From urban to national heat island: The effect of anthropogenic heat output on climate change in high population industrial countries

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Key Points:
- Annual heat output for the United Kingdom and Japan is determined from national energy consumption during 1965–2013
- Strong correlations are found between energy consumption and temperatures above or below global background levels
- Heat output may affect climate change in countries of high population density

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From urban to national heat island: The effect of anthropogenic heat output on climate change in high population industrial countries

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Abstract The project presented here sought to determine whether changes in anthropogenic thermal emission can have a measurable effect on temperature at the national level, taking Japan and Great Britain as type examples. Using energy consumption as a proxy for thermal emission, strong correlations (mean $r^2 = 0.90$ and 0.89, respectively) are found between national equivalent heat output (HO) and temperature above background levels Δt averaged over 5- to 8-yr periods between 1965 and 2013, as opposed to weaker correlations for CMIP5 model temperatures above background levels Δmt (mean $r^2 = 0.52$ and 0.10). It is clear that the fluctuations in Δt are better explained by energy consumption than by present climate models, and that energy consumption can contribute to climate change at the national level on these timescales.

1. Introduction

It has long been known that within large cities, thermal emission from heated buildings, industry, and transport can contribute to a microclimate up to 12°C warmer than background levels in the surrounding area, a phenomenon known as the urban heat island (UHI) effect [*Howard*, 1833; *Arakawa,* 1937; *Oke*, 1973; *Knight et al.*, 2010]. However, some of this heat difference is attributed to contrasts in evaporative cooling and albedo [*Taha*, 1997], absorbed and re-emitted solar radiation [*Rizwan et al.*, 2008], and convection [*Zhao et al.*, 2014]. Here, we consider thermal emission alone, but our study is not restricted to cities, but extends the concept to encompass heat generated by entire nations, thus including heat from smaller urban areas, rural districts, and transport networks.

Weather systems do not respect political boundaries, so heat generated in one country could affect nations downwind. Japan and Britain are particularly suited to such a study, both being high population-density island nations largely isolated from the heat output (HO) of neighboring countries by the surrounding ocean.

2. Data and Methods

All data used in this study are derived from existing published values. Figure 1 shows this primary data, as plots of annual mean temperature, background global temperature, local data extracted from global CMIP5 model temperatures, and annual energy consumption of Japan and the United Kingdom between 1965 and 2013.

Temperatures for Great Britain are from the Central England Temperature series, which combines data from four stations carefully selected to be representative [*Manley*, 1974; *Parker et al.*, 1992]. Those for Japan are the means of the 19 longest unbroken data sets from weather stations on Japan's main island (Honshu), and published by the *Japan Meteorological Agency* [2015]. Specifically, these are Fukuoka, Gifu, Hamada, Hikone, Ishigakujima, Kochi, Kumagaya, Maebashi, Matsuyama, Naze, Sakai, Shimonoseki, Tadotsu, Tokushima, Tokyo, Tsu, Tsuruga, Wakayama, and Yokohama. Global temperatures are from the HadCRUT 4 data set [*Morice et al.*, 2012].

Model temperatures are the means of 42 CMIP5 (Coupled Model Intercomparison Project) global models [*Taylor et al.*, 2012; *Collins et al.*, 2013], from which model temperatures for Japan's main island were extracted (131°.25–138°.75E long. and 33°.75–36°.25N lat.), and those for central England (4°W–1°E long.

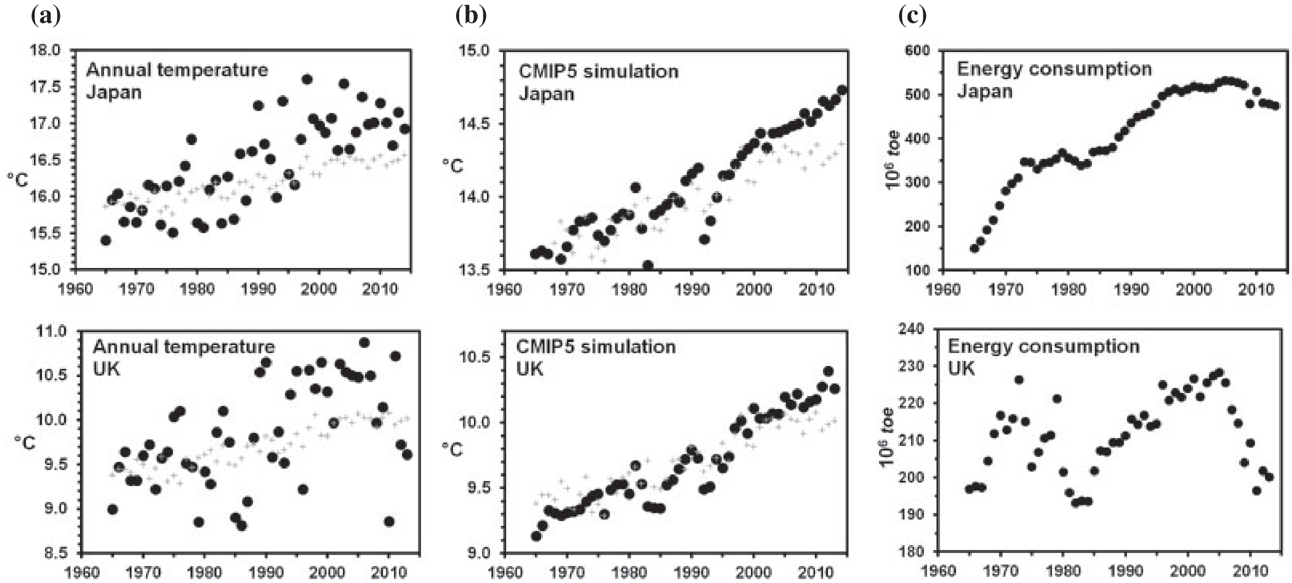

Figure 1. Source data used in this study. (a) Black circles are annual mean temperature *t* for Japan (top) and Central England (bottom) between 1965 and 2013, together with global temperature *H*4 (gray crosses) from the HadCRUT4 data set. (b) Mean multi-model temperatures mt extracted from 42 global CMIP5 models for the areas (top) 131°.25 – 138°.75E long. and 33°.75 – 36°.25N lat. (Japan), and (bottom) 4°W – 1°E long. and 51° – 53°.5 N lat. (Central England), also with HadCRUT4 global temperatures. (c) Annual energy consumption in millions of tons of oil equivalent (toe).

and 51° – 53°.5N lat.). The CMIP5 suite of coupled atmospheric models is the most sophisticated so far developed [*Taylor et al.*, 2012], incorporating not only the effects of changes in greenhouse gas concentrations but also dust from volcanic eruptions [*Robock*, 2000] and solar variations [*Lean and Rind*, 2008; *Foster and Rahmstorf*, 2011] on climate. All the three effects can be taken into account at global levels [*Jones et al.*, 2013], which improves correspondence with observed values, despite discrepancies between different models [*Räisänen and Ylhäisi*, 2013] and uncertainties associated with methodology [*Jones et al.*, 2013].

The anthropogenic heat flux was derived from annual primary energy consumption for both countries, given in the *Statistical Review of World Energy* [2014], the longest consistent data set for both countries, that lists values back to 1965. Virtually, all energy consumed is dissipated as heat on timescales of less than a few days [*Flanner,* 2009].

To isolate national changes of temperature from world-wide changes, global temperature is subtracted from the annual Japan and United Kingdom temperature to give residual temperature Δ*t*, i.e., $\Delta t = t - H4$, where *t* is observed mean monthly temperature and *H*4 is mean monthly global temperature from the HadCrut4 data set. The changes in Δ*t* can then be compared with CMIP5 model residual temperatures Δmt. In this context, $\Delta mt = mt - H4$, where *mt* is the CMIP5 multi-model mean. Finally, Δ*t* can also be compared directly with HO, derived from energy consumption of the two nations considered, so that the effect of anthropogenic heat on local temperature changes can be quantified.

Both nations have large year to year variations in annual temperature, so in Figure 2, 7 yr means are plotted to minimize the effects of weather, solar cycles, and *El Niño* events and thus isolate climate change. Seven years is less than a quarter of the 30 yr period for measurement of climatological normals [*Trewin*, 2007], but close to the maximum needed to retain sufficient data points to characterize the major temperature changes in Figure 1. Seven years also avoids any possible synchronization with the 11 yr solar cycle, which might affect means of 5 or 6 yr [*Friis-Christenesen and Lassen*, 1991].

3. Results

Figure 2a shows the 7 yr mean residual temperature Δ*t* between 1965 and 2013. Figure 2b shows the multi-model mean Δ*mt* from 42 CMIP5 models for Japan and Central England.

Plotting Δ*mt* against observed Δ*t* yields varying fits of $r^2 = 0.71$ and $r^2 = 0.05$ for Japan and Central England, respectively (Figure 3a). Figure 2c shows 7 yr means of Japan's and Britain's equivalent HO from 1965 to 2013,

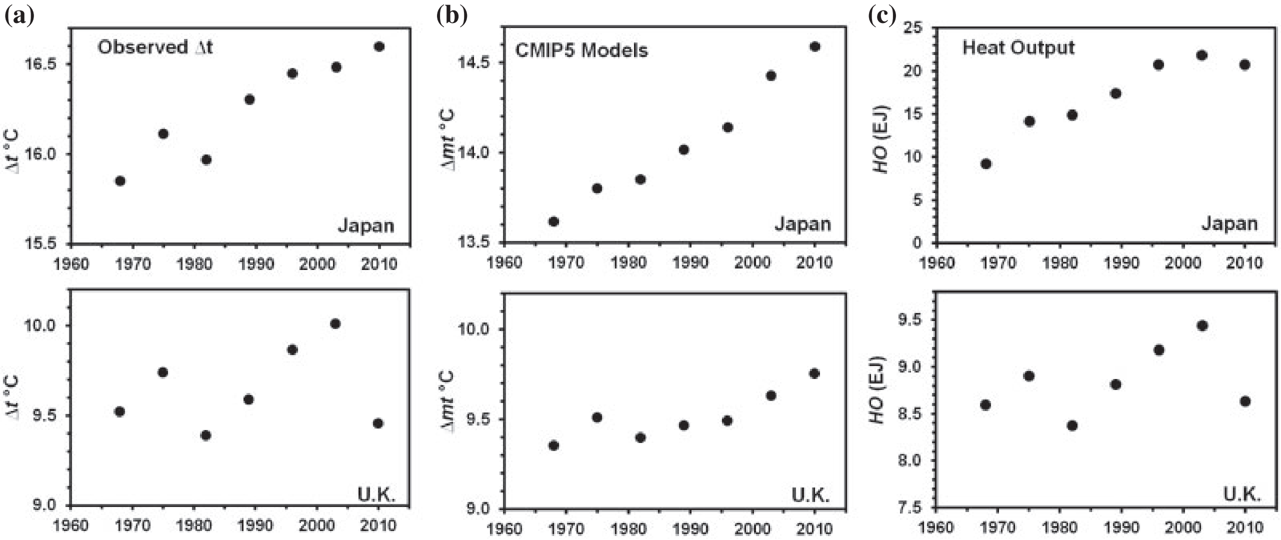

Figure 2. (a) Seven years means of observed Japan (top) and United Kingdom (bottom) residual temperature (Δ*t*) 1965–2013. (b) Similar presentation, but showing mean residuals Δ*mt* of 42 CMIP5 global model temperature simulations for a 7 1/2° long. × 2 1/2° lat. quadrangle over Japan (top), and a 5° long. × 2 1/2° lat. quadrangle over Central England (bottom), instead of Δ*t*. (c) Variations in Japanese and United Kingdom energy consumption (expressed as equivalent heat output (*HO*) in ExaJoules) over the same period. See text for further details.

derived from national primary energy consumption in tonnes of oil equivalent (toe), using the relation 1 toe = 41.87 GJ [*International Energy Agency*, 2015]. In contrast to Δ*mt*, the changes in HO match observed Δ*t* changes over this period (Figure 2a), with high correlations in both nations of $r^2 = 0.90$ and 0.97 (Figure 3b).

The choice of 7 yr as the averaging interval *A* is not critical. *A* was set at all values between 1 and 16 yr, and the r^2 values for Δmt and HO models plotted against *A* for the two countries in Figure 4. When *A* is small there are lots of data points, so even modest values of r^2 can be highly significant (as they are for Japan in relation to HO), but r^2 itself is low for both countries: the CMIP5 and HO models (for the United Kingdom at least) are as good as each other, and neither accounts for the fluctuations in observed Δ*t*. When *A* is large, we have high values of r^2 for HO but very few data points, and for $A > 16$ only two data points so r^2 must equal 1. Values of *p* (the probability of such a large value of r^2 occurring by chance, on the null hypothesis that HO and residual temperature are unrelated) for the United Kingdom are low when $A = 5–8$ ($p < 0.004$), but greater when *A* lies outside this range; for Japan, $p < 0.004$ for $A = 1–9$.

The heat equivalent of Japanese energy consumption averages 17 EJ yr^{-1} 1965–2013, which reduces to 1.5 J m^{-2} s^{-1}. Equivalent values for the United Kingdom are 8 EJ yr^{-1}, which because of its smaller land mass reduces to 1.2 J m^{-2} s^{-1}. Much less than 1% of this energy consumption is liable to be lost as radiation without warming the atmosphere–land–ocean system [*Flanner,* 2009]. Japan and the United Kingdom have a mean vertical velocity component in the low troposphere at 700 hPa between about 0.01 and 0.05 Pa s^{-1} in a downward direction [*Kallberg et al.,* 2005], aiding heat generated to remain at lower levels.

An interesting further test is to look at seasonal changes in temperature and energy consumption. Unfortunately, annual seasonal energy consumption values are not available for either country, but what evidence shows is that in Japan, where summer temperatures are more than 8°C higher than the United Kingdom, electricity demand is 10–25% higher in summer than in winter [*Kempton and Kubo,* 2000; *Akil and Miyauchi,* 2013] because of air conditioning. In the United Kingdom, where air conditioning is almost absent, the opposite is true, winter electricity demand being about 30% higher than in summer [*U.K. Dept. of Energy and Climate Change,* 2014]. When summer (May–September) and winter (November–March) residual temperatures Δ*t* against annual energy consumption for both countries were plotted, as expected Japan shows stronger correlations in summer than in winter, and the United Kingdom stronger correlations in winter than in summer for most averaging intervals (Figure 5). However, r^2 values, especially those for the United Kingdom, are lower than for annual Δ*t* (Figure 4), as both winter and summer values are perforce included in the energy consumption data.

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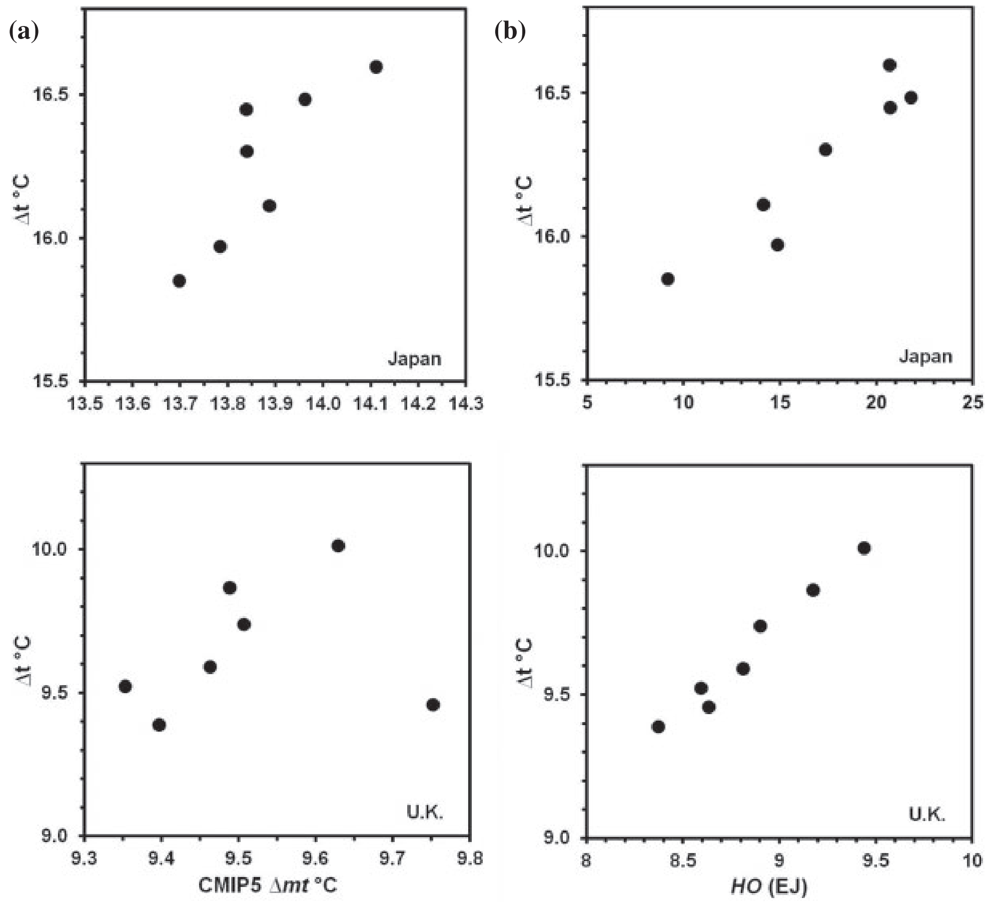

Figure 3. (a) Seven years means of observed residual temperature (Δt) 1965–2013 for Japan (top) and Britain (bottom) plotted against mean Δmt of 42 CMIP5 global model temperature simulations as in Figure 2. (b) Similar plots using national equivalent heat output (*HO*) in ExaJoules instead of Δmt. Correlations of observed Δt with Δmt are $r^2 = 0.71$ and $r^2 = 0.05$ in Japan and United Kingdom, respectively, and $r^2 = 0.90$ and $r^2 = 0.97$ for *HO*. Values of *p* (see text) are 0.001 for Japan and 0.00007 for the United Kingdom.

4. Discussion and conclusions

Both countries are rather extreme cases, Japan having a mean annual energy consumption per unit area during 1965–2013 of 1114 toe km^{-2}, the 8th highest in the world during 1965–2013, and the United Kingdom 870 toe km^{-2}, the 13th highest [*Statistical Review of World Energy,* 2014]. Of the two nations, Japan has a warmer climate and consequently lower heating requirements, and 60–65% cloud cover [*Norris and Wild*, 2009]. However, Japan's more consistently increasing energy consumption parallels world CO_2 levels, meaning that the correlations with Δmt are consistently higher than the United Kingdom, so the distinction between the two models is not so pronounced. Britain is better suited to this study, being cold enough to require indoor heating for about 6 months per year, and with 75% cloud cover [*Kontoes & Stakenborg*, 1990], meaning that less surface-generated heat is lost by radiation. Most importantly, Britain is a country where annual energy consumption has fallen significantly as well as risen during the time period considered, so that the greater effect of HO than other causes on United Kingdom temperature can be more clearly distinguished (Figure 4a).

The reliability and importance of our conclusions does not rest on the probabilities returned by our statistical tests, significant though these are by conventional standards:

1. First, our hypothesis was not suggested by the data, but by its qualitative reasonableness.
2. Second, our results are reproducible, in that our statistical study of the United Kingdom data was completed, and the results noted, before testing our conclusions by consideration of the Japan data.
3. Third, we carried out no other statistical study of these or any other data sets.

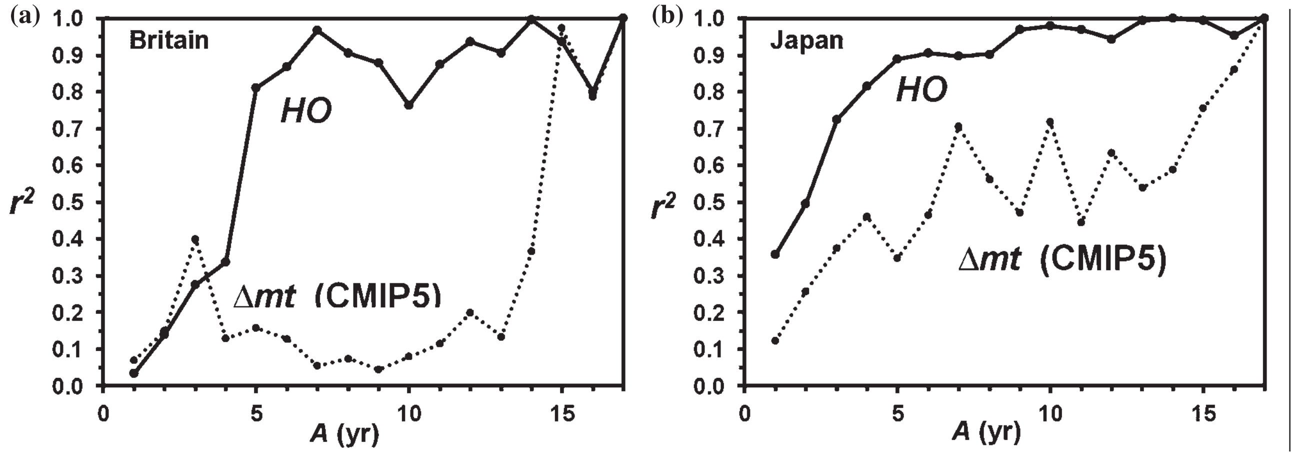

Figure 4. r^2 values for heat output (*HO*) and CMIP5 multi-model Δ*mt* against observed Δ*t* for different averaging intervals *A* for the United Kingdom (a) and Japan (b). All intervals *A* above 3 yr show higher r^2 values for *HO*, those with the lowest probability *p* of occurring by chance being between 5 and 8 yr for the United Kingdom, and up to 10 yr for Japan. Mean r^2 values for 5–8 yr averaging intervals for the United Kingdom and Japan are 0.89 and 0.90, respectively, for *HO* and 0.10 and 0.52 for CMIP5 Δ*mt*. Values of *p* in this range of *A* are all <0.004 for both nations.

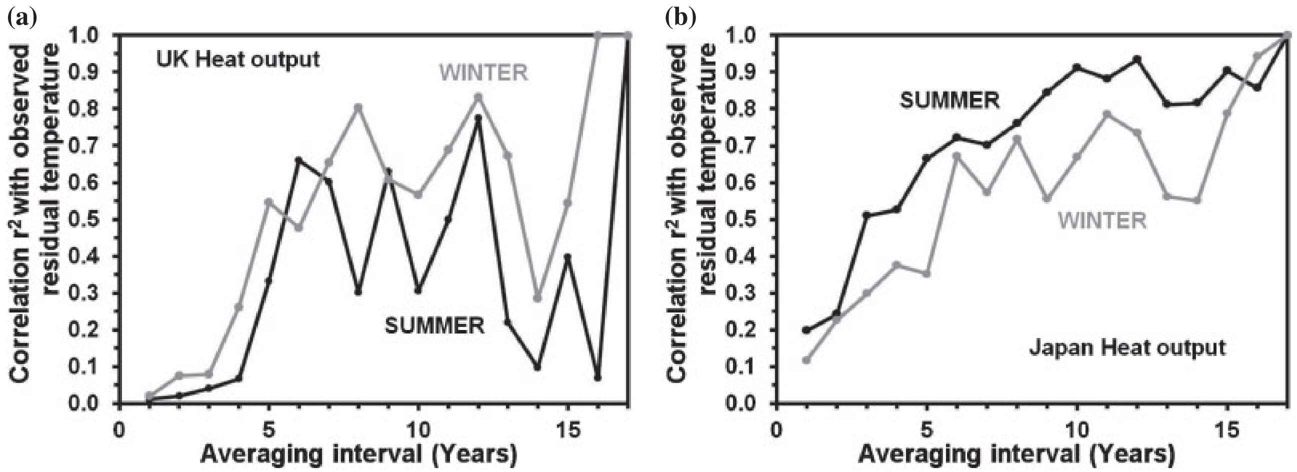

Figure 5. r^2 values for annual heat output (*HO*) plotted against observed summer and winter Δ*t* for different averaging intervals *A* for the United Kingdom (a) and Japan (b). Japan shows stronger correlations in summer than in winter, because of the cooling load of air conditioning. See text for details.

4. Fourth, the effect appears large, in that variations of HO correlate (Figure 2, bottom row) with temperature changes of a few tenths of a degree.

It may appear that, reasonable though it is, our hypothesis is harder to justify quantitatively, in the sense that HO (of order 1 J m^{-2} s^{-1}) is much smaller than insolation, by two orders of magnitude. On the other hand, what is at issue is the relative importance of fluctuations in these quantities.

The fact that the statistically significant results require averaging over several years is because of the small area of the Earth's surface being sampled in both locations. At this scale, temperatures vary widely from one year to the next compared with world values (Figure 1a).

Our results are strong evidence that changes in energy consumption contribute to temperature change over sub-decadal timescales in the two nations considered. Britain has experienced a drop in temperature of about 0.5°C since the early years of the millennium (Figure 2, lower left) at a time when world temperatures have remained virtually stable, whereas Japan experienced a rise in Δ*t* of 1.0°C between the early 1980s and 2000 (Figure 2, upper left), double the world rise in temperature over the same period. Both these changes reflect changes in energy consumption in each country.

These conclusions might be perceived to be in contrast to recent studies of the UHI effect that relate to large cities, where warming of only ∼0.1°C per decade or less is detected, compared with nearby rural districts [*Parker,* 2010; *McCarthy et al.,* 2011]. However, such studies are designed to detect urban/rural contrasts, not the effects of overall increases or decreases in heat emission in entire nations. UHIs are most pronounced in calm weather [*Oke*, 1973; *Wilby*, 2003], and are best measured at such times [*Knight et al.*, 2010]. Under average conditions, generated heat will drift downwind and may affect rural weather stations [*Parker,* 2010]. In addition, the problem of nearby road and urban development at long-lived rural control stations, which may have affected recorded temperatures, is discussed by *Hansen et al.* [2001]. Certainly in Japan, *Fujibe* [2009] detected temperature anomalies from towns of population less than 1000.

Because anthropogenic heat is generated close to where temperatures are measured in both countries, we have not used a climate model to investigate the transport of such released heat further afield. Early attempts to do this globally found temperature variations of a similar order to the model's natural fluctuations [*Washington,* 1972], and *Flanner* [2009] found no significant effect for the present day. *Oleson* [2012] used CMIP5 simulations to model future changes in urban minus rural temperatures in response to changing climate over the 21st century, rather than the effects of changing energy consumption. More recently however, *Zhang et al.* [2013] despite including only 42% of world energy consumption in their model, found significant winter and autumn temperature changes up to 1°C in mid- and high-latitudes, far from heat sources, that correspond well to areas of previously unexplained differences between observed and modeled temperatures. *Chen et al.* [2014], entering anthropogenic heat flux into a refined model that included long wave radiation, found higher and more widespread increases over standard models: 1–2°C in mid- to high-latitude areas of Eurasia, North America, and parts of the southern hemisphere, and concluded that anthropogenic heating is an important factor in global warming that should not be ignored. Our study is the first of its kind that provides direct observational evidence of this.

If projections of energy consumption prove to be true, then future contributions of anthropogenic heat to climate change in Japan and the United Kingdom will have fallen by 2040. Japan is predicted to have an 18% fall [*U.S. Energy Information Administration*, 2016], corresponding to a temperature drop of about 0.3°C, and the United Kingdom a 3% fall [*U.K. Dept. of Energy & Climate Change*, 2015], producing a negligible drop in temperature.

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