



Urban heat island effects on estimates of observed climate change

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Urban heat islands are a result of the physical properties of buildings and other structures, and the emission of heat by human activities. They are most pronounced on clear, calm nights; their strength depends also on the background geography and climate, and there are often cool islands in parks and less-developed areas. Some old city centers no longer show warming trends relative to rural neighbourhoods, because urban development has stabilised. This article reviews the effects that urban heat islands may have on estimates of global near-surface temperature trends. These effects have been reduced by avoiding or adjusting urban temperature measurements. Comparisons of windy weather with calm-weather air temperature trends for a worldwide set of observing sites suggest that global near-surface temperature trends have not been greatly affected by urban warming trends; this is supported by comparisons with marine surface temperatures. The use of dynamical-model-based reanalyses to estimate urban influences has been hindered by the heterogeneity of the data input to the reanalyses and by biases in the models. However, improvements in reanalyses are increasing their utility for assessing the surface air temperature record. High-resolution climate models and data on changing land use offer potential for future assessment of worldwide urban warming influences. The latest assessments of the likely magnitude of the residual urban trend in available global near-surface temperature records are summarized, along with the uncertainties of these residual trends. © 2010 John Wiley & Sons, Ltd. *WIREs Clim Change* 2010 1 123–133

It is important to know whether, and to what extent, estimates of global warming trends have been affected by the growth of urban heat islands. A confirmation of widespread rural warming supports our understanding and models of the response of global climate to increasing atmospheric greenhouse gases; it also affirms the widespread independent indications of global warming, such as glacier retreat and earlier plant blooms. Although improved urban design for human health and comfort is very important, policies for mitigation of, and adaptation to, large-scale climate change depend ultimately on our observation and understanding of the global climate system. Accordingly, the influence of urban warming on measured global warming trends has

been a subject of debate since the first assessment of the Intergovernmental Panel on Climate Change (IPCC¹; Jones et al.²). In this article we review this subject. We begin with a description of the salient features of urban heat islands—though for a full account of the underlying physical mechanisms the reader is referred to Arnfield.³ Next we point out some limitations on the influence of urban heat islands on estimated global warming. Following that, we describe some techniques that have been used to estimate or verify the true large-scale temperature trends. Finally, we present estimates of the urban contribution to estimated global warming.

Because land air temperatures, and not land surface temperatures, are used in estimates of global warming, we consider only the air temperature aspects of urban heat islands. Heat islands in land surface temperature can differ radically from those in air temperature, especially by day.⁴ We do not assess

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urban influences on other climate parameters such as humidity and precipitation.

BACKGROUND ON THE URBAN HEAT ISLAND

The urban heat island is the elevation of air temperature within cities, and to a smaller extent within towns and villages, relative to the surrounding countryside. It is caused mainly by the retention of solar heat in the fabric of buildings and ground surfaces, and the obstruction and re-absorption of night-time outgoing longwave radiation by buildings which obstruct the sky view. Paved ground surfaces transport more solar heat downwards than soil; this heat is then available for release overnight. Reduced ventilation can hinder the dispersal of urban heat islands. An important contribution to some urban heat islands is the emission of heat by human activities such as transport, and by heating and air conditioning of buildings. Accelerated run-off of rainwater, along with reduced vegetation cover can reduce moisture availability in cities. This can enhance the urban heat island by reducing the fraction of solar energy converted into latent heat and increasing the fraction becoming sensible heat. Conversely, dry-climate cities with irrigated vegetation can have an urban cool island. Local enhancement of atmospheric aerosol concentrations may also affect urban temperatures. Generally, the urban heat island is strongest at night in high-rise city centers, weaker in residential suburbs, and also reduced in parks,⁵ although exceptions to this have been reported.⁶ During daytime, some of the solar heat absorbed by the urban structures is transferred to the overlying air; turbulent convection then mixes the warm air with cooler air aloft, so that the urban heat island is weak and may even be completely annulled locally by shading of the ground by tall buildings. Because both solar and outgoing longwave radiation are restricted by cloud, the urban heat island is weakened in cloudy weather. Because winds and the associated turbulence mix air both horizontally and vertically, the urban heat island is also weakened in windy weather. For full discussions of the nature of the urban heat island, see Refs ^{3,7,8}.

Urban heat islands differ from city to city because of the different design of the structures and because of the different background climate. A city with few high-rise buildings will have a weaker heat island than one with many tall structures. The effect of urbanization will also depend on the nature of the natural land surface: if, for example, the land is marshy, the construction of the city may not raise

night-time air temperatures because these would have naturally been elevated by the thermal properties of the marsh. A city in a cloudy climate will have a weaker heat island, on average, than a city with a sunny climate. A city in a coastal sea-breeze zone may sometimes, but not always, have a weaker heat island than a city further inland.⁹ A city in a mountainous setting may have anomalous thermal regimes owing to katabatic winds.¹⁰ The urban heat island may also be displaced downwind, affecting suburbs or nearby rural areas,¹¹ albeit with reduced amplitude.

URBAN HEAT ISLANDS AND DETECTION OF CLIMATE CHANGE

With the above provisos, urban development results in increasing urban warmth in the developing areas. So, if observations of temperatures in growing cities are used in the assessment of global warming trends, these trends may be overestimated. However, the centers of well-established cities may not undergo further warming relative to rural areas because the urban infrastructure is no longer increasing its ability to retard outgoing longwave radiation and the anthropogenic heat inputs are stable. Thus, Jones et al.¹² have shown that temperatures in central London and Vienna did not rise relative to rural locations nearby in recent decades. Nevertheless, suburban sites continue to warm relative to nearby rural areas until local urbanization is complete, as shown for London's Heathrow airport by Jones and Lister.¹³

In some regions, such as China, the impact of urban development on temperature trends is likely to be greater than in the world as a whole, owing to concentrated urban development in the region. In such regions it may be difficult to find sufficiently rural sites with which to define the background temperature trend free of urban influence.^{2,12,14,15} However, for the world as a whole, a Global Climate Observing System (GCOS) Surface Network (GSN) has been established,¹⁶ choosing the stations through a scoring scheme (Table 1) which militates against urban sites both explicitly and implicitly through the weight given to homogeneity and to membership of the World Meteorological Organization set of Climate Reference Stations. Furthermore, the influence of urban heat islands on estimates of global warming is limited by the fact that about 70% of the Earth's surface is ocean and is absolutely unaffected by urban warming. The sea surface temperatures (SSTs) from this vast area are included in estimates of global temperature trends.¹⁷

TABLE 1 | Station Selection Criteria for the Global Climate Observing System (GCOS) Surface Network (GSN)

Characteristic of Station	Scoring Algorithm	Maximum Score
Number of years N of data in the past century	$20 * N/100$	20
Number of years H of homogeneous data in the past 50 years	$20 * H/50$	20
Number of years R as a World Meteorological Organization (WMO) Reference Climate Station (RCS)	$10 * R/50$	10
Current reporting status	Maximum of (a, b, c, d) where $a = 10$ points if some data available for 1990 or later, $b = 20 * \text{fraction of daily data reports available for 1995}$; $c = 20 * \text{fraction of monthly data reports available for 1995}$; $d = 15$ points if an RCS.	20
Population	20 points if rural; 15 if a small town; 10 if population unknown, 0 if urban.	20
Membership of other networks	2 if in Regional Basic Synoptic Network; 1 if in Global Atmospheric Watch; 1 if in GCOS Upper Air Network; 4 if WMO Normals station; 2 if WMO Agrometeorological station.	10

After Peterson et al.¹⁶

TECHNIQUES FOR ESTIMATING TRUE LARGE-SCALE TRENDS

There are at least five ways to avoid, assess or compensate for possible effects of the urban heat island on estimates of global temperature trends. These are: (1) exclusion of sites showing urban warming; (2) adjustment of urban records to match nearby rural observations; (3) analysis of temperatures in windy, cloudy weather; (4) analysis of, or comparison with, trends in ocean surface temperatures; and (5) use of atmospheric reanalyses. In future, high-resolution climate models are likely to provide further guidance on the large-scale influence of urban warming.

Exclusion of Sites Showing Urban Warming

This strategy was followed by Jones et al.^{18,19} who excluded 38 Northern hemisphere sites (1.5% of the total) and 3 Southern hemisphere sites (0.5% of the total) showing warming trends relative to neighbouring sites. They also excluded 239 Northern hemisphere sites (9% of the total) and 25 Southern hemisphere sites (4.1% of the total) with complex heterogeneities including multiple jumps and non-climatic cooling trends relative to neighbouring sites. Full details are provided in the appendices of Jones et al. (both Northern hemisphere²⁰ and Southern hemisphere²¹). The very small percentages of sites specifically rejected owing to spurious warming trends suggest that strong urban warming is not pervasive in the raw global land surface air temperature (LSAT) data. However, the rejections for complex heterogeneity also filtered out some sites

with suspected urban warming (e.g., Aberystwyth, United Kingdom; Larissa, Greece²⁰) as well as some urban or peri-urban sites with discontinuities in the record (e.g., Berlin-Dahlem; Phoenix, Arizona²⁰). Such discontinuities can arise from site moves or from sudden changes in the immediate environment such as demolition of an old building or construction of a new one.

A weakness of this technique is that if urban warming affects all or most sites in a region, it may not be detected by comparing stations, although the most rapidly urbanising sites will be identified. Furthermore, real but weak urban warming may not be identified because the urban warming trend may not be statistically significant because of the brevity of the record and/or the natural variability of climate. Brohan et al.¹⁷ whose land air temperatures are upgrades of Jones et al.^{18,19} acknowledge these problems by including urbanization in their estimates of uncertainty.

Peterson et al.²² went further in selecting only rural stations as identified by maps and Defense Meteorological Satellite Program (DMSP) satellite-observed night-time surface lights.²³ They found that the global rural temperature series and trends were very similar to those based on the full Global Historical Climatology Network (GHCN) data set. So Smith and Reynolds²⁴ used the full GHCN without urban exclusions or adjustments, although they included the same urbanization uncertainty estimates as Brohan et al.¹⁷ Peterson et al.'s²² results suggest that the urban warming influence in, for example, Brohan et al.¹⁷ is small. However, it may not be zero because, given the physical reasons for

the urban heat island (see Section Background on the Urban Heat Island), some urban warming is possible in small human settlements. This has been noted in Japan by Fujibe.⁹ Hansen et al.²⁵ found about 0.1°C urban warming during the 20th century at peri-urban sites in the United States with a population of 0.1 to 10 persons per hectare, but they suggested, by extrapolation from larger cities, that the urban warming at rural sites, as classified by DMSP night-time surface lights, would not exceed a few hundredths of a degree.

Exclusion of urban sites, or selective use of rural sites, requires information ('metadata') about the site and its surroundings.²⁶ The maintenance of metadata, as well as the actual observational data, is a key GCOS principle (appendix 3 of GCOS).²⁷ Some forms of metadata, such as city population statistics, must be used with care because they may not be representative of the immediate vicinity of the observing site. Thus, Hansen et al.²⁵ did not find a close correspondence between population metadata and satellite-observed night-time surface lighting, which, if at high geographical resolution, is likely to be more representative of the site. Gallo et al.²⁸ found that predominant land use and land cover (LULC) within 100 m of observing sites in the United States had more influence on diurnal temperature range than did LULC within 1000 or 10,000 m. As expected, urban LULC was associated with reduced diurnal temperature range. This accords with Peterson's⁵ finding that urban influence is reduced in parks, as well as with physical expectations, based on the causes of urban heat islands (see Section Background on the Urban Heat Island), that small settlements may be affected by urban warming. Detailed information on LULC worldwide, matching that used for the United States by Gallo et al.,²⁸ has not been readily available but may become so through information technology developments such as Google Earth.²⁹ Best use of this, however, requires that the locations of sites must be known to better than 100 m.

There is a 'grey' area between the urban heat island and the regional forcing of climate by widespread land surface modification. The difficulty of finding truly rural sites in China¹² is a symptom of this. However, the overall effect of land surface modification on the absorption of solar radiation is likely to be near zero or a weak cooling,³⁰ facilitating efforts to separate the urban heat island from larger-scale forcings. Hansen et al.²⁵ chose to adjust their data to account for urban warming) but to retain the influences of changes of regional land use, regarding them as part of the large-scale climate changes.

Adjustment of Data from Sites Showing Urban Warming

Hansen et al.²⁵ adjusted temperatures from urban, peri-urban and small-town sites which showed trends relative to their rural neighbours. Sites in or bordering the United States were classified by satellite-observed night-time surface lighting; elsewhere, they were classified by population data. The temperature data were from the GHCN which includes the United States Historical Climate Network (USHCN). The USHCN data had already been adjusted by Easterling et al.³¹ for other heterogeneities, such as site moves and changes in observing time. Hansen et al.^{25,32} quality controlled the remaining GHCN data, which included further sites in the United States as well as the rest of the world. They removed or adjusted heterogeneous data for <2% of stations, and combined nominally collocated series using overlapping segments of data. Finally, they made the urban adjustments to the whole GHCN. The combination of station records is likely to have removed some heterogeneities arising from site changes and observing time changes.³² Urban adjustments were made last because other heterogeneities can affect estimates of urban warming trends. For example, a site move from a city centre to a cooler airport site, preceded and followed by urban warming at each site, could cause a data series to have no overall trend relative to a fixed rural neighbour. In such circumstances, if an urban adjustment were attempted first, followed by a site-change adjustment, the urban adjustment would be zero and the site-change adjustment would be positive, warming the more recent data, so the final series would warm relative to the rural neighbour (figure 1 of Hansen et al.²⁵).

Hansen et al.'s²⁵ adjustments consisted of separate changes to the trend before and after a flexible date. This date and the changes to the trends were chosen to minimise the mean square difference between the adjusted urban (or peri-urban or small town) record and the mean of its rural neighbours. As on September 2009, 53%, 19%, and 28% of the stations used globally by Hansen et al. were designated rural, small town, and urban by population (http://data.giss.nasa.gov/gistemp/station_data/station_list.txt). The adjustment made the trend cooler in 58% of cases but warmer in 42% of cases. From this, Hansen et al.²⁵ inferred that the urban effect is often less than the combination of regional variability in temperature trends, which affect the comparisons with neighbours, and errors and other heterogeneities remaining in the data after quality control. In other words, despite their prior adjustments, their urban

adjustments are likely to have incorporated other residual heterogeneities.

Hansen et al.'s²⁵ adjustments removed about 0.15°C of urban warming over the United States during the 20th century. Their adjustments removed about 0.1°C more warming than those applied to the USHCN by Karl et al.,³³ who used a population-based empirical equation. Estimated adjustments may be sensitive to the choice of 'rural' stations, as well as to the period and method of analysis, as is shown by the contrast between the estimates of urban warming in northern China by Li et al.¹⁴ for 1954–2001 and Ren et al.¹⁵ for 1961–2000 of near zero and 0.11°C per decade urban warming.

Increases in extremes of warmth are characteristic of global anthropogenic climate change.³⁴ However, urban sites also experience more extremes of warmth than rural sites.³⁵ For analyses of trends in extremes, an alternative option to exclusion of urban sites is to adjust the frequency distributions of urban temperatures to match those of rural neighbours, following the method of Della-Marta and Wanner.³⁶ The adjusted data can then be used in assessments of global changes in extremes of warmth. However, the *unadjusted* values are the most relevant to assessing the possibly severe impacts on city-dwellers.

Analysis of Temperatures in Windy, Cloudy Weather

On the premise that urban heat islands are strongest in calm conditions but are largely absent in windy weather, Parker³⁷ analysed daily minimum and maximum air temperatures for the period 1950–2000 at a worldwide selection of mainly GSN sites separately for windy and calm conditions, and compared the global and regional trends. The trends in temperature were almost unaffected by this subsampling, indicating that the observed warming trends were not a consequence of urban development or other local or instrumental influences. The overall trends of temperature averaged over the selected land sites were in close agreement with published trends based on much more complete networks such as Jones and Moberg,³⁸ indicating that the smaller selection used by Parker³⁷ was sufficient for reliable sampling of global trends as well as interannual variations.

The potential influence of urban heat islands on estimates of mean temperature depends on the algorithm used to calculate the mean. Urban heat islands are likely to be particularly strong in the evening.³⁹ Therefore if, for example, mean temperature is calculated by averaging temperatures at 7 a.m., 2 p.m., and 9 p.m. local solar time, with double

weighting given to temperature at 9 p.m., the urban influence will be slightly greater than if the average of daily minimum and maximum temperatures is used. The algorithm $0.25(7 \text{ a.m.} + 2 \text{ p.m.} + 2 \times 9 \text{ p.m.})$ is widely used in continental Europe and Latin America.⁴⁰ However, this corresponds to only about one-sixth of the world's monitored land area. Any enhanced urban influence did not prevent agreement between Parker's³⁷ trends based on the average of daily minimum and maximum temperatures and Jones and Moberg's³⁸ results based on national averaging algorithms.

Systematic changes in atmospheric circulation could introduce regional biases into Parker's³⁷ technique: a small tendency for windy days to have warmed more than the other days in winter over Eurasia was the opposite of that expected from urbanization and is likely to have been a consequence of atmospheric circulation changes. The unavailability of sufficient, high quality observations of cloudiness at the observing sites is a further limitation, as a combination of wind and cloud will have a stronger diminutive effect on the urban heat island than wind alone. Over very large urban areas, distance from the rural surroundings may reduce the ability of winds to mitigate the urban heat island, so the urban influence may be underestimated by Parker's³⁷ method. On the other hand, urbanised regions such as China could be treated as regional modifications to land use and qualify for inclusion in the global warming estimate (see Section Exclusion of sites showing urban warming). Brandsma et al.¹¹ found that the influence of advection of urban warmth at a nearby rural site was greatest for light or moderate winds, because stronger winds would be associated with turbulent upward dispersal of the urban heat; Parker's³⁷ technique remains applicable wherever the main urban influence is associated with the lightest tercile of wind strength.

Pielke and Matsui⁴¹ concluded that increasing atmospheric greenhouse gases should raise calm-night temperatures more than windy-night temperatures, because the extra heat would be stored in a shallower layer on calm nights with a thermally stable boundary layer and restricted turbulent upward heat transfer. However, this is only true for a local forcing at the surface. A global greenhouse forcing warms the oceans, which in turn warm the entire troposphere until the outgoing longwave radiation at the top of the atmosphere increases sufficiently to balance the net solar input. There is then no greenhouse-gas-induced disequilibrium at the surface.

A related technique that could be used to detect sites with urban warming is that of Robeson and

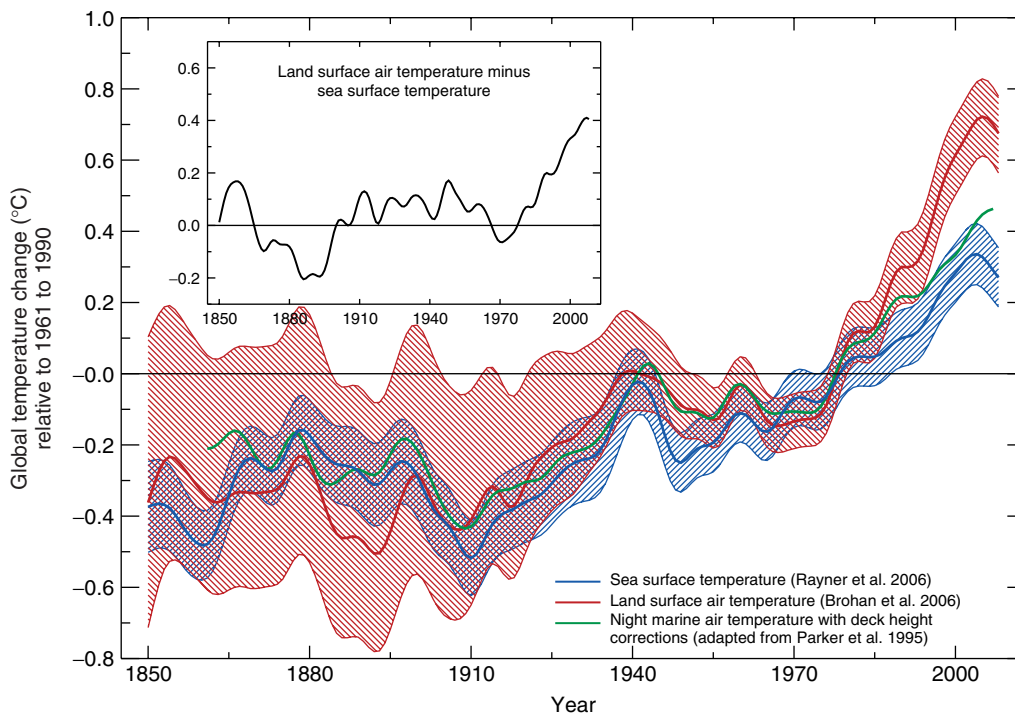


FIGURE 1 | Globally averaged anomalies, relative to 1961–1990, of land surface air temperature (LSAT), sea surface temperature (SST), and night marine air temperature. Also shown are 90% uncertainty ranges (± 1.65 standard errors) for LSAT and SST. The anomalies and uncertainties have been smoothed with a 21-point binomial filter to highlight decadal and longer term variations.

Doty.⁴² Because the urban heat island is strongest on clear, calm nights and these nights are among the coldest at rural sites, analysis of changes in the fifth percentile of minimum temperatures is likely to pinpoint the affected stations. See also the final paragraph of Section Adjustment of data from sites showing urban warming.

Comparison with Trends of Ocean Surface Temperature

Given the difficulty in creating a truly rural record for China, Jones et al.¹² used SSTs averaged over the area 20° – 45° N, 110° – 125° E to the east of China as a reference series to estimate the amount of urban related warming over China. One of their land air temperature data sets omitted western China, making the comparison with the SSTs more appropriate than if an all-China data set had been used; however, their all-China air temperature data set yielded very similar results. Jones et al.¹² concluded that over the period 1951–2004 the urban warming in China averaged about 0.1°C per decade and that the true climate warming was about 0.16°C per decade, i.e., about 60% of the measured warming. This technique assumes that the SSTs are homogeneous, which may not be quite true although the heterogeneities remaining after the analysis of Rayner et al.⁴³ are unlikely to be comparable to a systematic 0.5°C change over half a century.⁴⁴ Use of SSTs as a reference

also assumes that the true air temperature changes over land are the same as those of the ocean surface: because air temperature changes over land may be amplified, as discussed below, Jones et al.¹² may have overestimated the urban warming over China. Nonetheless, their estimate of 0.1°C per decade urban warming is similar to that made by Ren et al.¹⁵ for North China for 1961–2000 using ‘rural’ (<50,000 population) stations as a reference.

On a global average, LSATs have increased more than SSTs and night marine air temperatures in recent decades (see Figure 1 and Ref. ³⁴). In Figure 1, the marine air temperatures⁴⁵ are restricted to nighttime to avoid the maritime counterpart of the urban heat island—daytime solar heating of decks which can bias the measured air temperatures by up to several degrees.⁴⁶ The data used are from an hour after sunset to an hour after sunrise, because of the thermal lag of the decking.

Amplification of temperature changes over land is not a symptom of urban warming, as it is reproduced in climate model experiments in which urban heat islands are not represented.^{47–49} Amplification of natural variations of temperature over land is apparent in Figure 1, e.g. in the fluctuation around 1880–1900. Dommenges⁴⁸ implies that slight lags of ocean behind land, which is another feature of Figure 1, arises from the greater thermal capacity of the ocean. Joshi et al.⁵⁰ have explained the amplification over land as follows. When the ocean warms, extra latent heat

enters the atmosphere through increased evaporation from the ocean. This warms the troposphere over the ocean and then, through transport of the warmer air by the winds, over the land. The tropospheric warming exceeds that at the surface because the Clausius–Clapeyron relationship between temperature and saturation vapour pressure is non-linear. The land surface then equilibrates with the overlying troposphere; in this process, limitations on surface evaporation allow a larger temperature rise at the land surface than that at the ocean surface. A contributory cause for enhanced warming over land is that the stomata of plants constrict in response to increasing atmospheric CO₂, reducing evaporation from plants, and so increasing surface temperature where vegetation is present.⁵¹

Because land surface warming is expected to exceed ocean surface warming by a factor of order of 1.5,^{48,50} the total influence of urban warming on the LSAT record is very unlikely to be comparable to the warming of global land relative to global ocean in Figure 1.

Use of Atmospheric Reanalyses

Atmospheric reanalyses are made by numerical weather prediction models which assimilate historical weather data. These data generally include upper-air temperature, moisture, and wind based on balloon ascents and aircraft reports until the 1970s, and then on a combination of these with satellite data. Surface pressure data are also assimilated, but surface air temperatures were *not* input to, for example, the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis.⁵² However, all reanalyses include *calculated* surface air temperatures. As these reanalyses are based on a fixed model, they avoid the heterogeneity of operational weather analyses which are based on models that evolve as numerical weather prediction develops. Also, the use of a model yields the benefit of dynamical self-consistency. However, reanalyses have so far proved largely unsuitable for the estimation of long-term climate trends because the input data have time-varying biases, and because changes in data coverage modulate the influence of innate model biases on the analyses.

Nonetheless, Kalnay and Cai⁵³ used the NCEP/NCAR reanalysis to estimate urban and land use related warming over the continental United States. Their analysis was restricted to sites at less than 500 m above sea level to avoid the complexities of surface air temperature in mountainous terrain. They avoided the inconsistency in the reanalysis when

satellite data were introduced in 1979, by calculating trends for the previous and subsequent 20 years. They found that between 1960 and 1999 observed surface air temperatures rose relative to the surface air temperatures calculated by the reanalysis. Because the reanalysis was independent of the surface air temperatures and took no account of changes to the land surface, they ascribed the relative warming of the observations to urbanization and changes in land use, rather than to, for example, residual biases in the reanalysis. However, as discussed by Trenberth et al.³⁴ and by Jones et al.,¹² Kalnay and Cai's⁵³ observed data had not been homogenised for other sources of bias, and the NCEP reanalysis did not include anthropogenic or natural forcings. Kalnay et al.⁵⁴ rectified some of these shortcomings and were able to show geographical correspondence between their estimates of urban and land use related warming and Hansen et al.'s²⁵ urban warming adjustments.

The data quality and analytical techniques used in the NCEP/NCAR reanalysis have now been superseded by second-generation reanalyses such as ERA-40.⁵⁵ In ERA-40, changes in lower-tropospheric temperatures between 1960 and 1999 are very similar to those in largely independent surface air temperature observations over the eastern United States,⁵⁶ suggesting that the urban influence on the LSAT trends was not large. This implies that the previous results of Kalnay and Cai⁵³ were biased by artefacts in the NCEP/NCAR reanalysis. Nonetheless, Zhou et al.⁵⁷ used an improved version of the NCEP reanalysis to infer that land use changes, including urbanization, had significantly affected winter surface air temperatures in southeastern China, to the tune of 0.05°C per decade for the period 1979–1998. But this is not much more than 10% of the total trend, and Jones et al.¹² found close agreement between annual Chinese LSATs and the almost-independent ERA-40 over that period.

A Potential Future Technique

McCarthy et al.⁵⁸ have presented preliminary results from climate model simulations that take account of modifications to the land surface, including urbanization, on spatial scales smaller than the grid resolution of the model. Their results suggest that average nighttime minimum temperatures have been raised by several tenths of degree celsius over a substantial proportion of the United Kingdom, whereas daytime maximum temperatures have been much less affected. The compensation for urban warming applied to the Central England temperature series by Parker and Horton⁵⁹ is broadly compatible with these model-based estimates. Exact compatibility is not to be

expected because, for example, observing sites may be in locations selected for their lack of urban development; currently available models are unlikely to be able to replicate the micrometeorology in the required detail. The requirements for fully reliable model-based estimation of worldwide urbanization effects on surface air temperature include sub-kilometre horizontal resolution, adequate representation of heat-transfer processes in the atmospheric boundary layer including the urban canopy, and globally complete information on the changing state of the land surface, again at sub-kilometre resolution.

URBAN CONTRIBUTION TO ESTIMATED GLOBAL WARMING

Trenberth et al.³⁴ assessed the literature available at the time^{2,5,22,37} and concluded that the urban heat island had only made a very small contribution to estimated large-scale temperature trends over land. Approximately following Brohan et al.,¹⁷ they assessed the urban related one standard error uncertainty in the global LSAT trend since 1900 as 0.006°C per decade. This uncertainty is one-sided because urban cooling is not expected on a physical basis. The urban related uncertainty was not used to adjust the best-estimate temperature anomalies, but only to augment the overall uncertainties. Figure 2, updated from Brohan et al.,¹⁷ shows globally, annually averaged LSAT anomalies relative to 1961–1990 and their 95% confidence ranges since 1850. The anomalies and uncertainties have been smoothed to highlight decadal and longer term variations. The inner dark grey band and the light grey band surrounding it represent the cumulative uncertainties arising respectively from random and sampling errors, and incomplete coverage. The outer black band represents the additional uncertainties arising from changes in thermometer exposure and from urbanization. Successive uncertainties were combined in quadrature. The impact of urbanization on the uncertainties can be seen from the asymmetry in the black bands. Brohan et al.¹⁷ double counted the urbanization uncertainty but this has been corrected here.

Because the Earth is about 70% ocean, the uncertainty on global overall temperature trends was assessed by Trenberth et al.³⁴ to be 0.002°C per decade. More recent augmented estimates of urban warming for China¹² do not substantially increase these estimates because of the avoidance¹⁷ or adjustment²⁵ of urban observations in the global LSAT series cited by Trenberth et al.³⁴ Furthermore, urban China is developing at a greater rate than most

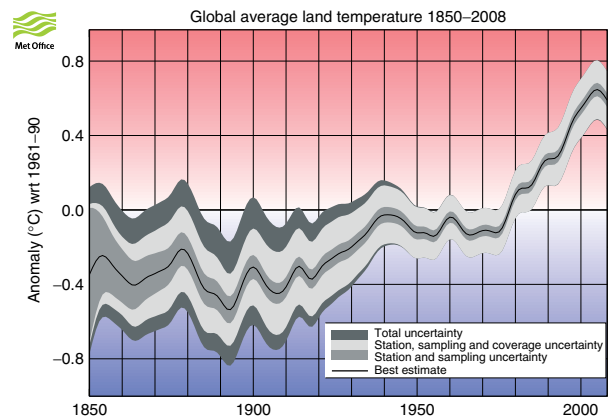


FIGURE 2 | Globally, annually averaged land surface air temperature (LSAT) anomalies, relative to 1961–1990, and their 95% confidence ranges (± 1.96 standard errors), since 1850. The anomalies (black line) and uncertainties (shaded bands) have been smoothed with a 21-point binomial filter to highlight decadal and longer term variations. The inner dark grey band and the light grey band surrounding it represent the cumulative uncertainties arising respectively from random and sampling errors, and incomplete coverage. The outer black band represents the additional uncertainties arising from changes in thermometer exposure and from urbanization; it is narrow in recent years because the data are referenced to 1961–1990. Successive uncertainties were combined in quadrature. The impact of urbanization on the uncertainties can be seen from the asymmetry in the black bands. Brohan et al.¹⁷ double counted the urbanization uncertainty but this has been corrected here. The overall uncertainty exceeds that for the LSAT curve in Figure 1 because here the two hemispheres are weighted equally, increasing the emphasis on the data-sparse Southern hemisphere, whereas Figure 1 is based on area-weighting of available data. (Updated from Brohan et al.¹⁷).

other parts of the world and is only a small fraction of the land surface.

Because the urban heat island is mainly a nighttime phenomenon, its influences on global trends of land air temperature at night since 1900 are likely to be about double those on mean temperature, i.e. 0.012°C per decade. The impact on diurnal temperature range will be about -0.012°C per decade. This is much smaller than the 0.07°C per decade decline in diurnal temperature range for 1950–2004 reported by Vose et al.⁶⁰

CONCLUSION

The urban heat island has had only a minor impact on estimates of global trends of LSAT. Its impact is much smaller than the 0.74°C global warming between 1906 and 2005.³⁴ The impact is small because assiduous efforts have been made by the compilers of global surface air temperature

records to avoid^{16,18,19} or compensate for²⁵ urban warming. This is confirmed by analyses using only rural stations²² or using only days and nights with windy weather.³⁷ Further support comes from comparisons with marine surface temperature trends in the light of the expected augmentation of trends over land. Atmospheric reanalyses, when used with care regarding their heterogeneity, do not oppose these conclusions. In future, assessments of worldwide urbanization effects on surface air temperature are likely to be possible using high-resolution, high-fidelity climate models along with high-resolution information on the changing land surface.

Nonetheless, city-dwellers experience urban warming superimposed on the regional manifestation

of global warming. Increased vegetation and/or reflective roofing have been proposed as means to mitigate urban heat islands: see for example Chicago at <http://www.globalchange.gov/images/cir/pdf/midwest.pdf>. The combined impacts of urban and global warming can be severe and justify urgent measures to initiate both mitigation and adaptation.⁶¹

NOTES

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REFERENCES

- IPCC. In: Houghton JT, Jenkins GJ, Ephraums, JJ, eds. *Scientific Assessment of Climate change—Report of Working Group I*. Cambridge, MA: Cambridge University Press; 1990, 365 pp.
- Jones PD., Groisman PYa, Coughlan M, Plummer N, Wang W-C, et al. Assessment of urbanization effects in time series of surface air temperature over land. *Nature* 1990, 347:169–172. DOI:10.1038/347169a0.
- Arnfield AJ. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int J Climatol* 2003, 23:1–26. DOI:10.1002/joc.859.
- Hartz DA, Prashad L, Hedquist BC, Golden J, Brazel AJ. Linking satellite images and hand-held infrared thermography to observed neighborhood climate conditions. *Rem Sens Environ* 2006, 104:190–200. DOI:10.1016/j.rse.2005.12.019.
- Peterson TC. Assessment of urban versus rural in situ surface temperatures in the contiguous United States: No difference found. *J Clim* 2003, 16:2941–2959. DOI:10.1175/1520-0442(2003)016<2941:AOUVRI>2.0.CO;2.
- Gaffin SR, Rosenzweig C, Khanbilvardi R, Parshall L, Mahani S, et al. Variations in New York city's urban heat island strength over time and space. *Theor Appl Climatol* 2008, 94:1–11. DOI: 10.1007/s00704-007-0368-3.
- Johnson GT, Oke TR, Lyons TJ, Steyn DG, Watson ID, et al. Simulation of surface urban heat islands under “ideal” conditions at night: Part 1: Theory and tests against field data. *Boundary Layer Meteorol* 1991, 56:275–294. DOI:10.1007/BF00120424.
- Oke TR. *Boundary Layer Climates*. 2nd ed. London: Methuen, Co. Ltd.; 1987, 464 pp.
- Fujibe F. Detection of urban warming in recent temperature trends in Japan. *Int J Climatol* 2009, 29:1811–1822. DOI: 10.1002/joc.1822.
- Sun C-Y, Brazel AJ, Chow WTL, Hedquist BC, Prashad L. Desert heat island study in winter by mobile transect and remote sensing techniques. *Theor Appl Climatol* 2009, 98:323–335. DOI 10.1007/s00704-009-0120-2.
- Brandsma T, Können, GP, Wessels HRA. Empirical estimation of the effect of urban heat advection on the temperature series of De Bilt (The Netherlands). *Int J Climatol* 2003, 23:829–845. DOI: 10.1002/joc.902.
- Jones PD, Lister DH, Li Q. Urbanization effects in large-scale temperature records, with an emphasis on China. *J Geophys Res* 2008, 113:D16122. DOI:10.1029/2008JD009916.
- Jones PD, Lister DH. The Urban Heat Island in Central London and urban-related warming trends in Central London since 1900. *Weather* 2010, 65: In press.
- Li Q, Zhang H, Liu X, Huang J. Urban heat island effect on annual mean temperature during the last 50 years in China. *Theor Appl Climatol* 2004, 79:165–174. DOI:10.1007/s00704-004-0065-4.
- Ren G, Zhou Y, Chu Z, Zhou J, Zhang A, et al. Urbanization effects on observed surface air temperature trends in North China. *J Clim* 2008, 21:1333–1348. DOI:10.1175/2007JCLI1348.1.
- Peterson T, Daan H, Jones P. Initial selection of a GCOS Surface Network. *Bull Am Meteorol Soc* 1997, 78:2145–2152. DOI:10.1175/1520-0477(1997)078<2145:ISOAGS>2.0.CO;2.
- Brohan P, Kennedy JJ, Harris I, Tett SFB, Jones PD. Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J Geophys Res* 2006, 111:D12106. DOI:10.1029/2005JD006548.

18. Jones PD, Raper SCB, Bradley RS, Diaz HF, Kelly PM, et al. Northern Hemisphere surface air temperature variations: 1851–1984. *J Clim Appl Meteorol* 1986, 25:161–179. DOI:10.1175/1520-0450(1986)025<0161:NHSATV>2.0.CO;2.
19. Jones PD, Raper SCB, Wigley TML. Southern Hemisphere surface air temperature variations: 1851–1984. *J Clim Appl Meteorol* 1986, 25:1213–1230. DOI:10.1175/1520-0450(1986)025<1213:SHSATV>2.0.CO;2.
20. Jones PD, Raper SCB, Santer B, Cherry BSG, Goodess CM, et al. *A grid point surface air temperature data set for the Northern Hemisphere*. United States Department of Energy Carbon Dioxide Research Division Technical Report 22, DOE/EV/10098-2, Washington, D.C., 1985, 251 pp.
21. Jones PD, Raper SCB, Goodess CM, Cherry BSG, Wigley TML. *A grid point surface air temperature data set for the Southern Hemisphere*. United States Department of Energy Carbon Dioxide Research Division Technical Report 27, DOE/EV/10098-6, Washington, D.C., 1986, 73 pp.
22. Peterson TC, Gallo KP, Lawrimore J, Huang A, McKittrick DA. Global rural temperature trends. *Geophys Res Lett* 1999, 26:329–332. DOI: 10.1029/1998GL900322.
23. Elvidge CD, Baugh KE, Kihn EA, Kroehl HW, Davis ER. Mapping city lights with nighttime data from the DMSP Operational Linescan System. *Photogramm Eng Rem Sens* 1997, 63:727–734.
24. Smith TM, Reynolds RW. A global merged land–air–sea surface temperature reconstruction based on historical observations (1880–1997). *J Clim* 2005, 18:2021–2036. DOI: 10.1175/JCLI3362.1.
25. Hansen J, Ruedy R, Sato M, Imhoff M, Lawrence W, et al. A closer look at United States and global surface temperature change. *J Geophys Res* 2001, 106:23947–23963. DOI: 10.1029/2001JD000354.
26. Peterson TC, Owen TW. Urban heat island assessment: Metadata are important. *J Clim* 2005, 18:2637–2646. DOI:10.1175/JCLI3431.1.
27. Global Climate Observing System. *Implementation plan for the Global Observing System for Climate in support of the UNFCCC*. GCOS-92 (WMO/TD. No. 1219). Available at: <http://www.wmo.int/pages/prog/gcos/>. (Accessed November 2, 2009). Geneva: World Meteorological Organization; 2004, 153pp.
28. Gallo KP, Easterling DR, Peterson TC. The influence of land use/land cover on climatological values of the diurnal temperature range. *J Clim* 1996, 9:2941–2944. DOI: 10.1175/1520-0442(1996)009<2941:TIO LUC>2.0.CO;2.
29. Strangeways I. Using Google Earth to evaluate GCOS weather station sites. *Weather* 2009, 64:4–8.
30. Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, et al. Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, et al., eds. *Climate Change 2007: The Physical Science Basis*. Cambridge, MA: Cambridge University Press; 2007, 129–234.
31. Easterling DR, Karl TR, Mason EH, Hughes PY, Bowman DP. United States Historical Climatology Network (U.S. HCN) Monthly Temperature and Precipitation Data. ORNL/CDIAC-87, NDP-019/R3. Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy; 1996.
32. Hansen J, Ruedy R, Glascoe J, Sato M. GISS analysis of surface temperature change. *J Geophys Res* 1999, 104:30997–31022.
33. Karl TR, Diaz HF, Kukla G. Urbanization: its detection and effect in the United States climate record. *J Clim* 1988, 1:1099–1123. DOI: 10.1175/1520-0442(1988)001<1099:UIDAEI>2.0.CO;2.
34. Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, et al. Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, et al., eds. *Climate Change 2007: The Physical Science Basis*. Cambridge, MA: Cambridge University Press; 2007, 235–336.
35. DeGaetano AT, Allen RJ. Trends in Twentieth Century temperature extremes across the United States. *J Clim* 2002, 15:3188–3205. DOI: 10.1175/1520-0442(2002)015<3188:TITCTE>2.0.CO;2.
36. Della-Marta PM, Wanner H. A method of homogenizing the extremes and mean of daily temperature measurements. *J Clim* 2006, 19:4179–4197. DOI: 10.1175/JCLI3855.1.
37. Parker DE. A demonstration that large-scale warming is not urban. *J Clim* 2006, 19:2882–2895. DOI:10.1175/JCLI3730.1.
38. Jones PD, Moberg A. Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. *J Clim* 2003, 16:206–223. DOI: 10.1175/1520-0442(2003)016<0206:HALSSA>2.0.CO;2.
39. Basara JB, Hall PK Jr., Schroeder AJ, Illston BG, Nemunaitis KL. Diurnal cycle of the Oklahoma City urban heat island. *J Geophys Res* 2008, 113:D20109. DOI:10.1029/2008JD010311.
40. Trewin BC. Effects of changes in algorithms used for the calculation of Australian mean temperature. *Aust Meteorol Mag* 2004, 53:1–11.
41. Pielke RA Sr, Matsui T. Should light wind and windy nights have the same temperature trends at individual levels even if the boundary layer averaged heat content change is the same? *Geophys Res Lett* 2005, 32:L21813. DOI:10.1029/2005GL024407.

42. Robeson SM, Doty JA. Identifying rogue air temperature stations using cluster analysis of percentile trends. *J Clim* 2005, 18:1275–1287. DOI:10.1175/JCLI3297.1.
43. Rayner NA, Brohan P, Parker DE, Folland CK, Kennedy JJ, et al. Improved analyses of changes and uncertainties in sea surface temperature measured in situ since the mid-nineteenth century: the HadSST2 dataset. *J Clim* 2006, 19:446–469. DOI:10.1175/JCLI3637.1.
44. Thompson DWJ, Kennedy JJ, Wallace JM, Jones PD. A large discontinuity in mid 20th century global-mean surface temperatures. *Nature* 2008, 453:646–649. DOI:10.1038/nature06982.
45. Parker DE, Folland CK, Jackson M. Marine surface temperature: observed variations and data requirements. *Clim Change* 1995, 31:559–600. DOI:10.1007/BF01095162.
46. Berry DI, Kent EC. The effect of instrument exposure on marine air temperatures: an assessment using VOSclim data. *Int J Climatol* 2005, 25:1007–1022. DOI: 10.1002/joc.1178.
47. Compo GP, Sardeshmukh PD. Oceanic influences on recent continental warming. *Clim Dyn* 2009, 32:333–342. DOI:10.1007/s00382-008-0448-9.
48. Dommenges D. The ocean's role in continental climate variability and change. *J Clim* 2009, 22:4939–4952. DOI: 10.1175/2009JCLI2778.1.
49. Folland CK. Assessing bias corrections in historical sea surface temperature using a climate model. *Int J Clim* 2005, 25:895–911. DOI: 10.1002/joc.1171.
50. Joshi MM, Gregory JM, Webb MJ, Sexton DMH, Johns TC. Mechanisms for the land/sea warming contrast exhibited by simulations of climate change. *Clim Dyn* 2007, 30:455–465. DOI:10.1007/s00382-007-0306-1.
51. Joshi MM, Gregory JM. The dependence of the land-sea contrast in surface climate response on the nature of the forcing. *Geophys Res Lett* 2008, 35:L24802. DOI:10.1029/2008GL036234.
52. Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, et al. The NCEP/NCAR 40-Year Re-analyses project. *Bull Am Meteorol Soc* 1996, 77:437–471. DOI:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.
53. Kalnay E, Cai M. Impact of urbanization and land-use change on climate. *Nature* 2003, 423:528–531.
54. Kalnay E, Cai M, Li H, Tobin J. Estimation of the impact of land-surface forcings on temperature trends in eastern United States. *J Geophys Res* 2006, 111:D06106. DOI:10.1029/2005JD006555.
55. Uppala S, Källberg P, Simmons A, Andrae U, da Costa Bechtold V, et al. The ERA-40 re-analysis. *Q J R Meteorol Soc* 2005, 131:2961–3012. DOI:10.1256/qj.04.176.
56. Simmons AJ, Jones PD, da Costa Bechtold V, Beljaars ACM, Källberg PW, et al. Comparison of trends and low-frequency variability in CRU, ERA-40 and NCEP/NCAR analyses of surface air temperature. *J Geophys Res* 2004, 109:D24115. DOI:10.1029/2004JD005306.
57. Zhou LM, Dickinson RE, Tian YH, Fang JY, Li QX, et al. Evidence for a significant urbanization effect on climate in China. *Proc Natl Acad Sci USA* 2004, 101:9540–9544. DOI:10.1073/pnas.0400357101.
58. McCarthy MP, Best MJ, Betts RA. *Cities under a changing climate*. Extended abstract for the Seventh International Conference on Urban Climate (ICUC-7), Yokohama, Japan, 29 June–3 July 2009.
59. Parker DE, Horton EB. Uncertainties in Central England temperature 1878–2003 and some improvements to the maximum and minimum series. *Int J Climatol* 2005, 25:1173–1188. DOI:10.1002/joc.1190.
60. Vose RS, Easterling DR, Gleason B. Maximum and minimum temperature trends for the globe: an update through 2004. *Geophys Res Lett* 2005, 32:L23822. DOI:10.1029/2004GL024379.
61. United Nations Human Settlements Programme. *Enhancing urban safety and security: global report on Human Settlements 2007 (Part IV)*. 2007, 448 pp.

FURTHER READING

1. Geiger R, Aron RH, Todhunter P. *The Climate Near the Ground*. 6th ed. Lanham, Boulder, New York and Oxford: Rowman & Littlefield Publishers, Inc.; 2003, xviii+584 pp
2. Georgescu M, Miguez-Macho G, Steyaert LT, Weaver CP. Climatic effects of 30 years of landscape change over the Greater Phoenix, Arizona, region: 1. Surface energy budget changes. *J Geophys Res* 2009, 114:D05110. DOI:10.1029/2008JD010745
3. Voogt JA, Oke TR. Thermal remote sensing of urban climates. *Rem Sens Environ* 2003, 86:370–384. DOI:10.1016/S0034-4257(03)00079-8