How much has urbanisation affected United Kingdom temperatures?

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RESEARCH ARTICLE

How much has urbanisation affected United Kingdom temperatures?

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This study aims to estimate the affect of urbanisation on daily maximum and minimum temperatures in the United Kingdom. Urban fractions were calculated for 10 km × 10 km areas surrounding meteorological weather stations. Using robust regression a linear relationship between urban fraction and temperature difference between station measurements and ERA-Interim reanalysis temperatures was estimated. For an urban fraction of 1.0, the daily minimum 2-m temperature was estimated to increase by 1.90 ± 0.88 K while the daily maximum temperature was not significantly affected by urbanisation. This result was then applied to the whole United Kingdom with a maximum T_{min} urban heat island intensity (UHII) of about 1.7K in London and with many UK cities having T_{min} UHIIs above one degree.
This paper finds through the method of observation minus reanalysis that urbanisation has significantly increased the daily minimum 2-m temperature in the United Kingdom by up to 1.70 K.

KEYWORDS
Surface temperature, United Kingdom, urban bias, urbanisation

1 | INTRODUCTION

The urban heat island intensity (UHII), which describes increased temperatures in urban areas, has long been known and attempts have been made to quantify it for many years (Mitchell, 1961; Oke, 1982). The urban heat island (UHI) develops through changes to the surface energy balance due to anthropogenic modifications to the land surface. The importance of understanding how these changes will affect the global climate and the potential bias to land temperature records arising from urbanisation has piqued interest in this area of research. Further, due to the consequences of increasing temperatures in urban areas, such as increasing air pollution and mortality rates (Johnson *et al.,* 2005; Stedman, 2004), many studies have attempted to quantify how temperatures in highly urbanised areas will be affected by increasing urbanisation.

Ian L. M. Goddard and Simon F. B. Tett contributed equally to this study.

Previous studies have generally concluded that urban warming has had a negligible effect on global scale temperature series (Peterson *et al.,* 1999; Parker, 2004). For example, Jones *et al.* (1990) showed that the urban warming effect corresponds to no more than 0.1 K over the last century. However on regional scales, the affect of urbanisation on temperature may be significant. Specifically in China, where there has been large expansion of urban areas, a significant effect has been estimated. Yan *et al.* (2010) concluded a large impact of urbanisation up to 0.54 K/decade on local temperature series in Beijing. Whilst Zhou *et al.* (2004) showed a smaller urban effect of about 0.05 K/decade in south east China.

This effect is not exclusive to Asia, several studies have found similar effects in Europe and parts of the United Kingdom (Emmanuel and Krüger, 2012; Grawe *et al.*, 2013; Trusilova *et al.*, 2008; Chrysanthou *et al.*, 2014). To quantify the UHII, Trusilova *et al.* 2008 and Grawe *et al.* (2013) both used atmospheric models to estimate the effect of urbanisation on temperatures in mainland Europe and the greater London area respectively. In Europe, Trusilova *et al.* (2008) quantified an average increase in the daily minimum temperature ($T^d_{\min}$) of 1.53 ± 0.49 K and observed that the maximum daily temperature ($T^d_{\max}$) may increase or decrease depending on local climate. They reported that in cooler climates $T^d_{\max}$ increased due to urbanisation. In the greater London area Grawe *et al.* (2013) found an average increase in ($T^d_{\min}$) and ($T^d_{\max}$) of 1.31 ± 0.30 and 0.57 ± 0.19 K respectively. Further, through the comparison of recorded minimum and maximum daily temperatures between urban and rural sites, Emmanuel and Krüger (2012) found for Glasgow, consistent with other studies, an average increase of 1.6 ± 1.2 and 0.8 ± 2.1 K in $T^d_{\min}$ and $T^d_{\max}$ respectively. The aim of this study is to estimate the impact of urbanisation across the entire United Kingdom.

Previous studies have used varying methods to quantify the impact of urbanisation on temperature. Yan *et al.* (2010) measured the significance of urbanisation by comparing temperature time series for urban and rural weather stations, observing a greater warming at urban sites. However, it is difficult to classify weather stations as either urban or rural. In their study Yan *et al.* (2010) used population density as a marker for urbanisation. However, this data is often out of date and can be hard to obtain for rural areas (Wang and Chen, 2016). Satellite data has also been used to asses the urbanisation of an area. Hansen *et al.* (2001) used satellite measurements of night-time light emissions to classify weather stations as either urban, semiurban or rural; where a station classed as urban was located in a bright area, a semiurban station was located in a dimly lit area and a rural station in an unlit area. However, a problem with this method is that stations classed as urban may be located inside well lit city parks, where the UHII is reduced by the park cool island (PCI) effect (Cao *et al.,* 2010). The PCI effect, caused by radiative exchanges with vegetation and its surroundings, partially mitigates the development of the UHI (Oliveira *et al.,* 2011). Hence, using night-time light emission data to characterise stations as urban or nonurban may lead to inaccurately characterising the effects of urban material on temperature. This study aims to deal with the problem of PCI mitigation of the UHI and the issues of urban/rural classification by determining the degree of urbanisation of a given weather station, rather than having discrete classes. This is done through the use of a land cover/land use dataset derived from satellite images to asses the fraction of urban material around weather stations (termed urban fraction).

We next detail the data and methodology used to determine both the degree of urbanisation of weather stations in the United Kingdom and the corresponding urbanisation effect. The results of the analysis are then reported before some discussion of the results and conclusions are given. This study finds there is no significant urban effect on the daily maximum 2-m temperature but does find a significant increase in the daily minimum 2-m temperature due to urbanisation.

2 | DATA AND METHODS

We estimated the effect of urbanisation by robustly regressing mean observed temperatures minus reanalysis temperatures against urban fraction and term this UHII. Uncertainties in the fit were computed using the bootstrap method (Efron and Tibshirani, 1994) and are quoted as 2 standard errors.

The ERA-Interim reaalysis is used in this study. This uses large-scale land cover properties in its land-surface model with no representation of urban areas (Hogan *et al.,* 2017; Dee *et al.,* 2011). Screen-level temperature and humidity are assimilated into the reanalysis through the soil temperatures and moisture by optimal interpolation from many station surface synoptic observations observations. These interpolated observations are then used to "nudge" the soil temperatures and humidity (Dee *et al.,* 2011; Douville et al, 2000). Thus, T_{min} and T_{max} sourced from ERA-Interim should be insensitive to the degree of urbanisation of a specific location. This approach is similar to Wang *et al.* (2017) except we use mean differences rather than trends. The effect of urbanisation was estimated for monthly, seasonal and annually averaged T_{min} and T_{max} (Figure 1).

The land use dataset used in this study was derived from the Corine Land Cover dataset (CLC 2012), which is a land cover dataset covering most of Europe and is derived from satellite data, consisting of an inventory of land cover data in 44 classes with a spatial resolution of 250 m (European

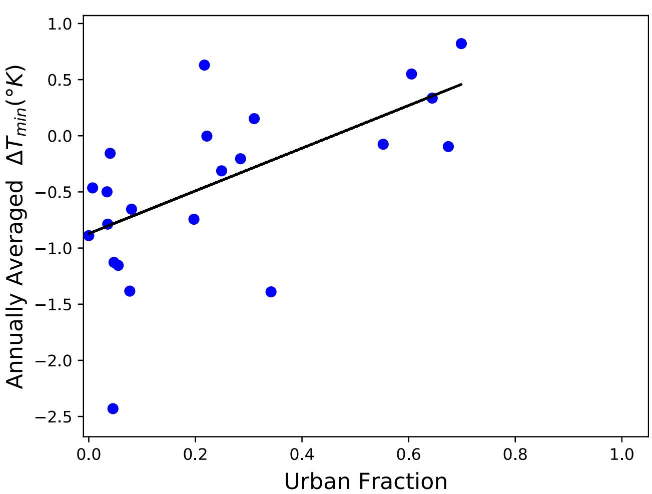

FIGURE 1 Annually averaged ΔT_{min} against urban fraction. The blue points represent the temperature differences between ERA-Interim and measured values for each station and their corresponding urban fraction. The black line is the robust regression linear fit to the data

Environment Agency, 2017). The land cover classes range from urban areas, agricultural areas, forest and semi natural areas through to water bodies. Documentation of of all 44 land cover classes is provided by EEA (European Environment Agency, 1995). The main concern for this study was to differentiate between urban and nonurban material, so to more easily represent the data, the 44 classes of CLC 2012 were reduced to six broad categories: urban, nonurban artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands and water bodies. In this study, classes 1–6 were considered urban and the urban fraction was defined as the linear summation of area covered by these six classes.

Following Wang *et al*. (2017) to find the urban fraction for a station, the fraction of urban cells in a 10 km × 10 km (corresponding to 40 × 40 cells) region centred on each weather station was computed. This size of region chosen was used to represent the scale over which urban structures effect the temperature of their surrounding environment. The 250 m resolution dataset was used, in preference to the 100 m resolution version, to reduce computational effort.

Temperature data for this study came from two sources. The first source was the ERA-Interim reanalysis (Dee *et al.*, 2011) which provides data on a uniform longitude-latitude grid. In this study, daily data for maximum and minimum 2-m temperatures were sourced at 3 hr intervals for the period 1990–2017. The spatial resolution of the dataset used was $0.75^{\circ} \times 0.75^{\circ}$ longitude/latitude, close to the native resolution of the forecast model (T255), where within a grid box the temperature is assumed constant. The maximum daily 2-m temperature ($T^{d}_{\max}$) was converted to a monthly mean (T_{max}) of the daily maximum 2-m temperature. Using these monthly means, an average monthly mean of the daily maximum 2-m temperature over the past 28 years (1990–2017) was found. The same method was applied to obtain the average monthly mean of the daily minimum 2-m temperature (T_{min}). The second source of temperature data was in situ observations of the monthly minimum and maximum 2-m temperature from 34 climate weather stations (Met Office, 2018). These were used to calculate average monthly maximum and minimum temperatures over the period 1990–2017. The temperature stations used in the analysis are all standard Stevenson screens which all use passive ventilation.

For each weather station the nearest grid-point in the ERA-Interim record was found by searching the record for the closest gridbox to the location of a given weather station. There were cases where the nearest gridbox was assumed as sea in ERA-Interim, so we removed those 12 stations from the analysis, leaving 22 stations for subsequent analysis. This reduced the number of stations from 34 to 22. A map of all 34 weather stations is shown in Figure 2 and detail of all stations and whether they were used in the analysis is given in the Supporting Information (Table S1).

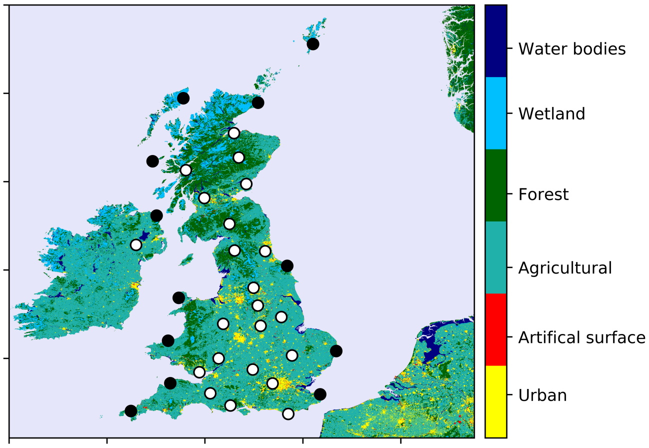

FIGURE 2 Weather stations in the United Kingdom and Ireland used in the analysis (white dots) and weather stations omitted due to being on ERA-Interim sea-points (black dots). Also shown is the land use dataset where colours correspond to the six broad categories (see colour bar)

We correct for height differences between ERA-Interim and station observations by assuming a constant linear lapse rate (Γ_e) of −6.5 K/km (The standard lapse rate for the International Standard Atmosphere (International Civil Aviation Organisation, 1993)). Weather stations have different heights from the values used in ERA-Interim largely because ERA-Interim is an average over a region, while the station values are point values. Temperature measurements from ERA-Interim or weather stations were both corrected to sea level using this value of Γ_e.

We carried out various sensitivity studies by changing several aspects of the analysis and compared them with the standard analysis. Errors in the fit difference were computed using the bootstrap method.

3 | RESULTS

We generally find weak and statistically insignificant relationships between monthly, seasonally or annually averaged ΔT_{max} and urban fraction (Figure 3). When ΔT_{max} is averaged annually, the linear relationship between this and urban fraction is insignificant (at a 97.7% confidence level) at 0.25 ± 0.42 K. The strongest relationships are observed in the winter months with December having an urbanisation effect of 0.67 ± 0.34 K. However, this relationship is insignificant for February through to October. The results suggest that urbanisation has had no significant impact on daily maximum temperature across most of the annual cycle.

A significant increase in monthly, seasonally and annually averaged ΔT_{min} is observed in areas of higher urban fraction. For annual average ΔT_{min}, an urbanisation effect of 1.90 ± 0.88 K is found (Figure 3). Stronger relationships are found for ΔT_{min} in the summer months where the maximum UHII reaches 2.17 ± 0.78 K in May.

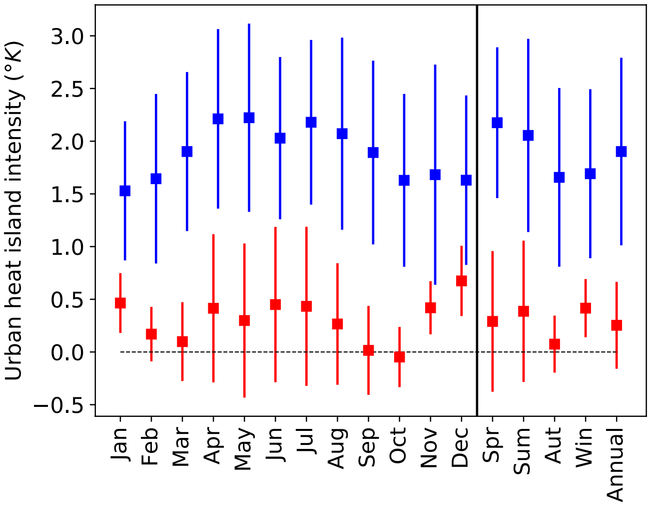

FIGURE 3 Robust linear regression between ΔT_{max} (red) and ΔT_{min} (blue), and urban fraction. The *y*-axis is the regression coefficient of ΔT_{max} or ΔT_{min} against urban fraction which we denote as the UHII. The *x*-axis shows the period over which ΔT_{max} or ΔT_{min} was averaged. The black dashed line shows zero regression coefficient. Uncertainty estimates (vertical lines) are 2σ errors. The solid black vertical line separates the months from the seasonal and annual results

To test the sensitivity of results to: the value of the lapse rate chosen; the size over which to consider the urban fraction; or the number the CLC classes that were considered urban; the analysis was repeated with some changes.

Firstly, the results were repeated using $\Gamma_e = 0$ and $\Gamma_e = -9.8$ K/km. We found little impact on ΔT_{min} with values differing by no more than 10% between the largest and smallest values of Γ_e. The relationships for ΔT_{max} change by a maximum of 0.23 K though the results remain insignificant (at a 97.7% confidence interval) throughout (Figure 4). Whilst we calculate large uncertainty estimates, they centre around zero deviation indicating little effect of altering this parameter on our result.

Testing the sensitivity to the area over which the urban fraction was considered produced a reasonably large change in the result when considering a 400 km^2 area (Figure 4). This increased the observed effect for both T_{min} and T_{max}, although the bootstrap estimates of the uncertainty are large in both cases. When considering an area of 25 km^2 the magnitude of the deviation is reduced, with a 10–15% decrease in both T_{min} and T_{max} from the original result (Figure 4). However it is likely that these deviations are nominal due to the relatively large error estimates.

In addition, the number of classes that were considered urban was changed from 6 to 11 with urban parks now included in the urban category. This produced only small changes in the magnitude but again did not alter the significance of the relationships found for ΔT_{max}. Further, this resulted in only a 10% reduction in the urbanisation effect on ΔT_{min} (Figure 4).

Finally, to understand how spatial variability of wind speeds across the United Kingdom may affect our results, we performed multivariate linear regression to estimate the effect of wind speed on observed minimum and maximum temperatures. We regressed ΔT_{min} and ΔT_{max} against both urban fraction and monthly-mean 10 m wind speed from ERA-Interim. We find no significant effect on our results for ΔT_{min}. However, for ΔT_{max} we find the urban fraction regression coefficient is 0.40 ± 0.44 (insignificant) and the 10 m wind coefficient is 0.10 ± 0.06. Hence, we observe a small but significant effect of the wind on ΔT_{max}. We speculate that, on average, the reanalysis does not transport enough heat from the soil into the atmospheric boundary layer through atmospheric turbulence, which is strongest

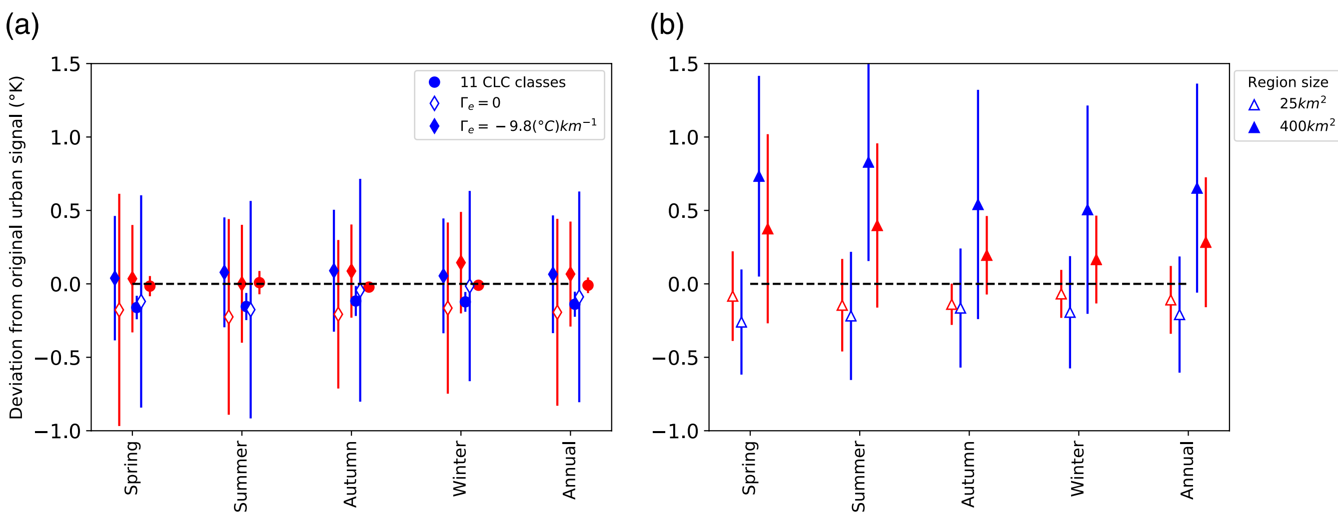

FIGURE 4 Sensitivity tests where points show the difference between the regression coefficient found with the original parameters and the regression coefficient found after the parameters were changed. Red corresponds to differences in the ΔT_{max} result and blue to ΔT_{min}. (a) Changes in classes (circles), zero lapse rate (open diamonds) and minimum lapse rate (filled diamonds). (b) Area size used to compute urban fraction for 25 (open triangle) and 400 (filled triangle) km^2. In both plots the error bars are $\pm 2\sigma$ values

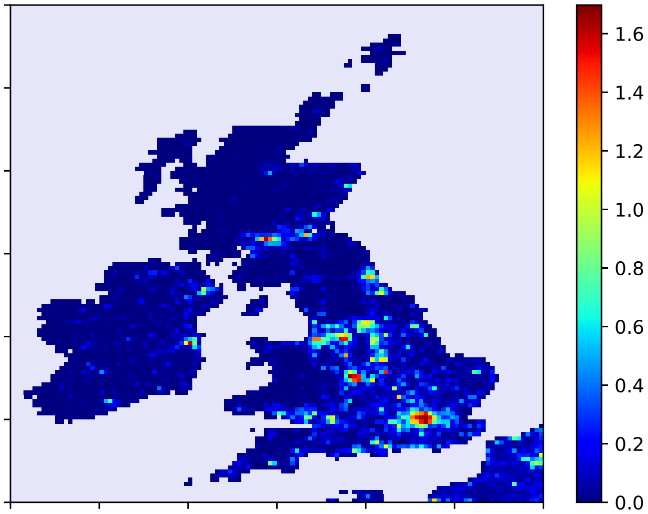

FIGURE 5 Map showing the change in T_{min} due to the urbanisation at the 10 km × 10 km scale over the United Kingdom and Ireland. The colour bar shows the magnitude of the temperature change in K

during the day. Thus, observations minus reanalysis increase with wind speed.

We have used our results to generate a map of the change in T_{min} due to urban material in the United Kingdom at the 10 km × 10 km scale (Figure 5). We define the UHII as the maximum change in temperature due to urbanisation within the city boundaries and we observe the largest UHII in central London with considerable UHIIs in many other cities. Refer to the Supporting Information for a table of the calculated UHIs of several major cities in the United Kingdom (Table S2).

4 | DISCUSSION AND CONCLUSIONS

The observed increase in T_{min} can be attributed to an increased intensity of the UHI during the hours after sunset and into the night. Many studies have previously shown that UHII is maximised during the night (Arifwidodo and Tanaka, 2015; Montávez *et al*., 2000; Ripley *et al*., 1996). The intensity is maximised during these hours, as heat absorbed by urban structures will be re-radiated back into the atmosphere at a slower rate, due to smaller sky views, than natural structures. Further, the increase in impervious surface in an urban area causes a reduction of the latent heat flux and a rise in the sensible heat flux (Zhou *et al.,* 2014). This leads to a difference between the rates at which the urban and natural area will cool during the night, with urban areas sustaining a higher temperature into the night. With minimum temperatures often occurring at night, the slowed rate of cooling in urban areas results in an increase of the observed minimum temperature.

The reduced effect seen in T_{max} may be the result of partial shading (reduced sky-view factor) in urban areas. If less short wave radiation is absorbed in an urban area than in rural areas, we expect that during the daytime the UHII will be smaller than at night and in some cases has been shown to be negative (Trusilova *et al.,* 2008). Further, the reduced effect may be attributed to higher storage in the day time energy budget of the urban over rural areas. Increased storage leads to less day time sensible heat flux in the urban area causing a reduced increase in temperature. Hence, we observe a smaller difference between the urban and rural temperatures and thus a lower UHII.

The results indicate some seasonal variability in the magnitude of the increase in both T_{min} and T_{max}. Our results for T_{min} agree with previous literature, showing that the UHII is larger in summer than in winter (Kłysik and Fortuniak, 1999; Philandras *et al*., 1999). This may be due to increased wind and cloud cover in the colder seasons resulting in more mixing of the atmospheric boundary layer and less available short wave radiation. Both of these factors would act to reduce the magnitude of the UHII. Further we observe a significant effect on T_{max} only in winter (Figure 3), possibly due to anthropogenic heating leading to a warmer climate in urban areas.

Unlike the studies performed by Wang *et al*. (2017); Yan *et al*. (2010); Zhou *et al*. (2004); Chrysanthou *et al*. (2014); who performed studies on the rate of warming against urbanisation rate, this study looked only at differences in recorded and reanalysis temperature data and not the rate at which they are changing with respect to one another. Analysis of older land use data sets (CLC 2000, CLC 2006) found no urbanisation changes in the regions around the weather stations used in the study suggesting that there has been no significant urbanisation changes in the United Kingdom since 2000.

In this study, relationships between the urban fraction around weather stations in the United Kingdom and temperature differences between observed and reanalysis values were examined. A small and statistically insignificant relationship was observed for T_{max}. After performing several sensitivity tests, it was found that in almost all cases the result remained insignificant and even when significant, the effect was very weak. This is in contrast to the results for T_{min} where urbanisation has caused significant warming. The results indicate that if an area is 100% urbanised, annual averge T_{min} would have increased by 1.90 ± 0.88 K. The results of the sensitivity tests suggest that whilst this value may be a slight under-estimate, the significance of the result is robust in most cases. We observe that when considering an area of 400 km^2 over 100 km^2 the effect may be increased, suggesting that a larger area may influence the UHII more than originally proposed in this study. The relationship found for T_{min} in this study is in agreement with the results found by Trusilova *et al*. (2008) and shows a slightly stronger relationship than that found by Grawe *et al*. (2013). However, the results from this study show a slight, and largely insignificant, increase in T_{max} due to urbanisation. Whilst the results are likely dependent on the ERA-interim data used for the analysis, we see that the results are consistent with previous literature, where a weaker relationship between urbanisation and T_{max} than in T_{min} is found (Wang *et al.,* 2017; Trusilova *et al.*, 2008). Albeit, our study does not capture as large an effect in T_{max} as the cited literature.

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REFERENCES

Arifwidodo, S.D. and Tanaka, T. (2015) The characteristics of urban heat Island in Bangkok, Thailand. *Procedia – Social and Behavioral Sciences*, 195, 423–428 World Conference on Technology, Innovation and Entrepreneurship.

Cao, X., Onishi, A., Chen, J. and Imura, H. (2010) Quantifying the cool island intensity of urban parks using aster and ikonos data. *Landscape and Urban Planning*, 96, 224–231.

Chrysanthou, A., Schrier, G., Besselaar, E., Klein Tank, A. and Brandsma, T. (2014) The effects of urbanization on the rise of the european temperature since 1960. *Geophysical Research Letters*, 41, 7716–7722.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.N. and Vitart, F. (2011) The era-interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137, 553–597.

Efron, B. and Tibshirani, R.J. (1994) *An Introduction to the Bootstrap*. New York: CRC Press.

Emmanuel, R. and Krüger, E. (2012) Urban heat Island and its impact on climate change resilience in a shrinking city: the case of Glasgow, UK. *Building and Environment*, 53, 137–149.

European Environment Agency (1995) *Corine Land Cover: Part 1 Methodology, Part 2 Nomenclature*. Copenhagen, Denmark: The European Environment Agency (EEA).

European Environment Agency (2017) Copernicus Land Service – Pan European Component: Corine Land Cover. Brochure. Available at: https://land.copernicus.eu/user-corner/publications/clc-flyer/view.

Grawe, D., Thompson, H.L., Salmond, J.A., Cai, X.-M. and Schlünzen, K.H. (2013) Modelling the impact of urbanisation on regional climate in the greater London area. *International Journal of Climatology*, 33, 2388–2401.

Hansen, J., Ruedy, R., Sato, M., Imhoff, M., Lawrence, W., Easterling, D., Peterson, T. and Karl, T. (2001) A closer look at United States and global surface temperature change. *Journal of Geophysical Research: Atmospheres*, 106, 23947–23963.

Hogan, R., Ahlgrimm, M., Balsamo, G., Beljaars, A., Berrisford, P., Bozzo, A., Giuseppe, F. D., Forbes, R., Haiden, T., Lang, S., Mayer, M., Polichtchouk, I., Sandu, I., Vitart, F. and Wedi, N. (2017) Radiation in numerical weather prediction.

International Civil Aviation Organisation. (1993) *Manual of the ICAO Standard Atmosphere*, 3rd edition. Montreal, Quebec, Canada: ICAO publication.

Johnson, H., Kovats, R., McGregor, G., Stedman, J., Gibbs, M. and Walton, H. (2005) The impact of the 2003 heat wave on daily mortality in England and Wales and the use of rapid weekly mortality estimates. *Euro Surveillance*, 10, 168–171.

Jones, P., Groisman, P., Coughlan, M., Plummer, N., Wang, W.-C. and Karl, T. (1990) Assessment of urbanization effects in time series of surface air temperature over land. *Nature*, 347, 169–172.

Kłysik, K. and Fortuniak, K. (1999) Temporal and spatial characteristics of the urban heat Island of łódź, Poland. *Atmospheric Environment*, 33, 3885–3895.

Met Office (2018) UK Climate – Historic Station Data. Available at: https://www.metoffice.gov.uk/public/weather/climate-historic/#\?tab=climateHistoric.

Mitchell, J.M. (1961) The temperature of cities. *Weatherwise*, 14, 224–258.

Montávez, J.P., Rodríguez, A. and Jiménez, J.I. (2000) A study of the urban heat Island of Granada. *International Journal of Climatology*, 20, 899–911. https://doi.org/10.1002/1097-0088%2820000630%2920%3A8%3C899%3A%3AAID-JOC433%3E3.0.CO%3B2-I.

Oke, T.R. (1982) The energetic basis of the urban heat Island. *Quarterly Journal of the Royal Meteorological Society*, 108, 1–24.

Oliveira, S., Andrade, H. and Vaz, T. (2011) The cooling effect of green spaces as a contribution to the mitigation of urban heat: a case study in Lisbon. *Building and Environment*, 46, 2186–2194.

Parker, D.E. (2004) Climate: large-scale warming is not urban. *Nature*, 432, 290.

Peterson, T.C., Gallo, K.P., Lawrimore, J., Owen, T.W., Huang, A. and McKittrick, D.A. (1999) Global rural temperature trends. *Geophysical Research Letters*, 26, 329–332.

Philandras, C., Metaxas, D. and Nastos, P.T. (1999) Climate variability and urbanization in Athens. *Theoretical and Applied Climatology*, 63, 65–72.

Ripley, E., Archibold, O. and Bretell, D. (1996) Temporal and spatial temperature patterns in Saskatoon. *Weather*, 51, 398–405.

Stedman, J.R. (2004) The predicted number of air pollution related deaths in the UKduring the august 2003 heatwave. *Atmospheric Environment*, 38, 1087–1090.

Trusilova, K., Jung, M., Churkina, G., Karstens, U., Heimann, M. and Claussen, M. (2008) Urbanization impacts on the climate in europe: numerical experiments by the psu-ncar mesoscale model (mm5). *Journal of Applied Meteorology and Climatology*, 47, 1442–1455.

Wang, L. and Chen, L. (2016) Spatiotemporal dataset on chinese population distribution and its driving factors from 1949 to 2013. *Scientific Data*, 3, 160047.

Wang, J., Tett, S.F.B. and Yan, Z. (2017) Correcting urban bias in large-scale temperature records in China, 1980–2009. *Geophysical Research Letters*, 44, 401–408.

Yan, Z., Li, Z., Li, Q. and Jones, P. (2010) Effects of site change and urbanisation in the Beijing temperature series 1977–2006. *International Journal of Climatology*, 30, 1226–1234.

Zhou, L., Dickinson, R.E., Tian, Y., Fang, J., Li, Q., Kaufmann, R.K., Tucker, C.J. and Myneni, R.B. (2004) Evidence for a significant urbanization effect on climate in China. *Proceedings of the National Academy of Sciences*, 101, 9540–9544.

Zhou, D., Zhao, S., Liu, S., Zhang, L. and Zhu, C. (2014) Surface urban heat Island in China's 32 major cities: spatial patterns and drivers. *Remote Sensing of Environment*, 152, 51–61.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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