

1 Allometric scaling of thermal infrared emitted from UK cities and its relation to urban form

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10 ABSTRACT

11 As a result of differences in heat absorption and release between urban and rural landscapes, cities
12 develop a climate different from their surroundings. The rise in global average surface temperature
13 and high rates of urbanization, make it important to understand the energy balance of cities,
14 including whether any energy-balance-related patterns emerge as a function of city size. In this
15 study, images from the Moderate Resolution Imaging Spectro-radiometer (MODIS) satellite
16 instrument, covering the period between 2000 and 2017, were sampled to examine the seasonal
17 (winter and summer) night-time clear-sky upwelling long-wave energy for 35 UK cities. Total (area-
18 summed) emitted energy per overpass per city is shown to correlate closely ($R^2 \geq 0.79$) with
19 population on a log-log 'allometry' plot. The production of emitted energy from the larger cities is
20 smaller than would be produced from a constellation of smaller cities housing the same population.
21 The mean allometry slope over all overpasses sampled is 0.84 ± 0.06 , implying an 'economy (or
22 parsimony) of scale' (i.e., a less-than-proportional increase) of about 21% (i.e. $100(2 - 10^{0.84 \log(2)})$) for
23 each doubling of city population. City area shows a very similar economy of scale, so that the scaling
24 of night-time emitted energy with urban area is close to linear (1.0 ± 0.05). This linearity with area
25 indicates that the urban forms used in UK cities to accommodate people more efficiently per unit
26 area as the urban population grows, do not have a large effect on the thermal output per unit area
27 in each city. Although often appearing superficially very different, UK cities appear to be similar in
28 terms of the components of urban form that dictate thermal properties. The difference between the
29 scaling of the heat source and literature reports of the scaling of urban-rural air (or surface)
30 temperature difference is very marked, suggesting that the other factors affecting the temperature
31 difference act to decrease strongly its scaling with population.

32

33 HIGHLIGHTS

- 34
- 35 • MODIS was used to assess the clear-sky upwelling long-wave energy for thirty-five (35) large
36 urban areas in Great Britain;
 - 37 • A robust, less-than-proportional, scaling relationship between total urban population and
38 total emitted energy demonstrates a thermal 'economy (or parsimony) of scale' with respect
to population.

- 39 • The scaling relationships with population for city area and for emitted energy suggest a
40 testable hypothesis regarding the similarity of energy budgets across urban areas of very
41 different sizes.

42 *Keywords: Urban Heat Island (UHI); Land Surface Temperature (LST); Allometry; Urban size and*
43 *population; Geographic Information System (GIS); MODIS and Emitted energy*

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46

1.0 INTRODUCTION

47 Urbanization is accelerating across the world, especially in developing countries across Africa
48 and Asia (Martins, 2000; Cohen, 2006). Current projections indicate that by 2050, the global
49 urban population will increase by 2.4 billion, i.e., about half the current population of 4.22
50 billion (United Nation, 2019) (Seto et al., 2012; Buhaug and Urdal, 2013; Bremner et al., 2010;
51 Bongaarts, 2009). The change of land surface characteristics caused by urbanisation leads,
52 amongst other things, to changes in the local energy balance that must be taken into account
53 when determining long-term temperature trends (Chrysanthou et al., 2014). This change in
54 thermal climate in urban areas, leads to the urban heat island (UHI), which is the tendency of an
55 urban area to have warmer near-surface air temperatures than its rural surroundings (Bornstein,
56 1968; Landsberg, 1981; Oke, 1995; Sheng et al., 2017). Related phenomena include: urban
57 thermal plumes (Oke, 1995; Heaviside et al., 2015) and urban precipitation anomalies (Han et al.,
58 2013).

59 Recent conceptual UHI models have emphasised the importance of different land uses within
60 cities (Stewart and Oke, 2012; Tomlinson et al., 2012), highlighting the prospect that urban
61 planning choices can be used to mitigate adverse urban climate trends (Davoudi, 2012; Davoudi,
62 2014). Implicit in most studies of UHI, from Howard (1818) on, is that local, one-dimensional
63 (i.e., vertical), energy budgets for urban land uses, combine through the action of fluid stirring
64 and mixing, to produce a three-dimensional dome of urban heating over a city — see, for
65 example, the very widely reproduced cross-sections of UHI through an idealised city (e.g.,
66 Lemmon and Warren, 2004).

67 We hypothesise that gross changes in urban form affect the storage of solar heating as the size
68 of cities increase. We focus on night-time, clear-sky, emitted long-wave energy as a primary
69 measure of heat storage, and we use population as our measure of city size. We use an
70 extensive property — total emitted energy (in Megawatts) per city per night — rather than
71 intensive property such as temperature or emission per unit area, to permit direct comparisons
72 with other extensive properties such as urban area, and to explore the extent to which the
73 behaviour of intensive properties, particularly UHI, differ from the behaviour of the extensive
74 properties.

1.1 Urban Form and urban heat

76 The urban form of a city is the result of its social, economic, and environmental context. We
77 focus on UK cities in this study; further work will focus on a different setting in order to try and
78 distinguish the general from that dependent on UK context (Abdulrasheed, 2020). A recognised
79 system of UK urban planning mostly originates from the industrial revolution, prior to which
80 most people lived and worked in the countryside (Inikori, 2002; CPRE, 2018). As industries grew,
81 people migrated to towns and cities in search of better wages, opportunities, and livelihoods
82 (Karp, 2013) leading to rapid growth in town and cities. Many decrees and ordinances were

83 issued to manage this growth, including, at the beginning of the 20th century, the Town Planning
84 Act 1909, which was introduced to ensure that local authorities prepared schemes of town
85 planning. This was followed by the Housing Act 1919, which required the design of houses to be
86 approved by the Ministry of Health, and the Housing Act 1930, which required clearance of high-
87 density 'slums', which were considered unsanitary (Carmon, 1999). The post-war 1940s was a
88 period of uncertainty for the architects and town planners tasked with rebuilding Britain's bomb-
89 damaged cities (Tsubaki, 2000; Ball and Maginn, 2005; Hollow, 2012). Residential rebuilding in
90 this period often involved the replacement of low-rise private dwellings with fewer, but larger,
91 high-rise public buildings (Carmon, 1999), sometimes with an intermediate period of low-rise
92 prefabricated structures (Short, 1982). Cities across the UK such as Bristol, Coventry, Hull,
93 Portsmouth, Southampton and Plymouth were very severely damaged during World War II
94 (Hasegawa, 2013), and so were subject to significant post-war changes. For those
95 neighbourhoods, which, by the 1960s and 1970s, had escaped slum clearance or destruction in
96 wartime, the tendency was for renewal rather than replacement of low-rise and mid-rise
97 residential buildings (Carmon, 1999). In the subsequent decades, and until the present day, a
98 more laissez-faire approach has dominated, with renewal and replacement of housing and
99 commercial buildings through private-public cost sharing of various kinds (Carmon, 1999;
100 Hasegawa, 2013; Webb, 2018).

101 Emerging in parallel, from the latter part of the nineteenth century and through the first part of
102 the 20th century, was the Garden Cities movement, which advocated public health improvement
103 by planning to build cities with more, and more accessible, green spaces, see e.g., (Burnett,
104 1986). This advocacy eventually led to the New Towns movement and New Towns Act 1946
105 (Goist, 1974; Rubin, 2009; Alexander, 2009; Tizot, 2018) which resulted in towns such as Telford,
106 Letchworth and Milton Keynes. All the 20th-century housing and town planning policies in the UK
107 led to notable changes in the urban form from the scale of individual dwellings, through
108 neighbourhood scale land-use, to the patterns of use across whole urban areas.

109 The nature and patterns of urban form (i.e. building geometry, pervious surface fraction,
110 building and tree densities, soil permeability etc.) determine the thermal characteristics of place.
111 Such characteristics can be used to define local climate zones (LCZ)(Stewart et al., 2014), which
112 may vary over time as a result of planned or unplanned changes. For example, slum clearance
113 often re-shaped low-rise, close-packed, terraced housing into a sparse array of high-rise towers
114 e.g., (Carmon, 1999). Suburban extension of cities replaced farm field (or, often, filled in
115 parkland estates around large houses) with semi-detached two storey housing in wide
116 boulevards (shifting from linear form to cul-de-sac mid-century). Infilling (building in what had
117 previously been back gardens) became prominent towards the end of the 20th century
118 (Whitehand and Whitehand, 1983).

119 As cities grow, green space — trees and vegetation — are replaced with grey space, i.e.,
120 buildings and transport and utility infrastructure. The magnitude and nature of the change is
121 often sporadic and patchy, and results in a wide variety of urban forms (Morris, 1974; Hopkins,
122 2012). In terms of the surface energy balance, changing from rural to urban land results, in
123 general, in the absorption of a higher fraction of incoming solar radiation and a decrease in the
124 Bowen ratio (i.e., the ratio of sensible to latent heat emission) (Arnfield, 2003; Aguado and Burt,
125 2015). Energy absorption and emission at the ground surface is therefore a key driver of urban
126 climate, strongly influencing the near surface air temperature and the radiant fluxes relevant for
127 health effects (e.g., Basu and Samet, 2002; Middel and Kravenoff, 2019). Satellite based studies
128 report thermal emission as land-surface temperature (or 'skin' temperature), from which surface

129 UHI intensity (SUHII) can be derived (e.g., Peng et al., 2012; Zhou D. et al., 2014; Zhou B. et al.,
130 2017). In-situ sensing reports air temperature directly. Near-surface air temperature UHI and
131 SUHII do not always correspond for a variety of physical reasons (Voogt and Oke, 1998; 2003;
132 Arnfield, 2003; Schwarz et al., 2011; Sheng et al., 2017) but both are driven by absorption and
133 emission of energy at the ground surface. The fundamental role of surface energy exchange
134 motivates us to investigate how surface energy parameters vary for a set of cities of very
135 different size and urban form, in order to understand this foundational driver of both the UHI
136 and SUHII.

137 Buildings also slow the wind near the surface, retaining the heat released from vehicles and
138 buildings (Golden, 2004; Arifwidodo and Tanaka, 2015). Energy removed from the mean wind is
139 lost to the surfaces or transformed into turbulent kinetic energy, affecting the dissipation of
140 scalars such as temperature and trace-gas pollutants e.g., (Belcher et al., 2003). Dense building
141 arrangements decrease the sky-view factor (Chapman and Thornes, 2004; Grimmond, 2007;
142 Yang et al., 2015). The net result of all these changes is the increased storage of heat, which is
143 the root cause of the UHI effect. Increased heat storage can lead to a number of issues such as
144 human health risk (Basu and Samet, 2002; Rosenzweig et al., 2011; Murray and Ebi, 2012; Smith
145 et al., 2011; Patz et al., 2005; Hondula et al., 2015; Wouters et al., 2017; Krayenhoff et al., 2018;
146 Middel and Krayenhoff, 2019), environmental hazard (e.g., Chapman and Thornes, 2006), and
147 infrastructure failure (Chapman and Bell, 2018; Dawson et al., 2018), which themselves add heat
148 to urban air and often require further energy consumption to offset (Li et al., 2015).

149 Researchers have long studied the effects of urban form on climate change, and the impacts of
150 climate change on urban environment, as reviewed in (Mills, 2007) and (Seto et al., 2010). Urban
151 planning responses to urban heat and climate change, including both mitigation and adaptation
152 strategies, continue to evolve, especially with respect to sustainable urban development in cities
153 (Jabareen, 2006 ; Rybski et al., 2017; Davoudi et al., 2009; Hendrickson et al., 2016; Castán
154 Broto, 2017; Fujii et al., 2017). Urban climate adaptation focuses on reducing vulnerability and
155 promoting resilience of people and properties (Amundsen et al., 2010; Carmin et al., 2012;
156 Anguelovski et al., 2014). Microclimate planning and design modification to outdoor
157 environment can also enhance thermal comfort, e.g., neighbourhood streets trees, green spaces
158 and parks, (Brown, 2011; OECD, 2014). We expect that planning responses to urban heat will
159 manifest in the relationship of urban form to city size.

160

161 1.2 Allometry and urban heat

162 Allometry is originally a concept from biology, relating morphological and physiological aspects
163 of organism biology to some more easily measured parameters such as body mass (Schmidt-
164 Nielsen, 1984; Gould, 1966; Lee, 1989; Small, 2012). Allometric approaches were introduced to
165 urban studies (e.g. West and Brown, 2005; Naroll and Bertalanffy, 1956; Nordbeck, 1971) and
166 used to model the relationship between a set of cities and the largest city within a geographical
167 region (Small, 2012). Urban allometry studies have sought to elucidate decadal evolution of
168 urbanized area (Lee, 1989; Longley et al., 1991), fractal spatial patterning (Chen, 2010), income
169 inequality (Sarkar et al., 2018), and between urban form and growth (Bettencourt et al., 2007).
170 Interpretations drawn from urban allometry include growth by innovation driven by economies
171 of scale (Batty, 2008), and urban form as a hierarchy of clusters, (Bettencourt, 2013).

172 In general, for urban studies, allometric scaling relates aspects of urban material, energy, or
173 economic flows to the size of cities as determined by their population (Bettencourt, 2013; Batty,
174 2008; Lee, 1989; Longley et al., 1992). Because it focuses on the relative rate of change of
175 properties with size, referred to as ‘scaling’ below, allometry lends itself to comparative studies
176 of properties of very different character (Bettencourt and West, 2010). In our previous study of
177 air pollutant emissions and concentrations, we found it informative to compare the scaling of an
178 intensive property (urban air concentrations) with the scaling of extensive properties (area-
179 summed pollutant emissions and urban area) (MacKenzie et al., 2019).

180 Allometric scaling recognises that the many microscopic interactions within a complex system
181 often collapse to a simple pattern (Cottineau et al., 2017). Scaling, therefore, allows us a
182 synthesising perspective on cities (Batty, 2008), by searching for simple patterns without
183 becoming overwhelmed by details of local context.

184 Allometric patterns, where they exist, conform closely to an equation of the form:

$$185 \quad Y = \beta X^\alpha \quad (1a)$$

186 The power law, equation (1a), describes a straight-line relationship between the X and Y
187 variables when the function is plotted on a double logarithmic coordinate system, i.e.

$$188 \quad \log(Y) = \log(\beta) + a \cdot \log(X) \quad (1b)$$

189 where $\log(\beta)$ is a constant offset and α is the rate of relative growth (the allometric scaling factor
190 or, simply, slope). Below, we will refer to α as defining the ‘scaling’ of Y with respect to X.

191 Using allometry, this study seeks a quantitative scaling relationship between population and
192 clear-sky upwelling emitted energy, in order to determine whether and how the many detailed
193 processes affecting this part of the urban energy budget combine at the city-scale. The study
194 evaluates whether simplicity emerges from urban complexity with respect to emitted long-wave.
195 We compare our findings on clear-sky upwelling long-wave to a classical result in the literature
196 of urban heat islands.

197 The empirical relationship between the UHI and structure of a city arises from the fact that tall,
198 close-packed, concrete and brick buildings store solar energy in day time and emit it at night
199 more slowly than a flat surface (Duckworth and Sandberg, 1954). The thermal infrared energy
200 emitted from a surface is acted on by wind and radiation transfer processes; structural elements
201 of a city affecting wind and radiative transfer will therefore influence UHI (Oke, 1973). Since
202 structural elements of cities are often laid out block by block, one approach to analysing a city is
203 to determine its energy budget and surface temperature explicitly on a block-by-block basis
204 (Terjung and Louie, 1974; Chandler, 1966). Land-use categories and urban morphology types
205 offer useful approaches to determining modifications to the surface energy budget that will
206 produce a nocturnal urban heat Island (Oke, 1981; Landsberg, 1981; Eliasson, 1996). Other
207 urban climate studies focus on the effect of the urban surface at the neighbourhood scale, using
208 land-use classifications to generalise results (e.g. Arnfield, 2003; Stewart and Oke, 2012). At city
209 scale the number of studies are fewer: (Landsberg, 1981) for North American settlements; (Lee,
210 1993) for Korea; (Eagleman, 1974) for Kansas city; and (Oke and Maxwell, 1975) for Montreal
211 and Vancouver.

212 Several studies in the urban climate literature offer an allometric perspective (Oke, 1982; Torok
213 et al., 2001; Manoli et al., 2019), and many other comparative studies show that UHI or SUHII
214 increases with some measure of the size of the city (e.g. Zhou B., et al., 2013; 2017; Schwarz and

215 Manceur, 2015) or focus on the largest cities because the UHI is assumed to be largest there
 216 (e.g., Peng et al., 2012; Zhou D., et al., 2014). Oke (1973; 1982) presented the relationship
 217 between a measure of maximum UHI ($\Delta T_{u-r}(\max)$) and population for European settlements
 218 (fig.1) and supports the hypothesis that the canopy air temperature, ΔT_{u-r} , is a function of city
 219 size, with the absolute UHI increasing by about 0.6 °C (i.e. $1.975 \cdot \log_{10}(2)$) for every doubling in
 220 population. Zhou et al. (2013) fitted a sigmoidal curve to the log-linear relationship of SUHII to
 221 urban area. The sigmoidal function is approximately linear for urban clusters with areas between
 222 2 and 200 km² with SUHII increasing by ~0.3°C for an area doubling (Zhou et al., their Figure 2).
 223 Zhou et al. (2017) plot SUHII against $\log_e(\text{urban area})$ similarly to find a log-linear regression in
 224 which SUHII increases by about 0.4 °C (i.e. $0.55 \cdot \log_e(2)$) for an area doubling.

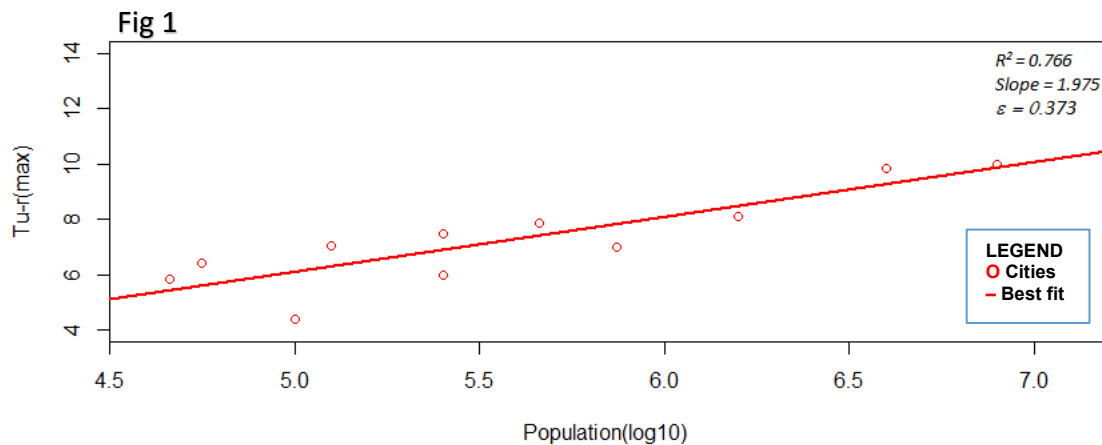
225 Fig S1 in the Supplementary Information presents the Oke (1973) data in a power-law log-log
 226 graph. Regressing on $\log_{10}(\Delta T_{u-r}(\max))$ gives more weight to the smaller cities, but a strong
 227 relationship is still found. The scaling of ΔT_{u-r} in Fig S1 is small, 0.11 ± 0.03 , but significantly
 228 different from zero — and equivalent to an increase of just 8% (i.e. $100(10^{0.11 \cdot \log(2)} - 1)$) in UHI for a
 229 population doubling. Using a similar log-log regression, Manoli et al. (2019) found a scaling with
 230 population of $\log_{10}(\text{SUHII})$ ranging between 0.15 and 0.24, equivalent to a maximum increase of
 231 18% (i.e. $100(10^{0.24 \cdot \log(2)} - 1)$) for a population doubling. Such relatively modest scalings with
 232 population have implications, such as that ‘densification’ of population into large urban centres
 233 presents a rather modest increased contribution of air temperature to thermal discomfort and
 234 associated health risk, at least to the extent that this can be gauged by the UHI of the 20th
 235 century city forms in Oke’s (1973; 1982) sample.

236 Having identified the best-fit scaling relationship, the residual offset from this best-fit for any
 237 individual city is also informative (Bettencourt et al., 2010). The residual for any city on any
 238 night, $r_{j,k}$, is calculated as the vertical distance of the datum for that city to the best-fit line:

$$239 \quad r_{j,k} = \log(Y_{j,k}) - \{ \log(\beta_k) + \alpha_k \cdot \log(X_j) \} \quad (2)$$

240 where $Y_{j,k}$ is the measured value of dependent variable (in our case, the summed emitted energy
 241 of city, j , on a given night, k), X_j is the population, of city j , and the parameters α_k and β_k define
 242 the allometric scaling relationship. In Oke’s scaling data (Figs 1 and S1), the largest-magnitude
 243 residual is a large negative deviation (i.e. less heat island than expected) for the UK town of
 244 Reading (Oke, 1973).

245



246
 247 **Fig.1.** Relation between maximum air temperature heat island intensity ($\Delta T_{u-r} (max)$, degrees Celsius)
 248 and population (P) for European Settlements (redrawn from Oke, 1982). Sources of $\Delta T_{u-r} (max)$ are
 249 literature and private communications dating from 1927 – 1972. It is not clear in Oke (1973; 1982) if
 250 the population data used is matched in time to the date for $\Delta T_{u-r} (max)$. Reported on the graph (top
 251 right) are the Coefficient of Determination (R^2) for the best-fit regression, the slope of the regression,
 252 and the error on the slope (ϵ).

253

254 Since both the canopy air temperature UHI, and the surface temperature SUHII result from heat
 255 storage, the scaling of emitted energy (with population or urban area) will be an important
 256 contributor to the scaling of UHI and SUHII. When the observed scaling of emitted energy is larger
 257 than that for UHI or SUHII, other factors must be acting to dampen the overall scaling. Thus, this
 258 paper seeks to use allometric scaling, and importantly an interpretation of the residual offset, to
 259 inform the role of bulk urban morphology as a control for levels of urban heat.

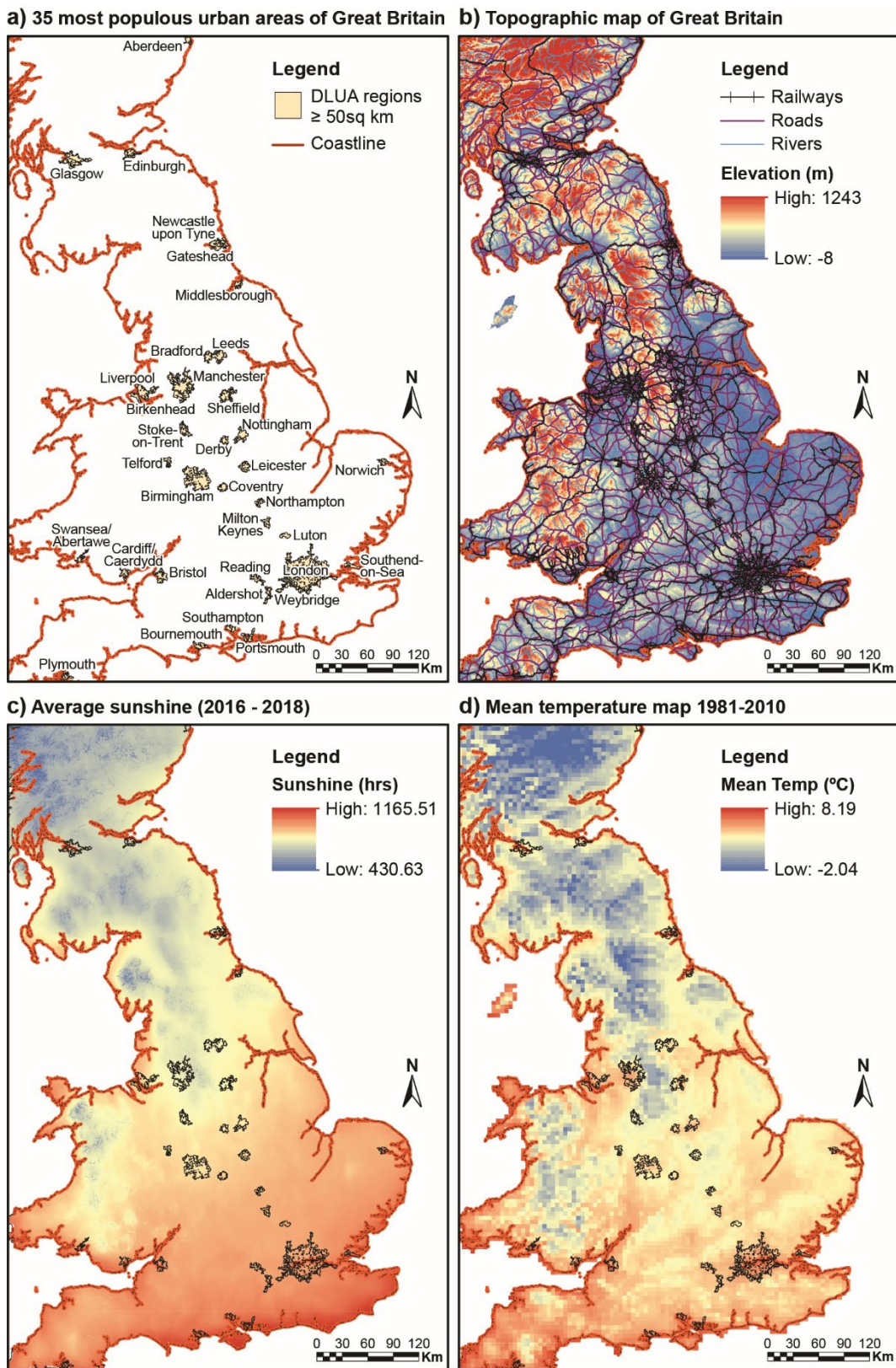
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261 2.0 METHODOLOGY

262 2.1 The study area

263 According to the Office for National Statistics (ONS), the population of UK as at 30th June 2016 is
 264 estimated to be 65,648,000, concentrated in urban areas in the southern half of the country (Figure
 265 2a), and with a rate of increase of 0.8% (538,000) per annum (Office for National Statistics, 2017).
 266 The climate of UK is temperate, but variable, particularly because of altitude and distance from the
 267 coast (Figure 2b). Average temperature is 4°C January (winter) and 15°C in July (summer) (Kennedy
 268 et al., 2017; Briney, 2019). Mean climate data are shown in figure 2. This study focuses on thirty-five
 269 (35) large (area > 50km²) settlements in the Great British mainland of the UK (see fig. 2a below and
 270 table S1 and fig S5 in supplementary section SI). Boundaries for the cities were extracted from
 271 medium scale digital map data (Meridian2; see Data Sources, below) produced by the Ordnance
 272 Survey (GB National Mapping Agency) and represent contiguous Developed Land Use Areas (DLUA)
 273 rather than administrative demarcations. UHI, SUHII, and urban allometry studies are sensitive to
 274 the choice of urban boundary and this should be borne in mind in the comparisons discussed below.
 275 The urban boundary used to define population in Oke (1973) is likely administrative; the urban
 276 cluster areas used in Zhou et al. (2013, 2017) are similar to our contiguous DLUA. Population counts

277 were retrieved from the Office of National Statistics (2017) at the lowest level of geographical
 278 aggregation (output area) and attributed to the contiguous DLUAs.



279
 280 **Fig. 2** (a) 35 most populous urban areas in Great Britain (urban boundaries are contiguous Developed
 281 Land Use Areas from Meridian2 data); (b) Topographic map of central Great Britain with cities and
 282 major roads; (c) Average Sunshine of central Great Britain; (d) Mean 2m Temperature map of central

283 *Great Britain. The data were sourced from Centre for Environmental Data Analysis (CEDA, 2011),*
284 *(SolarGIS, 2019), and ArcGIS tool were used to plot the maps.*

285 *2.2 Data collection and analysis*

286 This study uses MODIS/Terra V006 composite products (MOD11A1) – MODIS/Terra Land Surface
287 Temperature and Emissivity Daily L3 Global 1km Grid SIN V006 (Wan et al., 2015). This product
288 provides gridded, high resolution, cloud-cleared, quality-controlled and quality-assured data, and
289 has accurate calibration in multiple thermal infrared bands designed for retrievals of Land Surface
290 Temperature (LST) and atmospheric properties (Wan and Dozier, 1996; Wan et al., 2015). LST from
291 MODIS are retrieved from clear sky observations at daytime and night-time with the aid of a
292 generalized split-window algorithm (Wan and Dozier, 1996; Wan, 2008). It is established that
293 satellite sensors looking in the nadir can oversample horizontal urban surfaces and undersample
294 vertical surfaces (Voogt and Oke, 1998; Arnfield, 2003). This will tend to overemphasise both day-
295 time heating and night-time cooling, the extent of which varies with the angle of view. Angle of view
296 also affects the native spatial resolution of the satellite radiances; interpolation in the MOD11A1
297 processing pipeline brings the dataset to a uniform 1-km grid. The MOD11A1 dataset contains
298 information on view angle but we have not implemented any further correction for off-nadir view
299 geometries. For simplicity, only night-time overpasses (0130h local time) are considered for the
300 present study.

301 Area-summed clear-sky night-time long-wave upwelling emitted energy (hereafter ‘emitted energy’)
302 for mainland Great Britain was derived for selected days from 2000-2017. We interpret emitted
303 energy in preference to LST because it gives proper weighting to radiance from the highest
304 temperatures and provides a sum in physically meaningful units. The LST data used was selected to
305 have as much clear sky over the region as possible. LST data for each pixel, i , within the city, j , on
306 night, k , was converted to emitted energy, $\epsilon_{i,j}$ in W m^{-2} , using the Boltzmann law:

$$307 \quad \epsilon_{i,j,k} = \sigma T_{i,j,k}^4 \quad (3)$$

308 where, σ is the Stefan-Boltzmann constant = $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, and $T_{i,j,k}$ is the LST in Kelvin. The
309 effect of varying surface emissivity is not taken into account. Area-summed emitted energy, $\langle E_j \rangle$ in
310 MW, for each city on each night, was then calculated by summing the p unobscured land-surface
311 pixels inside the city boundary:

$$312 \quad \langle E_{j,k} \rangle = \sum_{i=0}^p \epsilon_{i,j,k} \Delta a \quad (4)$$

313 where $\Delta a = 1 \text{ km}^2$ and the factor of 10^6 converting km^2 into m^2 is accommodated in the units of $\langle E_j \rangle$.
314 A default 50% threshold of clear sky was set for each city on each image based on the assumption
315 that adequate coverage of the study region can be achieved by sampling a large enough set of
316 imagery. The threshold was implemented in ArcGIS simply by comparing the maximum area of each
317 city as given by the Meridian dataset (Table S1) with the area inside the city containing valid LST (i.e.
318 $p \cdot \Delta a$) from the satellite dataset. The effect of using a 75% clear-sky threshold is discussed below.

319 *2.3 Scaling Study Methodology*

320 35 cities were selected for study using an arbitrary threshold of city area greater than 50 km^2 , from
321 which population and emitted energy were derived (table S3 in SI). Clear-sky nights were selected
322 based on the prevalent synoptic meteorology (i.e., fog-free anticyclone conditions in the absence of
323 fronts). A total of 28 nights was selected: 15 in winter (30 November – 28 February) and 13 in
324 summer (1 June -31 August) in the period 2000 – 2017.

325 3.0 RESULTS

326 Area-summed emitted energy varies over 1.5 orders of magnitude for cities with populations ranging
327 over 2 orders of magnitude (Figure 3a). Although the exact slope varies from night to night (Figure
328 3b), the tight log-log correlation is always present. Strong correlations are present on both summer
329 and winter nights (table 1) with no obvious pattern, suggesting that scaling of emitted energy may
330 not be as seasonal as the UHI or SUHI itself (cf. Zhou et al., 2013; Bechtel et al., 2019). The
331 correlations suggest that population is a good predictor variable for total emitted energy, despite
332 substantial differences in urban form of British cities. Figure 3b shows the plots for all dates
333 sampled in this study. Slopes are similar, varying between 0.73 ± 0.06 (13 December 2010; Table 1)
334 and 0.92 ± 0.09 (17 December 2011) and are ranked in Table 1 by their R^2 value when using a 50%
335 cloud-free threshold. Standard error on the slope increases as R^2 decreases but there is no obvious
336 trend in the value of the slope.

337 The derived regression equation for the averaged allometry over 28 nights is:

$$338 \log(\bar{Y}) = \log(\bar{\beta}) + \bar{\alpha} \cdot \log(\langle \bar{E}_j \rangle), \quad (5)$$

339 where

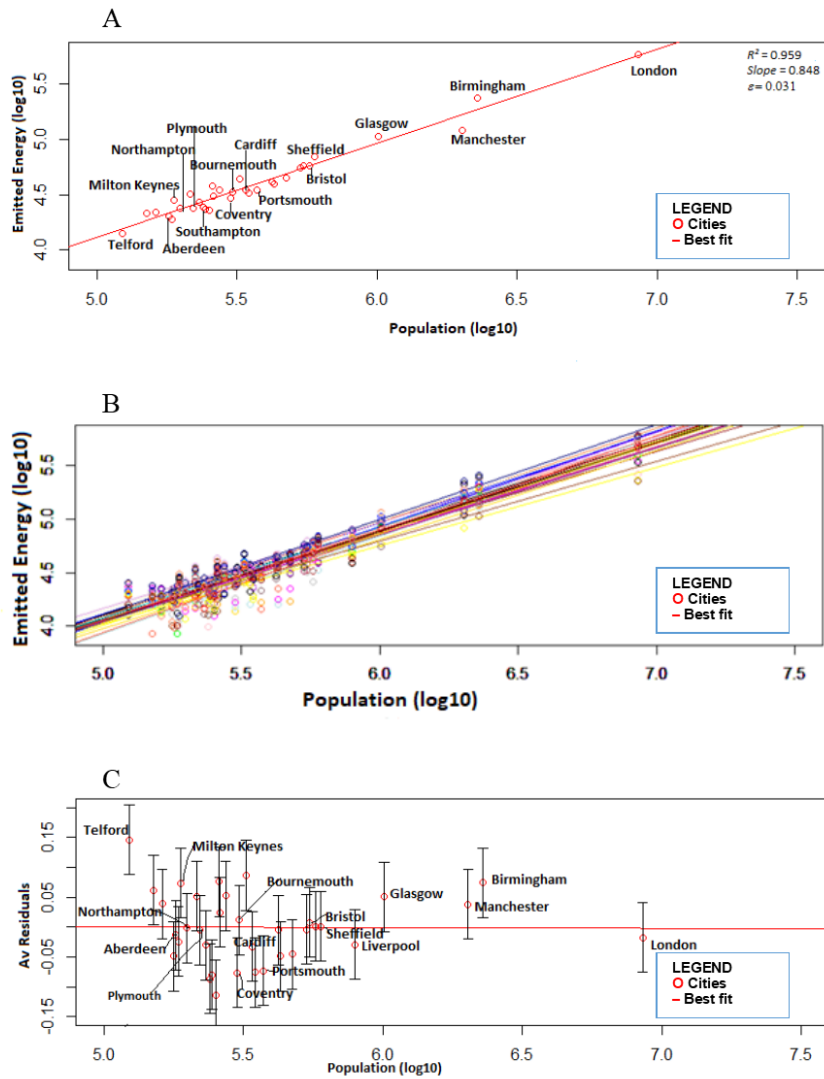
$$340 \langle \bar{E}_j \rangle = \frac{\sum_{k=0}^n E_{j,k}}{n}. \quad (6)$$

341 That is, $\langle \bar{E}_j \rangle$ is the average emitted energy (in MW) over all nights for city, j , and n is the number of
342 nights = 28.

343 Although the two extreme values of the allometric slope are statistically different (i.e., the means
344 are further apart than the sum of the standard errors, Table S3, Supplementary SI), Figure 3a does
345 not show any clustering of the regression slopes in the sample. It is assumed, therefore, that, to a
346 first approximation at least, the results indicate that a single overall allometric scaling of total
347 emitted energy with population of 0.84 ± 0.06 is plausible (fig.3b). If this assumption is justified, the
348 variation observed in the regression slope must derive from difficult-to-quantify errors in the
349 retrieval of the emitted energies, including the effect of partially obscured urban areas on the slope.

350 To test the impact of partial cloud obscuring, the analysis was repeated increasing the threshold for
351 inclusion of an urban area in the analysis to 75% cloud-free (see table S3 and fig. S6 in
352 supplementary SI). The scaling of emitted energy with population under this more stringent
353 condition has a slope of 0.86 ± 0.05 (Table S3 in Supplementary SI), which is, within error,
354 indistinguishable from the mean slope from Table 1.

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357

358 Fig. 3: (A) An example of allometric scaling of night-time emitted energy $\text{Log}_{10}\langle E_j \rangle$, in MW) against
 359 urban population for the 35 largest cities in Great Britain. Reported on the graph (top right) are the
 360 Coefficient of Determination (R^2) for the best-fit regression, the slope of the regression, and the error
 361 on the slope (ε). (B) The ensemble of allometric relationships derived for the nights studied (Table 1).
 362 (C) Residual emitted energy (mean and standard deviation of $\text{Log}_{10}\langle E_j \rangle$ in MW) for urban areas with
 363 respect to the allometric scalings shown in (B).

364

365 **Table 1.** Night-time emitted energy for thirty-five (35) UK large Cities on selected summer and
 366 winter nights. Results are ranked by the strength (R^2) of the log-log correlation between emitted
 367 energy and population, for which the slope, and error on slope are reported at 50% cloud free
 368 pixels

Rank	DATE	Number of CITIES	R^2	SLOPE (α)	ERROR ON SLOPE
1	13 th Feb. 2017	26	0.97	0.86	0.03
2	15 th Feb. 2016	25	0.96	0.85	0.03
3	06 th Jun. 2000	33	0.96	0.85	0.03
4	22 nd Feb. 2003	28	0.96	0.88	0.04

5	07 th Jul. 2007	34	0.96	0.84	0.03
6	01 st Jan. 2007	32	0.96	0.85	0.03
7	02 nd Jan. 2017	35	0.94	0.84	0.04
8	26 th Dec. 2009	24	0.93	0.81	0.05
9	27 th Jun. 2010	32	0.93	0.80	0.04
10	16 th Aug. 2016	35	0.92	0.89	0.04
11	29 th Feb. 2000	21	0.92	0.83	0.05
12	01 st Jan. 2012	24	0.92	0.89	0.06
13	30 th Nov. 2016	20	0.92	0.86	0.06
14	13 th Dec. 2010	17	0.92	0.73	0.06
15	28 th Aug. 2001	25	0.91	0.88	0.06
16	30 th Aug. 2005	22	0.90	0.82	0.06
17	20 th Jan. 2009	18	0.88	0.83	0.08
18	09 th Jul. 2006	34	0.88	0.88	0.06
19	20 th Jan. 2011	22	0.88	0.74	0.06
20	08 th Aug. 2012	25	0.88	0.83	0.06
21	05 th Jan. 2005	34	0.88	0.80	0.05
22	10 th Jun. 2003	27	0.87	0.81	0.06
23	13 th Jul. 2002	28	0.87	0.77	0.06
24	03 rd Aug. 2017	22	0.86	0.82	0.07
25	25 th Feb. 2009	26	0.85	0.91	0.08
26	28 th Aug. 2009	30	0.84	0.81	0.07
27	17 th Dec. 2011	26	0.83	0.92	0.09
28	18 th Feb. 2006	25	0.79	0.84	0.09
	Mean			0.84	0.06
	Median			0.83	

369

370

371 Table S4 (supplementary SI) tests the effect of a population threshold by comparing the correlations
372 for cities with populations greater than 250,000 and greater than 500,000. The mean slope of the
373 regression is not significantly different for both subsets of cities.

374

375

376 4.0 DISCUSSION

377 The findings from this study indicate that population is a good predictor variable for total emitted
378 energy despite the differences in the urban form of UK cities. This study finds a much more
379 significant scaling for upwelling clear-sky long-wave with population than was found for $\Delta T_{u-r} (max)$
380 by Oke (1973; 1982) (i.e., Fig. S1 in SI). Energy emitted from the surface is acted on by turbulent and
381 radiative transfer processes, the net result of which is $\Delta T_{u-r} (max)$ (Oke, 1982). Although it is plausible
382 that turbulent transfer processes scale with city size (as discussed in (MacKenzie et al., 2019)), it
383 appears that the overall effect on the energy budget is to dampen very significantly the scaling of
384 $\Delta T_{u-r} (max)$ compared to the scaling of emitted energy. The difference in the scalings of the heat
385 source and the final temperature difference is very marked. Investigating this further will require a

386 detailed investigation of the scaling of each aspect of the urban energy budget, which is outside the
387 scope of the present study.

388 The scaling of emitted energy with population is very similar to that of total urban area with
389 population (Fig S2A in the SI). Hence, emitted energy varies linearly with urban area for the 35 cities
390 in our study (Fig S3), even though that area becomes increasingly densely populated as city
391 population increases. The implication is that, on average, there is no structural change of relevance
392 to the total emitted energy between a single city the size of London or ten cities each a tenth of the
393 area (i.e., roughly the size of Bristol). This quantitative scaling without qualitative structural change
394 may be consistent with Oke's 1973 study on city size and the urban heat Island, and with his study in
395 1981 on canyon geometry and the nocturnal urban heat Island, in which he cited Chandler's 1967
396 observation on the similarities of London and Leicester temperature on the same night, despite their
397 difference in size and population (Oke, 1973; 1981). Non-linearities may become more important
398 when smaller urban centres are included, as in the study of Zhou et al. (2013).

399 Further information pertaining to the urban form can be derived by inspection of the residuals, i.e.,
400 the distances of each urban area from the line of best fit (Fig 3c). We postulate that differences in
401 urban form across Great British cities will be evident in both the magnitude and sign of the residuals.
402 Firstly, however, we discount geographical and climate factors. Comparisons between mean
403 emitted-energy residuals and each of altitude, latitude, mean hours of sunshine, and mean annual
404 temperature for each city showed no significant correlations (see figs. S9, S10, S11 and S12 in
405 supplementary SI).

406 The magnitude of residual can be interpreted as the degree to which an individual city deviates
407 positively or negatively from the value expected for a city of its size (Bettencourt et al., 2010). For
408 the case of emitted thermal energy, positive anomalies correspond to cities with warmer surfaces
409 than expected and negative anomalies correspond to surfaces cooler than expected based on the
410 best-fit population-based allometry. There is a tendency for the magnitude of residuals to be larger
411 for the smaller urban areas (Fig 3c). For example, the residual for Telford is positive and about 4% of
412 its mean area-summed emission, whereas, for London, the residual is about 0.2% of the mean area-
413 summed emission.

414 The cities of Coventry and Plymouth, which were reconstructed post-war (Hasegawa et al., 2013)
415 have large negative residuals (-0.075 and -0.004 y-axis units ($\log_{10}(\langle E_j \rangle$ in MW)), Fig 3c), whereas the
416 New Town 'Garden Cities' of Milton Keynes and Telford both have large positive residuals (0.08 and
417 0.15 units). These unexpected results do not seem to arise from sampling issues affecting the overall
418 allometry because the residuals are robust for the various nights studied (variation bars in Fig 3c).
419 Instead, the results may arise from a greater area of impervious, low albedo, surface per person in
420 the lower density Garden Cities. Residuals for the area allometry for each city are reported in (table
421 S2 supplementary SI). Milton Keynes and Telford have large positive residuals compared to their
422 expected area (0.087 and 0.155 units, respectively), whilst Coventry and Plymouth have large
423 negative residuals (-0.056 and -0.050 units). So, the Garden cities emit more than expected for their
424 populations but spread that emission over a wider surface area than expected, whereas Coventry
425 and Plymouth emit much less than expected from their population but spread that emission over a
426 smaller-than-expected area.

427 Northampton, situated about 60 miles (97km) north-west of London and 45 miles (72km) south-east
428 of Birmingham, had a population of 212,100 at the 2011 census. Northampton is predominantly a
429 post-war settlement in which growth was limited until it was nominated as a New Town in 1968
430 (Whitehand and Whitehand, 1984). Its mean energy emission residual is close to zero, similar to

431 Bristol (fig. 3c), despite being radically different in terms of population and their histories of urban
432 development. The residuals for urban area are also similar for Northampton and Bristol. However,
433 Milton Keynes, the city closest to Northampton in population (table 1, supplementary SI), similarly
434 situated (about 50 miles (80km) north-west of London), and also a classic post-war New Town, has a
435 large positive mean emitted energy residual (fig 3c) and large positive area residual.

436 City configuration, street patterns and orientation, structure of buildings and density, and ultimately
437 the intensity of human activities are key factors that determine thermal behaviour in the city. In
438 summary, the residuals (fig. 3c) allow an assessment of the similarities and differences in emitted
439 energy, relative to that expected by the best-fit line, for settlements of very different size.

440

441

442 **5.0 CONCLUSION**

443 This study aimed at evaluating the extent and rate of clear-sky emitted long-wave energy with
444 population in the cities for MODIS/Terra V006 composite products (MOD11 A1). This was achieved
445 by assessing the night-time emitted energy across cities in Great Britain for 28 night-time samples
446 across summer and winter between 2000 and 2017. British cities show a strong and consistent sub-
447 linear allometric scaling of total emitted energy with population. That is, there is a substantial
448 'economy (or parsimony) of scale' in terms of nocturnal heat production in British cities: the
449 production from the larger cities is smaller than would be produced from a constellation of smaller
450 cities housing the same population. This uniformity of scaling occurs despite of the obvious
451 differences in architecture and urban form in settlements with Medieval centres (e.g. Aberdeen),
452 predominantly commercial/military (e.g. Southampton) or residential (Bournemouth) coastal
453 settlements, and post-second-world-war planned settlements (e.g., Milton Keynes).

454 The scaling of emitted energy with population is much larger than the scaling reported in the
455 literature for the scaling of air temperature urban heat island (UHI) with population (Oke, 1973; Oke,
456 1982) or for the scaling of surface urban heat island intensity (SUHII) (Zhou et al., 2013; 2017). It is
457 possible to compare these scalings even though emitted energy and UHI or SUHII have different
458 units, because the logarithmic scaling produces a dimensionless slope quantifying relative changes
459 (e.g., Bettencourt and West 2010). Since long-wave emissions from the relatively warm urban
460 surface are the source of the nocturnal UHI and SUHII, turbulent and radiative transfer in the
461 atmosphere must act to dampen significantly the scaling signal for heat island metrics. The
462 concentration of population into larger urban areas, rather than spread out over more, smaller,
463 cities, has only a marginal worsening effect on the risk to health arising from air temperature UHI
464 but a much larger effect arising from radiant flux (cf., e.g., Middel and Krayenhoff, 2019).

465 The scaling of total emitted energy with population has a similar slope, within statistical error, as the
466 scaling of urban area with population. This equality of scaling suggests that energy emitted per unit
467 area averages out to be approximately the same everywhere in cities at the granularity of the
468 current analysis. This 'emergent simplicity' in the scaling of emitted energy for urban areas of
469 different sizes seems counter intuitive given our understanding of the role of urban form in heat
470 storage and emission in the built environment (Arnfield and Grimmond, 1998; Nunez and Oke,
471 1977). Instead, the particularities of British urban form seem to manifest in the residuals for each
472 city, i.e., the magnitude of the difference in emitted energy measured from that predicted by the
473 best-fit line. As yet, we have not been able to find any simple rules that would allow us to predict the

474 size of the residual from its geographical context (including climate) or from its development history
475 but we believe this merits further study.

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- 816
- 817 **Data Sources**
- 818 Meridian_data, 2017

819 https://digimap.edina.ac.uk/webhelp/os/data_information/os_products/meridian_2.htm, data
 820 downloaded on 31st January 2017

821 MODIS/Terra Land Surface Temperature and Emissivity Daily L3 Global 1km Grid SIN V006
 822 <https://search.earthdata.nasa.gov/search>, Data downloaded on 23rd August 2017(Earthdata, 2017).

823 For a description of the dataset, see <https://lpdaac.usgs.gov/products/mod11a1v006/>

824 <https://www.planninghelp.cpre.org.uk/planning-explained/history-of-the-planning-system>, last
 825 accessed 26th September 2019.

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828 SUPPLEMENTARY MATERIALS

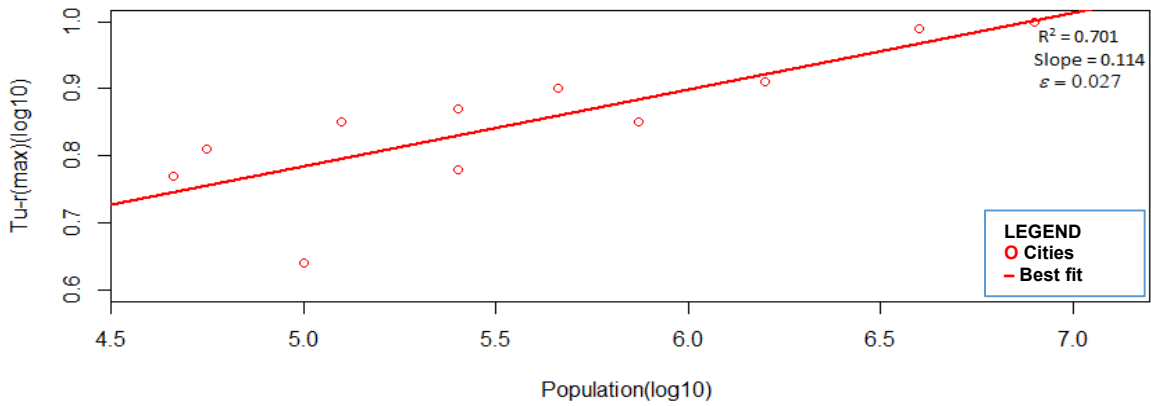
829 Supplementary (SI)

830 **Table S1.** Hierarchical population distribution and area for 35 biggest cities in Great Britain
 831 (50km² and above; source: Meridian data 2017)

NAME OF CITY	POPULATION	AREA (km ²)
London	8519128	1,365.43
Birmingham	2273321	558.07
Manchester	2018064	506.06
Glasgow	1006585	261.85
Liverpool	792665	191.28
Sheffield	596456	164.23
Bristol	573382	135.52
Nottingham	546720	133.02
Leeds	531516	135.50
Edinburgh	472217	105.28
Leicester	429753	98.25
Newcastle Upon Tyne	420710	103.31
Portsmouth	371300	81.52
Bradford	347653	78.96
Cardiff / Caerdydd	339746	80.84
Stoke-On-Trent	323762	107.18
Bournemouth	305788	80.08
Coventry	300924	71.98
Reading	272658	78.04
Gateshead	260779	71.95
Weybridge	259047	88.69
Luton	251115	51.56
Southampton	243807	53.91
Southend-On-Sea	239424	59.37
Derby	231497	59.78
Plymouth	220942	55.91
Aldershot	214691	76.37
Northampton	198564	54.55
Milton Keynes	188643	66.86
Birkenhead	184461	53.58
Aberdeen	181027	50.27

Norwich	177619	51.98
Middlesbrough	161596	52.43
Swansea / Abertawe	150201	53.01
Telford	123416	54.26

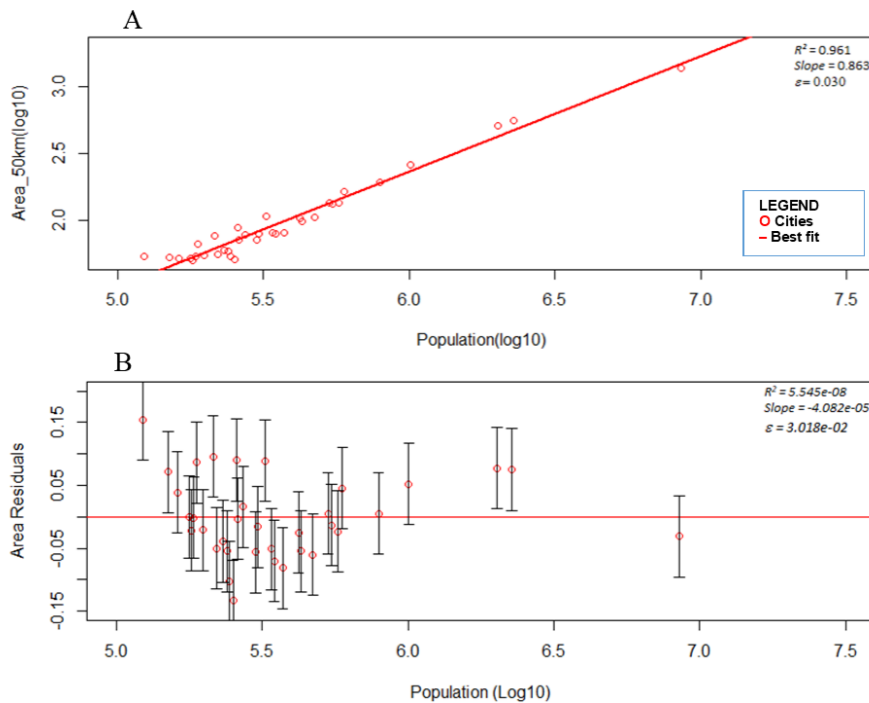
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833

834 **Fig. S1.** As for Figure 1 of the main text but re-drawn on log-log axes to show the power-law scaling.
 835 Reported on the graph (top right) are the Coefficient of Determination (R^2) for the best-fit regression,
 836 the slope of the regression, and the error on the slope (ϵ).

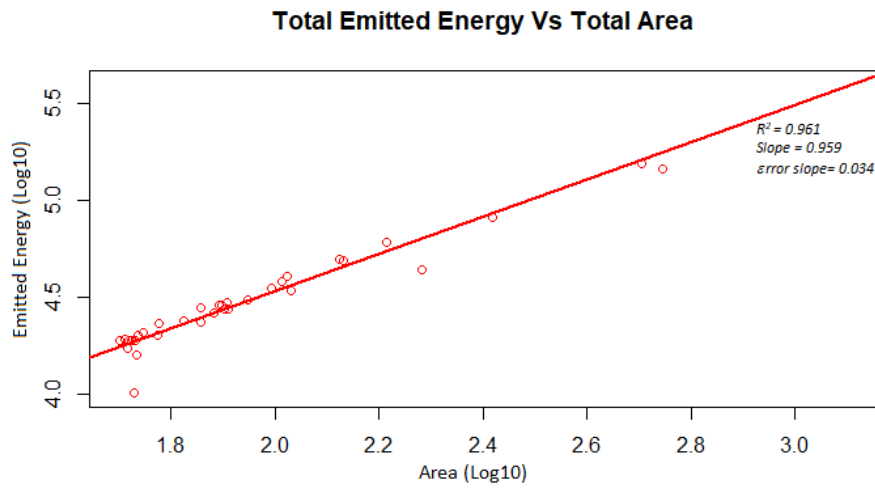
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839 **Fig. S2 (A)** Relationship between total city area and total population for 35 cities in Great Britain. The
 840 allometric regression relationship shown has a coefficient of determination ($R^2 = 0.961$) and

841 slope = 0.86±0.03. (B) Residuals (equation 2, main text) of city area plotted against city population.
 842 The best-fit regression values are reported but are not significant.
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Fig S3. Relationship between emitted energy and urban area for 35 cities in Great Britain. Reported on the graph (top right) are the Coefficient of Determination (R^2) for the best-fit regression, the slope of the regression, and the error on the slope (ϵ).

Table S2. Residuals for Emitted Energy and surface area for 35 biggest cities in Great Britain (cities are ranked by emitted energy residuals)

NAME OF CITY	EMITTED ENERGY RESIDUAL ($W m^{-2}$)	AREA RESIDUAL (km^2)
Telford	0.146	0.155
Stoke-On-Trent	0.086	0.089
Weybridge	0.075	0.090
Birmingham	0.074	0.075
Milton Keynes	0.073	0.087
Swansea / Abertawe	0.062	0.071
Reading	0.052	0.016
Aldershot	0.051	0.096
Glasgow	0.050	0.052
Middlesbrough	0.038	0.039
Manchester	0.038	0.078
Gateshead	0.025	-0.003
Bournemouth	0.012	-0.016
Nottingham	0.008	-0.013

Sheffield	0.001	0.045
Bristol	0.001	-0.023
Northampton	-0.002	-0.021
Leeds	-0.004	0.005
Plymouth	-0.005	-0.050
Newcastle Upon Tyne	-0.005	-0.025
Aberdeen	-0.014	-0.022
London	-0.017	-0.031
Birkenhead	-0.024	-0.001
Liverpool	-0.029	0.005
Derby	-0.030	-0.039
Cardiff / Caerdydd	-0.033	-0.051
Edinburgh	-0.046	-0.060
Norwich	-0.049	0.000
Leicester	-0.049	-0.055
Portsmouth	-0.073	-0.081
Bradford	-0.076	-0.070
Coventry	-0.077	-0.056
Southampton	-0.080	-0.103
Southend-On-Sea	-0.087	-0.054
Luton	-0.114	-0.133

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855 **Table S3.** Summary of night-time emitted energy scalings for thirty-five (35) UK large Cities on 28
856 selected summer and winter nights between 2000 and 2017. Results are ranked by the strength ($*R^2$)
857 of the log-log correlation between emitted energy and population, for a threshold for inclusion of a
858 city in the scatter plot of 75% cloud-free pixels. The table reports the allometry slope, error on slope,
859 intercept, and sample size at 50% and 75% cloud free pixels (*=75% cloud free pixels).

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RANK	DATE	NUMBER OF CITIES(n)	NUMBER *OF CITIES(n)	R ²	*R ²	SLOPE (α)	SLOPE *(α)	ERROR ON SLOPE (ε)	ERROR ON *SLOPE (ε)	INTERCEPT	*INTERCEPT
1	13th Feb. 2017	26	25	0.97	0.97	0.86	0.84	0.03	0.03	-0.23	-0.15
2	02nd Jan. 2017	35	33	0.94	0.97	0.84	0.83	0.04	0.03	-0.13	-0.09
3	15th Feb. 2016	25	25	0.96	0.96	0.85	0.85	0.03	0.03	-0.18	-0.18
4	06th Jun. 2000	33	32	0.96	0.96	0.85	0.88	0.03	0.03	-0.13	-0.28
5	29th Feb. 2000	21	19	0.92	0.96	0.83	0.78	0.05	0.04	-0.08	0.19
6	22nd Feb. 2003	28	28	0.96	0.96	0.88	0.88	0.04	0.04	-0.37	-0.37
7	07th Jul. 2007	34	34	0.96	0.96	0.84	0.84	0.03	0.03	-0.08	-0.08
8	01st Jan. 2007	32	32	0.96	0.96	0.85	0.85	0.03	0.03	-0.16	-0.16
9	20th Jan. 2011	22	17	0.88	0.95	0.74	0.82	0.06	0.05	0.33	-0.06
10	09th Jul. 2006	34	30	0.88	0.95	0.88	0.84	0.06	0.04	-0.31	-0.04
11	30th Aug. 2005	22	18	0.90	0.95	0.82	0.84	0.06	0.05	0.00	-0.06
12	20th Jan. 2009	18	14	0.88	0.94	0.83	0.80	0.08	0.06	-0.18	0.01
13	28th Aug. 2001	25	23	0.91	0.94	0.88	0.86	0.06	0.05	-0.30	-0.18
14	10th Jun. 2003	27	20	0.87	0.94	0.81	0.82	0.06	0.05	-0.02	-0.02
15	16th Aug. 2016	35	34	0.92	0.94	0.89	0.87	0.04	0.04	-0.31	-0.21
16	27th Jun. 2010	32	31	0.93	0.94	0.80	0.81	0.04	0.04	0.16	0.13
17	17th Dec. 2011	26	20	0.83	0.93	0.92	0.94	0.09	0.06	-0.65	-0.74
18	25th Feb. 2009	26	19	0.85	0.93	0.91	0.97	0.08	0.06	-0.62	-0.89
19	26th Dec. 2009	24	24	0.93	0.93	0.81	0.81	0.05	0.05	0.03	0.03
20	05th Jan. 2005	34	30	0.88	0.93	0.80	0.86	0.05	0.05	0.06	-0.25
21	13th Jul. 2002	28	22	0.87	0.92	0.77	0.80	0.06	0.05	0.22	0.14
22	30th Nov. 2016	20	17	0.92	0.92	0.86	0.82	0.06	0.06	-0.30	-0.08
23	18th Feb. 2006	25	23	0.79	0.92	0.84	0.86	0.09	0.06	-0.15	-0.21
24	01st Jan. 2012	24	24	0.92	0.92	0.89	0.89	0.06	0.06	-0.43	-0.43
25	08th Aug. 2012	25	20	0.88	0.89	0.83	0.99	0.06	0.08	-0.07	-0.95
26	03rd Aug. 2017	22	18	0.86	0.86	0.82	0.84	0.07	0.09	-0.06	-0.17
27	13th Dec. 2010	17	15	0.92	0.84	0.73	0.91	0.06	0.11	0.35	-0.62
28	28th Aug. 2009	30	21	0.84	0.82	0.81	0.88	0.07	0.09	-0.02	-0.36
	Mean					0.84	0.86	0.06	0.05	-0.13	-0.22
	Median					0.83	0.85				

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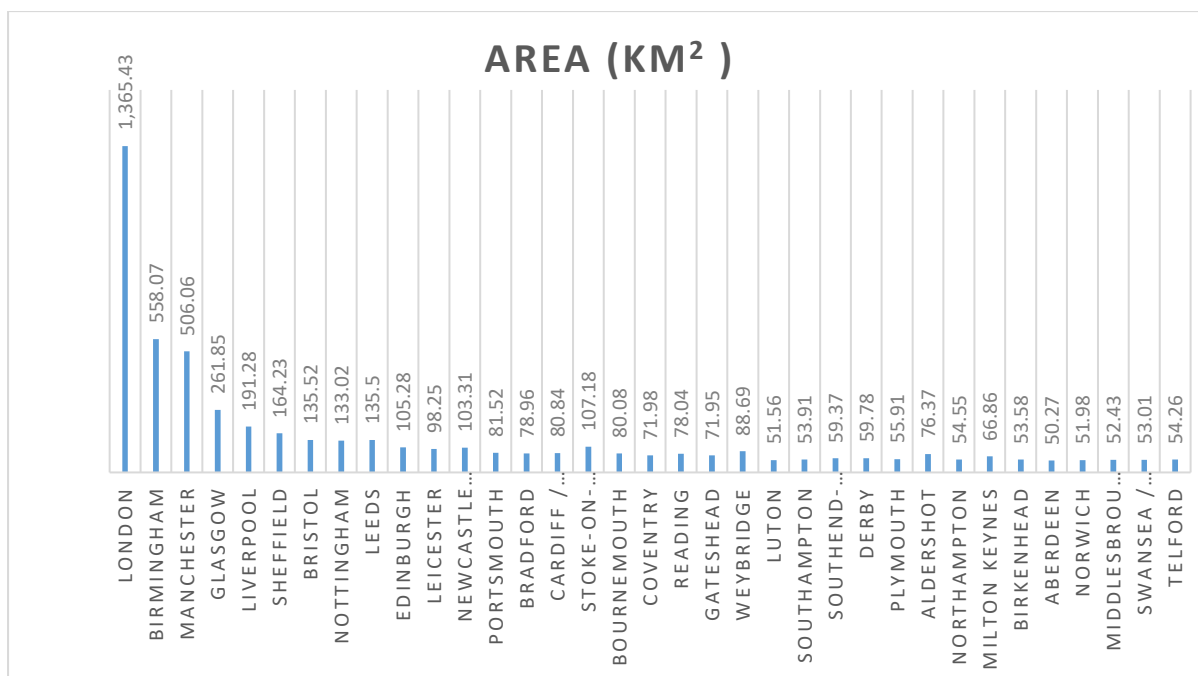
866

867 **Table S4.** Summary of night-time emitted energy for UK large Cities with populations >250,000 and
868 >500,000 on selected summer and winter nights. Results are ranked by the strength (R² [@50%]) of
869 the log-log correlation between emitted energy and population, for which the slope, error on slope,
870 and intercept are reported

RANK	DATE	NUMBER OF CITIES (n)	NUMBER OF CITIES *(n)	R ²	*R ²	SLOPE (α)	SLOPE *(α)	ERROR ON SLOPE (ε)	ERROR ON SLOPE *(ε)	INTERCEPT	*INTERCEPT
1	15th Feb. 2016	16	7	0.98	0.99	0.86	0.85	0.04	0.04	-0.23	-0.19
2	13th Feb. 2017	16	7	0.97	0.97	0.82	0.84	0.04	0.06	-0.02	-0.10
3	16th Aug. 2016	22	9	0.97	0.98	0.87	0.89	0.03	0.04	-0.22	-0.32
4	07th Jul. 2007	22	9	0.97	0.98	0.85	0.86	0.03	0.05	-0.13	-0.16
5	01st Jan. 2007	21	8	0.97	0.98	0.85	0.87	0.04	0.06	-0.17	-0.30
6	29th Feb. 2000	15	7	0.97	0.96	0.81	0.78	0.04	0.07	0.03	0.24
7	02nd Jan. 2017	22	9	0.96	0.96	0.83	0.84	0.04	0.06	-0.07	-0.14

8	06th Jun. 2000	21	8	0.96	0.96	0.83	0.82	0.04	0.07	-0.02	0.06
9	22nd Feb. 2003	19	8	0.95	0.98	0.88	0.87	0.05	0.05	-0.35	-0.27
10	28th Aug. 2001	15	4	0.95	0.99	0.89	0.84	0.06	0.07	-0.38	0.01
11	09th Jul. 2006	22	9	0.95	0.95	0.82	0.85	0.04	0.08	0.05	-0.15
12	30th Nov. 2016	11	2	0.95	1.00	0.90	0.84	0.07	NA	-0.52	-0.10
13	26th Dec. 2009	13	5	0.94	0.98	0.84	0.92	0.07	0.07	-0.14	-0.68
14	01st Jan. 2012	16	7	0.93	0.95	1.02	0.98	0.07	0.10	-1.15	-0.93
15	13th Dec. 2010	10	5	0.92	0.93	0.66	0.58	0.07	0.09	0.81	1.31
16	05th Jan. 2005	21	9	0.92	0.90	0.81	0.65	0.05	0.08	0.03	1.01
17	27th Jun. 2010	20	8	0.92	0.95	0.81	0.87	0.06	0.08	0.14	-0.25
18	20th Jan. 2011	16	7	0.90	0.98	0.69	0.55	0.06	0.04	0.66	1.52
19	30th Aug. 2005	15	6	0.90	0.94	0.79	0.88	0.07	0.11	0.18	-0.38
20	20th Jan. 2009	12	4	0.89	0.88	0.90	0.85	0.10	0.22	-0.58	-0.29
21	03rd Aug. 2017	14	6	0.87	0.83	0.85	0.74	0.09	0.17	-0.21	0.47
22	28th Aug. 2009	20	8	0.87	0.92	0.88	0.80	0.08	0.09	-0.43	0.12
23	10th Jun. 2003	16	6	0.87	0.93	0.83	0.97	0.09	0.13	-0.11	-0.99
24	08th Aug. 2012	17	7	0.87	0.84	0.84	0.85	0.08	0.16	-0.16	-0.20
25	13th Jul. 2002	15	5	0.86	0.99	0.79	1.00	0.09	0.05	0.13	-1.20
26	25th Feb. 2009	16	7	0.85	0.88	1.02	0.93	0.11	0.16	-1.27	-0.72
27	18th Feb. 2006	16	6	0.82	0.98	1.02	0.98	0.13	0.08	-1.20	-0.92
28	17th Dec. 2011	16	6	0.79	0.76	0.92	0.83	0.13	0.23	-0.67	-0.12
	Mean					0.85	0.84	0.07	0.09	-0.21	-0.13
	Median					0.84	0.85				

871 * = Population >500,000



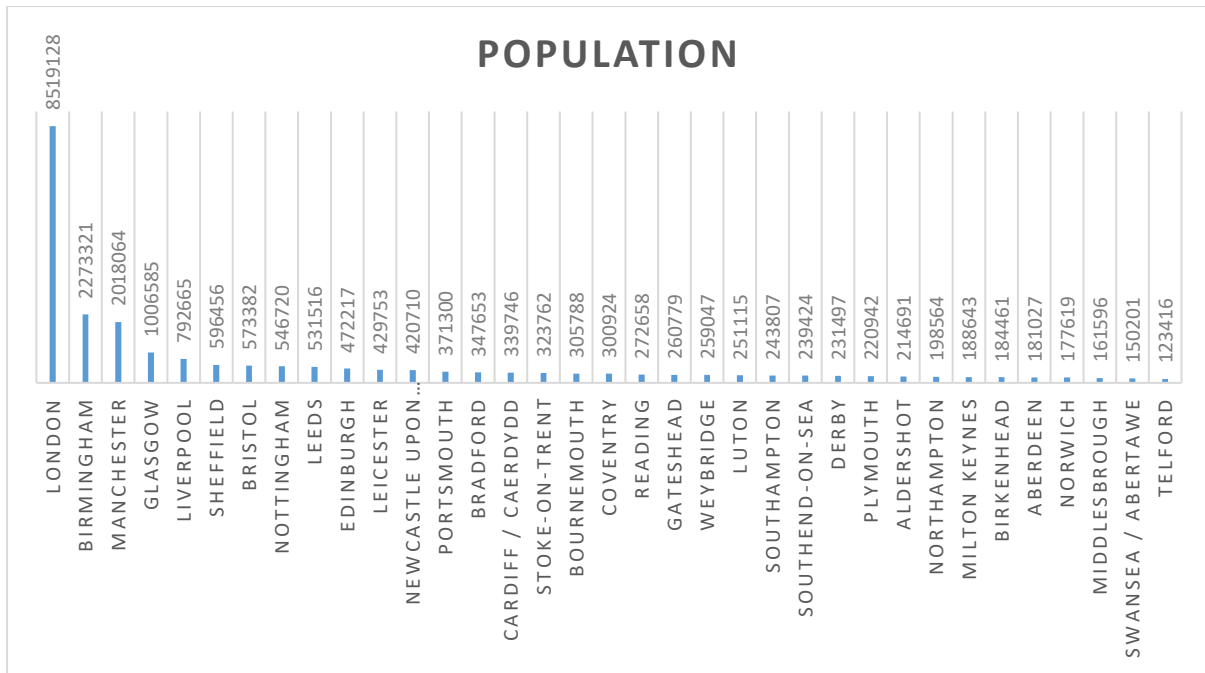
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873 **Fig. S4** Hierarchical Area distribution for the 35 biggest cities in Great Britain

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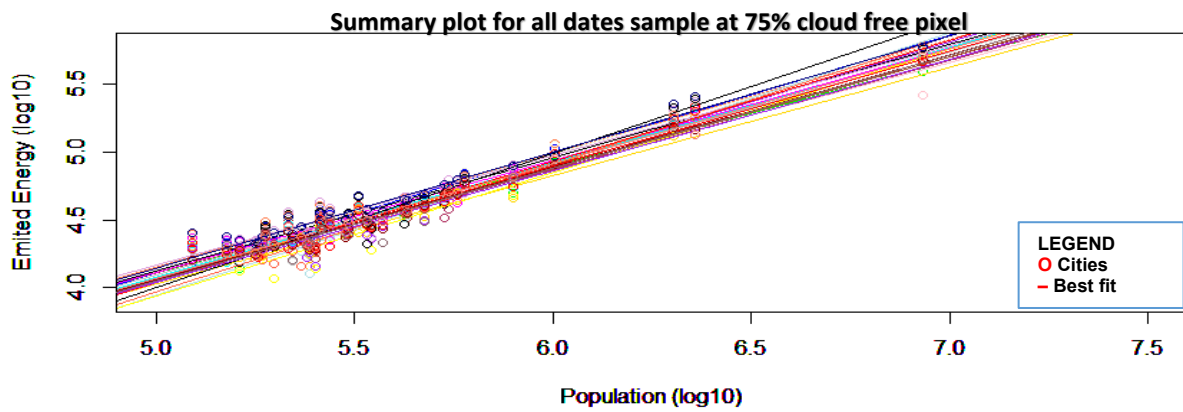
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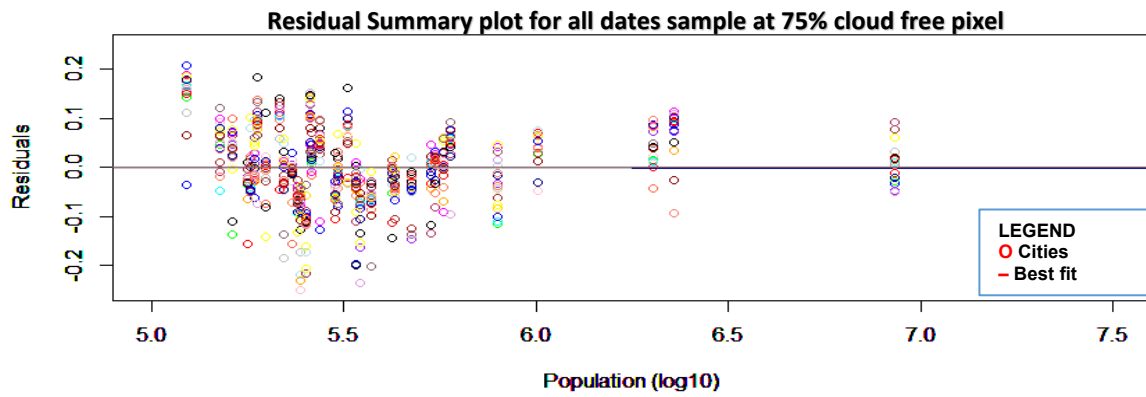
878 **Fig. S5** Hierarchical population distribution for the 35 biggest cities in Great Britain

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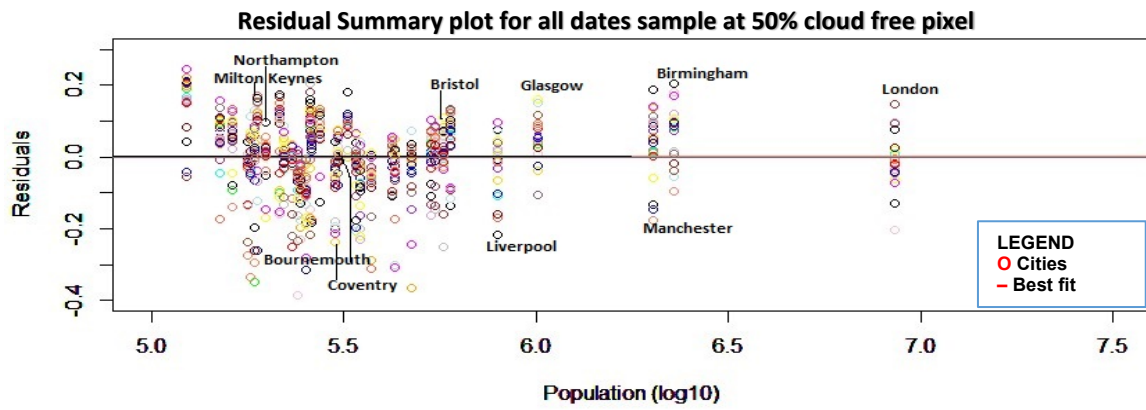
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881 **Fig. S6** Relationship between total emitted energy and total population across Cities in Great Britain for
 882 selected nights, listed in Table 3. Each colour represents a different night. Allometric regressions are plotted for
 883 each night, the equations for which are reported in Table 3. The overall best straight line through the data is
 884 **0.86±0.05**.

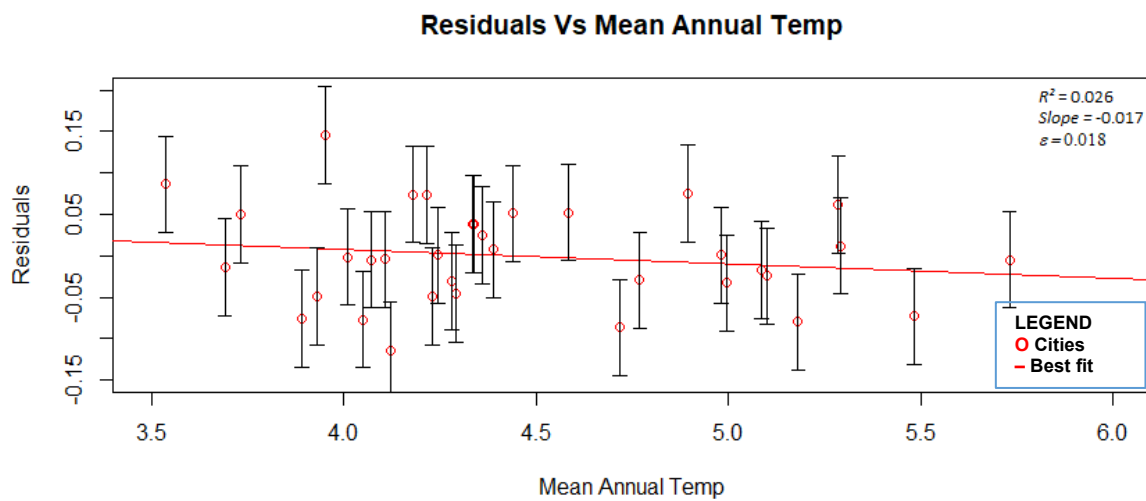


885
886 **Fig. S7** *Residual Summary plot for all dates sample at 75% cloud free pixel*

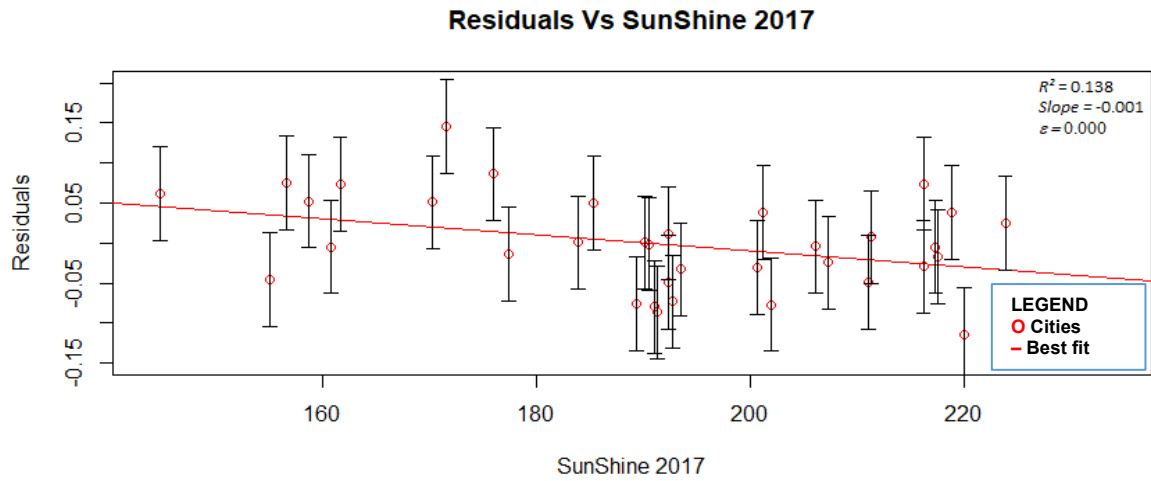
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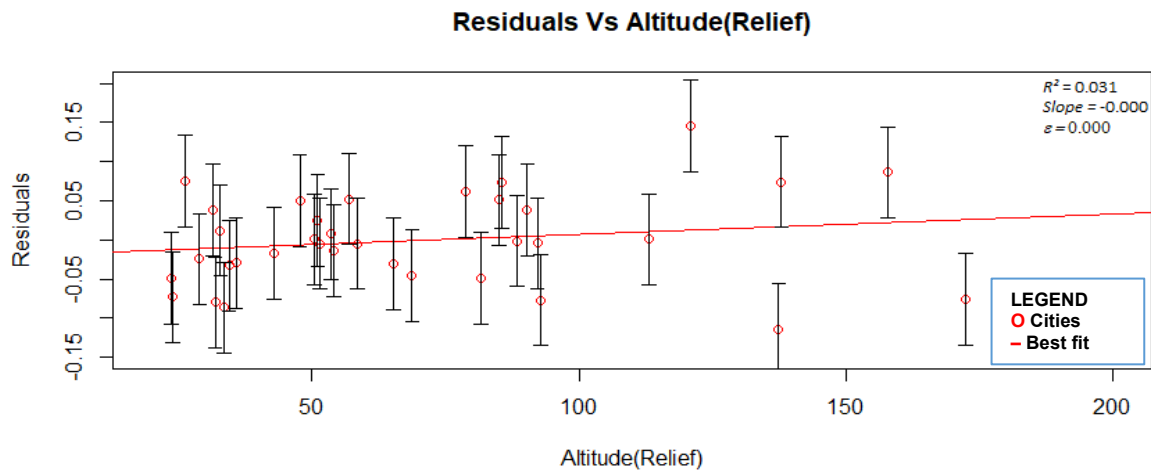
888
889 **Fig. S8** *Residual Summary plot for all dates sample at 50% cloud free pixel*



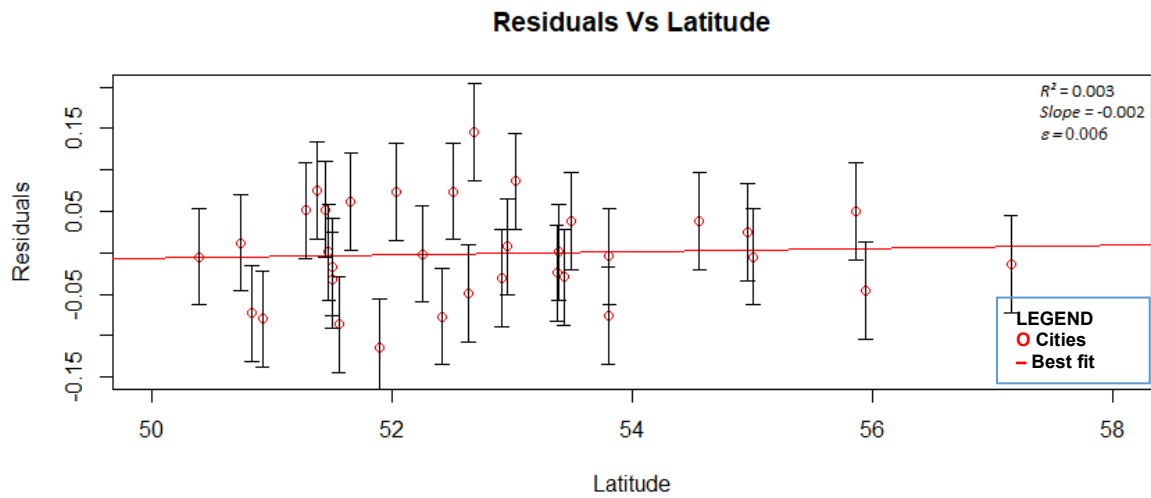
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891 **Fig. S9** *Mean Residuals plots Vs Mean Annual Temperature*



892
893 **Fig. S10** *Mean Residuals plots Vs Hours of Sunshine*



894
895 **Fig. S11** *Mean Residuals plots Vs Altitude*



896

897 **Fig. S12** *Mean Residuals plots Vs Latitude. The regression is not significantly different from zero*
898 *and explain 0.3% of the variance.*