulphurous oxides (SO_2 and SO_4) from the burning of coal (Molina and Molina 2004) culminated in the "Great Smog of December 1952". The latter resulted in the premature deaths of 12,000 (Bell et al. 2003[55]) and was sufficient to trigger public awareness of air pollution with consequent legislation (the 1956 Clean Air Act). In 1957 a smoke-free zone in central London was initiated (Chandler 1962). This stimulated a number of scientific studies and advances which have themes related to air pollution, air pollution and health/mortality, climatology and weather. Recent examples of such studies include DAPPLE[9], REPARTEE[56] and CleafLO[114].

The Great Smog was associated with particularly cold temperatures. As people burnt coal to heat their houses, emissions combined with those from factories, were trapped by the lower boundary layer. This impacted visibility and brought the city to a halt. Today, new instruments, many some form of LiDAR, allow almost real-time observations of boundary layer height. In conjunction with air quality measurements and forecast modelling, these provide the basis of systems to communicate rapidly to those who are vulnerable (e.g. Air Alert http://www.airalert.info; Air Text, http://www.airtext.info/).

Air quality remains an important issue in London today both for health reasons (e.g . Kaur et al. 2005[57], 2007[58]) and because EU Law requires directives to be met (GLA 2010, Defra 2011). As one of Europe's Mega-cities, in a national context which is committed to more sustainable cities, and with a local government administration (Greater London Authority) that takes an active interest in climate issues and actively engages the scientific community, London provides a particularly interesting location to study urban climate and its implications and uptake into urban design.

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[51] Manley G (1944) Topographical features and the climate of Britain: a review of some outstanding effects. Geographical Journal,103: 241-258
[52] Chandler T, S Gregory (1976) 'The Climate of the British Isles'.
[53] Wheeler D, J Mayes (1997) Regional Climate of the British Isles, Routledge, London, 343 pp.
[54] Mayes J 1997 South-East England, 67-88
[55] Bell ML, Davis DL, Fletcher T (2003) A Retrospective Assessment of Mortality from the London Smog Episode of 1952: The Role of Influenza and Pollution. Environ Health Perspect 112(1): doi:10.1289/ehp.6539
[56] http://nora.nerc.ac.uk/8465/REPARTEE-I and REPARTEE-II (Regent's Park and Tower Environmental Experiment); http://www.atmos-chem-phys-discuss.net/special_issue95.html
[57] Kaur S, MJ Nieuwenhuijsen, RN Colvile (2005) Personal exposure of street canyon intersection users to PM2.5, ultrafine particle counts and carbon monoxide in Central London, UK, Atmospheric Environment 39, 3629–3641
[58] Kaur S, MJ Nieuwenhuijsen, RN Colvile (2007). Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. Atmospheric Environment, 41, 4781-4810

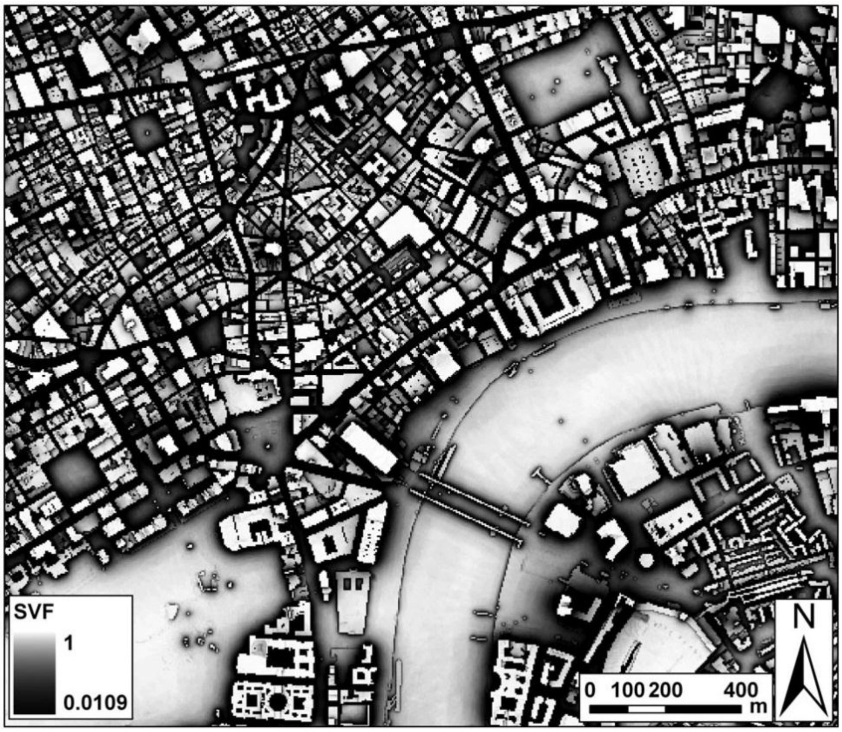

Figure 2: Sky View Factor of inner area of London (Lindberg and Grimmond, 2010). A value of 1 is an unobstructed view. St James's Park and Somerset House are visible.

The Urban heat island (UHI)

The first use of the term 'heat island' is ascribed by Landsberg (1981) to Manley (1958[59]). Manley (1958) in his discussion of the effect of the artificial warmth of London relative to snowfall patterns notes that inverse relation between 'heat island' strength and wind speed. He comments on the expected change in the precipitation from snow to sleet. But the term had already appeared in Balchin and Pye (1947[60]) in their study of Bath (p 303, 304). Also, in the English translation of the 2nd edition of Kratzer's (1956) book, the city is described as being 'like an island in a sea of cold air produced by the terrain' (p96). As Kratzer's book demonstrates there had been extensive research on German and Austrian urban climates in the early part of the century.

Manley's (1958) analysis, like Bilham's (1938), makes use of data collected at stations that were previously installed, many of them airfields. Chandler (1960, 1962, 1965[61]) provides one of the first detailed studies of the UHI of London. He (1960, 1962) identifies that although there are 17 climatological stations in London and the vicinity, which may be considered to be 'lavish' in comparison to other areas, that this is not enough to generate spatial analyses. He added 39 supplementary stations (primarily at schools) in the north east Lea Valley area of London and performed automobile traverses to understand the 'changing intensity and form' of the heat island. These appear to be the first mobile traverses in London (Discussion of Chandler 1962 paper), but others had previously conducted such studies elsewhere using cars and bicycles; for example in Vienna (Tollner 1932; cited by Middleton and Millar 1936), Karlsruhe (Peppler 1929a,b[62]), Munich (Budel and Wölf 1933[63]) and in Toronto (Middleton and Millar 1936).

[59] Manley G (1958) On the frequency of snowfall in metropolitan England. QJRMS, 84,359, 70-72
[60] Balchin WGV , N Pye (1947) A micro-climatological investigation of Bath and the surrounding district. QJRMet Soc. 73, 297-319.
[61] Chandler TJ (1965) The Climate of London Hutchinson & Co., Ltd: London.
[62] cited by Krater 1956 Peppler, A. "Die Temperaturverha" ltnis se von Karlsruhe an heissen Sommertagen" (Temperature conditions in Karlsruhe on hot summer days), Deutsche s Meteorologisches Jahrbuch fUr Baden, 61: 59 f. 1929.

Chandler's (1962) specific contributions with respect to air temperature were to use fixed stations to analyse the presence and temporal characteristics of the UHI using daily and hourly records, along with mobile transects too (from Ware, north east of London along the terraces of the Lea to Canning Town or to Liverpool Street and then back to Ware). Importantly, he noted the impact of choice of the rural environment as influencing the results of urban-rural differences (he compares the implications of chosing Wisley, Swanley and Bayfordbury). He also highlighted the effect of vegetation surrounding Kensington Palace and St James's Park site. His explanation of the UHI focused on differences in heat capacity and conductivity of materials; presence of haze/fog (altering solar radiation receipt); mixing of air because of increased roughness of the surface; and nocturnal radiation trapping. He suggested that high thermal capacity is the most important single factor (p296).

In the discussion that followed the Chandler (1962) paper, there is evidence of plans to use the Crystal Palace tower and the Post Office tower (now known as the BT tower) were in place. It is not clear if Chandler ever conducted measurements on the BT tower, but the use of that as platform for conducting observations has been pursued more recently (e.g. Matin et al. 2011[64], Wood et al. 2010[65], Gouvea et al. 2011[21], Helfter et al. 2011[66]) .

Although there have been a number of other UHI studies (see other sections), Lee's (1991[67]) study, like Chandler's (1962, 1965), was concerned with the actual processes in the city. His interest was urban/rural differences in humidity, but he also studies the UHI, using the London Weather Centre (LWC) and Gatwick stations. Atkinson (1985) cites a number of other studies of London UHI conducted by Lee in 1975[68], 1977[69], 1979[70].

Global Climate Change

Much of the research related to London's urban heat island stems from the city's long temperature record. Thus there interest has been on the urban influence as a 'contaminant' of the signal for larger scale global warming trends (e.g. Moffitt 1972[71], Lee 1992, Barrow and Hulme 1997 p37, Dukes and Eden 1997 p263). The temperature record has had numerous corrections (e.g. change in siting, instrumentation, discontinued data sets) that are summarized in Jones and Hulme (1997[72]). The analyses have been primarily concerned with determining regional and global trends in temperature.

Peppler, A. "Das Auto als Hilfsmittel der meteorologischen Forschung II (The automobile as an aid in meteorological research), Das Wetter, 46: 305-308, 1929.

[63] Budel' H. 3 and J. Wolf. "Munchener stadtklimatische Studien" (Climatic studies in the city of Munich), Das Wetter, 49: 4-10, 1933.

[64] Martin, D., Petersson, K. F., White, I. R., Henshaw, S. J., Nickless, G., Lovelock, A., Barlow, J. F., Dunbar, T., Wood, C. R. and Shallcross, D. E. (2011) *Tracer concentration profiles measured in central London as part of the REPARTEE campaign.* Atmospheric Chemistry and Physics, 11 (1). pp. 227-239. ISSN 1680-7316

[65] Wood CR, Lacser A, Barlow JF, Padhra A, Belcher SE, Nemitz E, Helfter C, Famulari D & Grimmond CSB (2010) Turbulent flow at 190 metres above London during 2006-2008: a climatology & the applicability of similarity theory. Boundary Layer Meteorology **137,** 77-96 DOI10.1007/s10546-010-9516-x

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[69] Lee DO 1977 Urban influence on wind direction over London,Weather, 32, 162-170.

[70] Lee DO 1979 Contrasts in warming and cooling rates at an urban and rural site, Weather, 34, 60-66.

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Some of the detailed analysis of the data sets have, however, been concerned with the impact of urbanization. For example, Moffitt (1972) concluded that since the 1880's urbanisation may have impacted temperature based on analysis of monthly data from the Kew Observatory (compared with Rothamsted) (for 1878-1968). Moffitt also identified the role of changing air quality on temperature differences. With improved air quality, winter air temperatures differences increased because of greater solar radiation receipt. The role of anthropogenic heat also was demonstrated to be important. The 1950's reduction of coal fires changed the method of building heating, as well as reduced the amount of smoke. Subsequent domestic heating has become more efficient (Moffitt 1972).

Lee's (1992[73]) study of the London's UHI, was driven by the interest in global warming data sets and the much used relation between population and UHI intensity (Oke 1973). Noting the decrease in London's population (Figure 1) he set out to determine if there had been a decrease in UHI using the stations of St James's Park and Wisely for 1962-89. Lee is careful to comment about the appropriateness of the two, with neither being ideal. He documents that daytime UHI size has decreased while night time UHI has increased in this period. From this he concludes that the population relation does not hold with decreasing population size and suggests that the reduced daytime UHI may relate to reduced anthropogenic heat emissions. However, that conclusion seems unlikely given the trends recently documented in these data (Iamarino et al. 2011[74]).

The London Climate Change Partnership (LCCP)[75] has the aim 'To ensure that London is prepared for climate change'. One action was an update of Lee's (1992) study. Wilby (2003[76]) used the same sites (St James's Park and Wisely), given the expectation that London will experience less cloud (citing Hulme et al. 2002[77]) in the future to investigate the meteorological conditions of the most intense UHI events (defined as being > 4 °C). Using past NCEP reanalysis data he developed a multivariate statistical model, which after testing for past conditions, was used to predict future intense UHI events under different emission scenarios. Since the 1960's the intensity of the UHI has increased by 0.12°C/decade. He predicted a further 0.26°C (equivalent to +0.04°C/decade) increase by the 2080s for the mid-range emissions scenario. Wilby (2008[78]) uses his 2003 results to draw attention to the methods for analysis for future conditions using statistical downscaling to the planning community.

Jones and Lister (2009[79]) expand on Lee (1992) and Wilby (2003) by including other stations (e.g. London Weather Centre (LWC), London Heathrow (LHR) plus others) and using longer periods of records in their analyses. The rural sites of Wisley and Rothamsted are used for comparison. They note that the Wisely site is regarded to have become more sheltered with time (citing Burt and Eden 2004[80]), providing more details about the sites than has been given for some years in publications. Notably, they give the locations of the LWC station: Kingsway (1959-1965), High Holborn (1965-1992), Clerkenwell Rd (1992-2010[81]). They conclude that since 1901 the warming trends at St James's Park, Rothamstead and Wisley are statistically the same. Thus since 1901 there is not urban

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'contamination' (it has not changed), so the sites can be used for global change investigations. Whereas the LHR site has experienced an increasing urbanizing effects from 1949 to 1980.

In 2011 Wilby et al.[82] revisit the London UHI again with respect to the change in UHI through time (1958—2010). Attention is paid to gap filling of data, length of record analysed and meteorological conditions. They conclude the need for care with analysing periods of data and identify that meteorological conditions only explains half of the summer-time night-time UHI.

UHI and Applications: Building Climate, Health, Decision Makers

Many recent studies have been interested in the UHI and its characteristics at the micro and local scale for applications. Of particular interest has been implications for building design (Watkins et al. 2002a[83],b[84], Short et al.2004[85], Kolokotronti et al. 2007[86], Mavrogianni et al. 2010[87], 2011[88]), along with heat waves and health (Rooney et al. 1998[89]). These studies have been possible because of the advent of relatively low cost sensors that can be deployed across the city.

Studies of particular note, which have deployed additional sensors are BRE[90] - Building Research Establishment, and LUCID[91] - The Development of a Local Urban Climate Model and its Application to the Intelligent Design of Cities.

Other applications have resulted in numerous reports for the London Climate Change Partnership including: 'London's changing climate - in sickness and in health' (2011[92]), 'Adapting to climate change: creating natural resilience' (2009[93]), 'Wild weather warning: a London climate impacts profile' (2009[94]) and 'Your Home in a Changing Climate' (2008[95]).

Other Urban Heat Islands

McGregor et al.'s (2006[96]) report provided the material for the GLA (2006[97]) report on the UHI for decision makers. This report included UHI determined based on air temperature data but also used

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[91] http://www.lucid-project.org.uk/; ESPRC funded 2007-2010 Lead: Mike Davies (UCL)
[92] http://www.london.gov.uk/lccp/publications/londons-changing-climate-sickness-health.jsp
[93]http://www.london.gov.uk/lccp/publications/londons-changing-climate-oct09.jsp
[94] http://www.london.gov.uk/lccp/publications/wild-weather-09.jsp
[95] http://www.london.gov.uk/lccp/publications/home-feb08.jsp
[96] McGregor GR, Belcher S, Hacker J, Kovats S, Salmond J, Watkins RW, Grimmond S, Golden J, Wooster M.

satellite observations from MODIS[98] of surface temperature which gives a complete spatial pattern at one instance in time. It is, however, biased by the spatial resolution of the pixels (1 km) and the surfaces in the field of view of the sensor (Voogt and Oke, 2003[99]).Measurements of the surface temperature at a number of different scales is ongoing (Kotthaus et al. 2011).

Numerical modelling of the UHI of London includes: statistical (Kolokotroni and Giridharan 2008[100], Giridharan and Kolokotroni 2009[101], with artificial neural networks; Koltoroni et al. 2010[102]); using meso scale numerical techniques (Atkinson 2003[103], Bohnenstengel et al. 2011[104], Coceal et al. 2011); and through analysis also of gobal climate model generated data (Kershaw et al. 2010[105], McCarthy et al. 2010[106]).

Role of anthropogenic heat

Repeatedly the heat generated by human activities, the anthropogenic heat, has been considered in urban climate studies. The early and current concerns about air quality are associated with anthropogenic heat releases (e.g. from burning of coal and more recently air conditioning energy demand).

Chandler (1976) suggested that the anthropogenic heat flux is 'relatively unimportant in the urban heat budget'. But since his studies, there has been increasing interest in this term for both in terms of air quality and energy impact. Based on domestic fuel consumption data, Craddock (1965[107]) calculates the impact of domestic heating to have an impact of about 0.6 °C on London's air temperature. McGoldrick (1980[108]) provides the first spatial estimates of anthropogenic heat use. This was expanded in the Harrison et al. (1984[109]) publication to cover the period 1971-76. More recently, in association with the LUCID project, Hamilton et al. (2009[110]) have determined the heat emission associated with buildings in London for 2005 at 1 km^2 resolution. Both Allen et al. (2010[111])

2006. *London's Urban Heat Island*. A report to the Greater London Authority. Centre for Environmental Assessment, Management and Policy, King's College London, 111pp.

[97] http://static.london.gov.uk/mayor/environment/climate-change/docs/UHI_summary_report.pdf

[98] Moderate Resolution Imaging Spectroradiometer (*MODIS*)is on a NASA's *satellite*

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[111] Allen L, F Lindberg, CSB Grimmond (2010) Global to city scale model for anthropogenic heat flux, International Journal of Climatology doi: 10.1002/joc.2210 http://onlinelibrary.wiley.com/doi/10.1002/joc.2210/pdf

and Iamarino et al. (2011[112]) address all the components of this flux (as part of MegaPoli, BRIDGE); taking transport and metabolism into account. The former is at a coarser spatial resolution (hourly temporal resolution) and the latter at a finer spatial resolution (200 m x 200 m, 30 min temporal resolution) than Hamilton et al. (2009). Iamarino et al. (2011) calculate this into the future under different development scenarios. Studies of this term have considered the size relative to solar radiation (Hamilton et al. 2009) and to the UHI (Kolokotroni et al. 2006[113]).

Living with Environmental Change: The current nature of urban climate research

Air pollution remains an important driver to efforts to understand the urban climate of London. The current NERC funded research project Clean Air for London, ClearfLO[114], brings together researchers to integrate observations and understanding of air pollution, boundary layer meteorology and health. The need for a GLA (2010a) 'Air Quality Strategy' continues to be important as London's air quality, although much improved from the past in many respects, is the poorest in Europe[115]. The impact of not meeting EU standards is potential fines of £300 million[116] and 4300 premature deaths a year (GLA 2010a p14) in London.

Sustainability, sustainable and low carbon cities all are themes that underlie current work. London is one of the cities in the EU Framework 7 project MegaPoli[117] (Megacities: Emissions, urban, regional and Global Atmospheric POLlution and climate effects, and Integrated tools for assessment and mitigation) and BRIDGE[118] (sustainaBle uRban plannIng Decision support accountinG for urban mEtabolism) and the EPSRC funded project ACTUAL[119].

Conclusions

A large amount of research has been conducted on the climate of London for a wide variety of reasons; some themes that are relevant have not been included here (most notably related to precipitation – see Atkinson 1968[120], 1969[121], 1971[122], 1975[123], Tabony 1980[124]), winds (Chandler, 1965, Lee 1979), boundary layer characteristics (Rigby and Toumi 2008[125],Barlow et al. 2011[126]), CO_2

[112] Iamarino M, Beevers S, CSB Grimmond (2011 in press) High Resolution (Space, Time) Anthropogenic Heat Emissions: London 1970-2025 International Journal of Climatology

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[114] http://www.clearflo.ac.uk/

[115] http://www.guardian.co.uk/environment/2010/jun/25/london-air-pollution-europe

[116] http://www.guardian.co.uk/environment/2011/mar/11/britain-300m-fine-london-air-pollution

[117] http://megapoli.info/

[118] http://www.bridge-fp7.eu/

[119] http://www.actual.ac.uk/

[120] Atkinson BW 1968: A preliminary examination of the possible effect of London's urban area on the distribution of thunder rainfall. Transactions of the Institute of British Geographers 44, 97-118.

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[125] Rigby M,R Toumi (2008) London air pollution climatology: Indirect evidence for urban boundary layer height and wind speed enhancement *Atmospheric Environment*, 42, 4932–4947

[126] Barlow, J. F., Dunbar, T. M., Nemitz, E. G., Wood, C. R., Gallagher, M. W., Davies, F., O'Connor, E. and Harrison, R. M. (2011) *Boundary layer dynamics over London, UK, as observed using Doppler lidar during REPARTEE-II.* Atmospheric Chemistry and Physics, 11 (5). pp. 2111-2125. ISSN 1680-7324

characteristics (Rigby et al. 2008[127], Sparks and Toumi 2010[128], Helfter et al. 2011), air quality (e.g. Beevers and Carslaw 2005[129], Fuller and Green 2006[130], Atkinson et al. 2009[131]).

There has been an interesting trend away from the extremely careful analysis of height differences to the deployment of large number of sensors (BRE, LUCID, OPAL). The latter made possible by technological changes. Remarkably no energy balance observations have been published yet but some of the components have been; most notably radiation (Ryder and Toumi 2011; Loridan et al 2011), and anthropogenic heat flux (Harrison et al. 1984, Hamilton et al. 2010, Iamarino et al. 2011). At KCL we are conducting observations at three sites, initial results will be presented.

London is still a megacity, but clearly no longer the largest globally or even in Europe. But given its size and the history of measurements, it has a large number of climate stations. Through time a wide range of stations have been used to characterize London's climate and the configuration of stations continues to change. The London Weather Centre closed last year, while new stations of varying exposure are being established (Robinson 2010, Ryder and Toumi 2011). Thus there has been very little consistency in the stations used in the study of the UHI. The temperature record continues to be extended and explored (Wilby et al. 2011) and despite closing stations it is hoped we learn from the past and data are not thrown away[132].

Through the study of the temperature in London we can see the many reasons why the climate of London been studied. From the earliest concerns about poor air quality, the first investigations of the measurement of weather variables, the first investigations of London as a location in a region, to the realization of the urban effect, to resurgence in interest in air quality again, the realization of the global effects of burning of coal. Attention today also remains focused on many attempts to mitigate problems in the past; e.g. planting trees, reducing emissions; notably of carbon (e.g. Evelyn 1661, GLA 2010, 2011).

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Gerald Mills first brought to my attention the location of Luke Howard's urban site and through his efforts copies of Luke Howard's and Kratzer's urban climate books are much more widely available.

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[132] The thermometric data sent to the Royal Society for the period 1707-1722 appear to be have been destroyed 'as of no further use' (Manley 1974, p391)