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Urbanization effects in large-scale temperature records, with an emphasis on China

P. D. Jones,[1] D. H. Lister,[1] and Q. Li[2]

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[1] Global surface temperature trends, based on land and marine data, show warming of about 0.8°C over the last 100 years. This rate of warming is sometimes questioned because of the existence of well-known Urban Heat Islands (UHIs). We show examples of the UHIs at London and Vienna, where city center sites are warmer than surrounding rural locations. Both of these UHIs however do not contribute to warming trends over the 20th century because the influences of the cities on surface temperatures have not changed over this time. In the main part of the paper, for China, we compare a new homogenized station data set with gridded temperature products and attempt to assess possible urban influences using sea surface temperature (SST) data sets for the area east of the Chinese mainland. We show that all the land-based data sets for China agree exceptionally well and that their residual warming compared to the SST series since 1951 is relatively small compared to the large-scale warming. Urban-related warming over China is shown to be about 0.1°C decade^{-1} over the period 1951–2004, with true climatic warming accounting for 0.81°C over this period.

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1. Introduction

[2] Numerous studies (see, e.g., the summary by *Oke* [2004]) have shown that urban sites are warmer than rural surroundings, but the emphasis is generally given to the largest monthly, daily, or even hourly, differences. For studies of the potential urban influence on global-scale temperature trends, we are not interested in extreme differences, nor in assessments of the Urban Heat Island (UHI) from individual locations, but changes to urban influences over periods of decades in large area averages based on many station records [see *Peterson*, 2003; *Parker*, 2004, 2006]. We should also be mindful of the fact that at the largest of scales (global) two thirds of the constituent data come from the marine realm, where any urban influence cannot be present. Also, as pointed out by *Peterson and Owen* [2005], instantaneous differences (or even monthly timescale differences) do not generally take into account factors such as elevational differences between the city center and rural site, the type of weather, distances from major water bodies and differences in time between the readings.

[3] The emphasis of this study is China, where there has been rapid economic development and growth over the past few decades. The aim is to determine the potential magnitude of the possible urban-related impacts on large-scale temperature trends. We set the stage (section 2) with two European examples (London and Vienna), then follow with extensive analyses for China. The purpose of the European examples is to show that while the city center locations are warmer than the outlying rural environs this doesn't have any effect on their recent temperature trends. In section 3, we discuss a number of studies that have looked at Chinese temperature trends and have come to a wide range of possible conclusions: from little effect (any urban-related trend is an order of magnitude smaller than the warming that has occurred) to almost all the observed warming being due to urbanization. The main difficulty with Chinese temperature series is that there are very few located in rural locations. To attempt to overcome this problem, we compare various compilations of Chinese mean temperature averages (series from over 700 stations to averages based on 42 locations) with sea surface temperatures from the coastal seas east of China and surface temperatures developed from the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year Reanalyses (ERA-40). The study does not explicitly consider monthly mean maximum and minimum temperature series, but we will comment on the usefulness of such series. We refer to appropriate literature and the data we use as necessary. We conclude in section 4.

2. European Examples

2.1. London

[4] *Howard* [1833] was possibly the first scientist to suggest that the temperature recorded in a city was likely warmer than that in the surrounding countryside. Over the years, much work has been undertaken on the urban influence and the UHI within London [see review by *Wilby*,

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[1] Climatic Research Unit, University of East Anglia, Norwich, UK.

[2] National Meteorological Information Center, China Meteorological Administration, Beijing, China.

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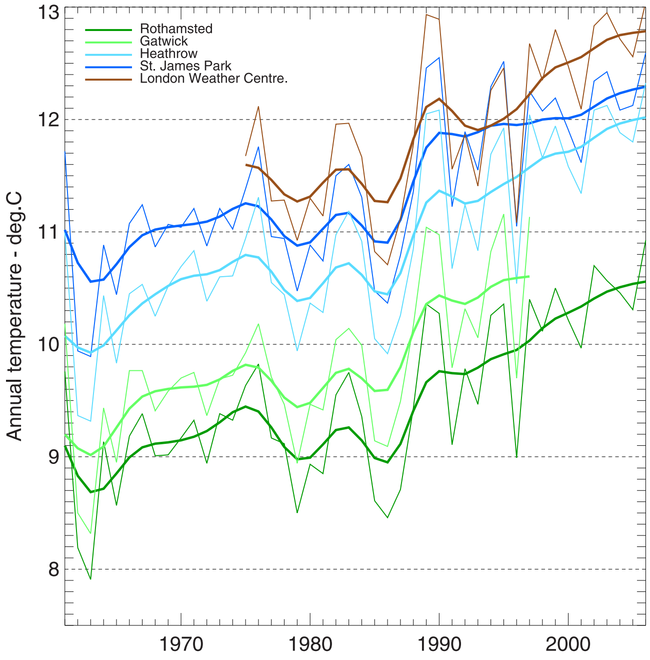

Figure 1. Annual temperature trends for five sites in and around London. The locations of the sites and the lengths of records are given in Table 1. The smooth lines in this and subsequent plots are produced using a 10-year data-adaptive Gaussian filter.

2003]. In the light of the Introduction, it is interesting to compare the course of temperature change from a number of locations within and around London. Figure 1 shows annual temperature series for five sites with Table 1 giving their location details and temperature trends over two periods (1961/1981 to 2006). Rothamsted (39 km north/northwest of London) is the truly rural site and is one of the three sites that constitutes the Central England temperature record [*Parker et al.*, 1992]. The only potentially long-term record of a totally urban downtown site in central London is in Holborn (known in the UK as the London Weather Centre, LWC). The location of LWC is non-standard, it being currently sited on the top of an office block, 23 m above ground level. St. James' Park is also in central London, but as its name implies it is not in a heavily urbanized part of the city. Heathrow and Gatwick are located 25 km west and 40 km south of central London, respectively, and the environs around the airports have grown extensively over the last 50 years, more so at Heathrow than Gatwick. Figure 1 shows annual average temperature (expressed in absolute degrees Celsius) and clearly the LWC and St. James' Park sites are the warmest, but the evolution of the time series is almost identical. As for trends since 1961 all sites give similar values. For the period from 1981 all trends are also similar, with the smallest trend at the St. James' Park site. So, in terms of anomalies from a common base period, all sites would give similar values.

[5] Another way of looking at the data set for the two urban sites (LWC and St. James' Park) and the rural (Rothamsted) site is to plot a histogram of the daily temperature differences. Figure 2 shows this on a seasonal basis, for all three pairs of daily differences. The two central London sites are almost always warmer than Rothamsted. There are few differences between the shapes of the histograms for the four seasons. Summer days and to a lesser extent spring days are likely to be more anomalously warm at St James' Park when compared to Rothamsted. This behavior is less evident when LWC is used. Both histograms involving LWC indicate a distinct positive skewness in the histograms, compared to the near normal distribution when St James' Park is compared to Rothamsted. Figure 2 gives a range of possible UHI values for central London locations, but in terms of monthly and annual anomalies from a common based period (see Figure 1), values only differ slightly with no significant differences in temperature trends.

[6] Further discussion of the London record will be found at the end of the next section. In the latest Climatic Research Unit (CRU) gridded land temperature data set [CRUTEM3(v), *Brohan et al.*, 2006], the records for Rothamsted and Gatwick are used for some of the time, but none of the other three sites report at present internationally over the World Meteorological Organization (WMO) CLIMAT network, nor are they included in the CRU data set.

2.2. Vienna

[7] The city has a long record (Hohe Warte) which has been the subject of extensive homogeneity assessment [*Böhm*, 1998]. The site is not in an industrial part of the city, nor is it in an area that has experienced much 20th century development. In Figure 3 we plot this record against a long rural site (Grossenzersdorf, situated 15 km east of the Austrian capital). Again, we plot the series as absolute temperatures, but although the city site is clearly warmer, there would be only minor differences if both were expressed as anomalies from a common base period. Trends of temperature in the two series since 1910 and since 1961 are essentially the same (Table 2). The Hohe Warte record is used in the CRUTEM3(v) data set, as relative to 1961–90 the site shows excellent agreement with its rural neighbors.

Table 1. Temperature Trends for Station Series in the London Area

Station Name	Distance (km) and Direction from Central London (Holborn)	Elevation (m)	Site Description	Temperature Trend (°C/10 years) for the Period 1961–2006	Temperature Trend (°C/10 years) for the Period 1981–2006
London Weather Centre (Holborn)	0	77	Urban/rooftop	Record only starts in 1975	**0.61**[a]
St. James's Park	2 (SW)	8	Urban parkland	**0.37**[a]	**0.56**[a]
Heathrow	25 (W)	25	Semi-urban airport	**0.43**[a]	**0.65**[a]
Rothamsted	39 (NW)	128	Rural	**0.38**[a]	**0.67**[a]
Gatwick	40 (S)	59	Semi-rural airport	**0.37**[a] actual period 1961–1997	0.74 actual period 1981–1997[a]

[a] Bold trend values indicate significance >95% level.

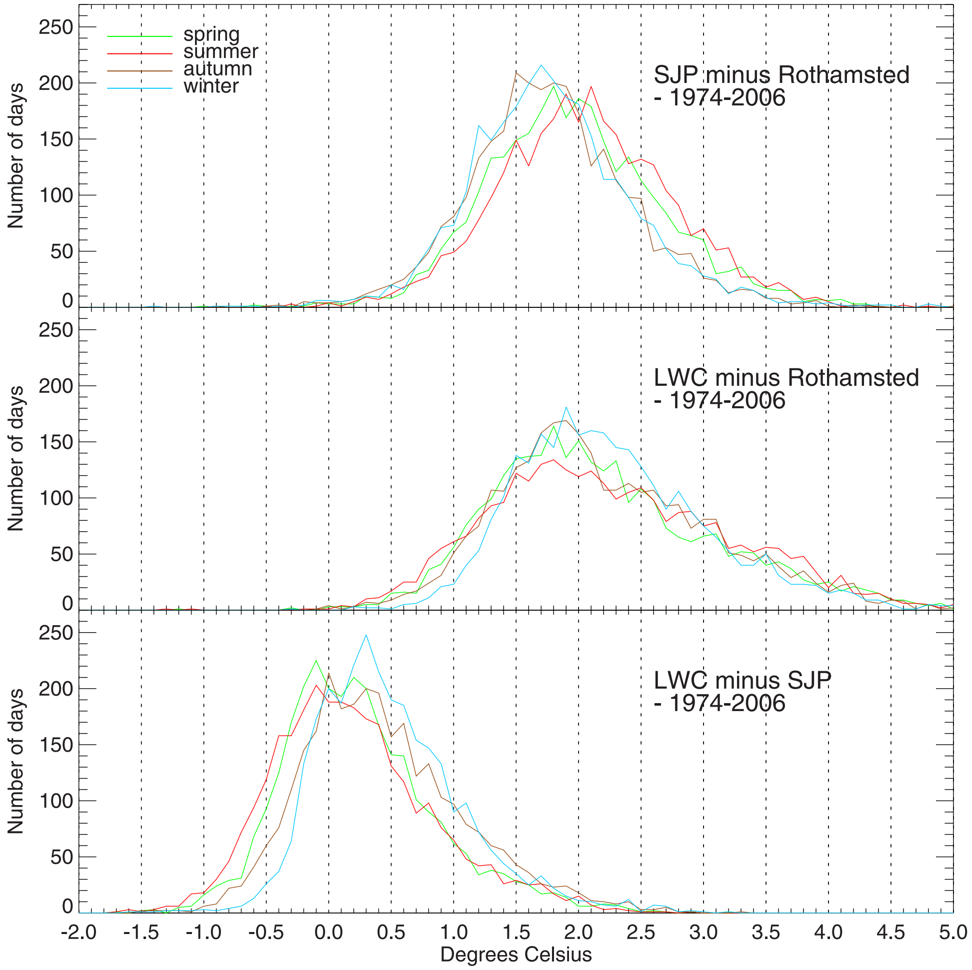

Figure 2. Histograms of the differences in daily mean temperature by season for the two central London locations [London Weather Centre (LWC) and St James' Park (SJP)] minus the rural site at Rothamsted. Spring is March to May, summer June to August, autumn September to October, and winter December to February.

[8] As with London, the obvious question is when did Vienna become warmer than its currently rural neighbors. The simple answer would be before the periods plotted in Figures 1 and 3, but this could be the 19th century or earlier. It is impossible to say how much earlier as limited numbers of long rural (and indeed for city center locations in some cities) site temperature series are available for centuries before 1900. As both cities have been in their present locations for centuries, the relative warming could have occurred over many centuries. It is also likely in the London case, that sites near the River Thames in the vicinity of where central London now is, would always have been slightly warmer than a site like Rothamsted (which is to the north of London and at a slightly higher elevation). The north–south temperature gradient across the UK cannot be ignored, just like that because of the elevation and distance from the coast and major water bodies (recall the discussion on the importance of metadata and local site details in *Peterson and Owen* [2005]). The magnitude (using annual average temperatures) of the UHI at London is of the order of 1.5°C (based on the difference between LWC and the average of Gatwick and Rothamsted), while for Vienna it is much smaller at about 0.3°C. A larger UHI for Vienna, of about 1.5°C, has been shown by *Böhm* [1998] but based on a more central downtown location than Hohe Warte.

[9] Even though these are just two examples of major European capital cities, it highlights both the difficulties of trying to develop a measure of urbanization (e.g., population, paved area or nightlights) that would be universally acceptable, and the clear need to look at the data (as opposed to saying that the record is from a city, therefore its trend over recent decades must be greater than nearby rural sites). It is clearly not good enough considering instantaneous absolute differences, but crucial to look at time series from a number of locations within and around the city. London and Vienna both undoubtedly have UHIs, but this doesn't mean any more warming over recent decades than their rural neighbors. Also neither, London nor Vienna can be considered broadly representative of urban influence throughout the UK or Austria, respectively. A recent study in New York City [*Gaffin et al.*, 2008] agrees with the European examples. This indicates that the long-term record (in Central Park in the center of Manhattan) warms marginally compared to an average of 23 surrounding rural and suburban stations (all well removed from the city) by 0.03°C decade^{-1} over the 20th century. The Central

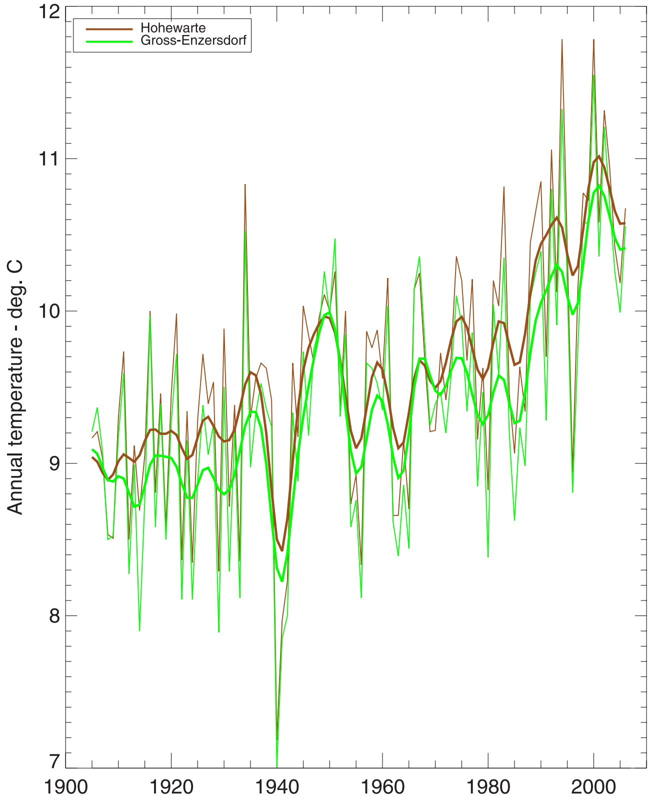

Figure 3. Annual temperatures for two sites in Vienna–Hohewarte in the center and the rural location of Grossenzersdorf.

Park site however has a clear UHI of between 2.0 and 2.5°C.

3. China

[10] China is a region quite different from Europe; it has experienced rapid economic growth over the last 30 years and a dramatic increase in the population and geographic size of its city areas. It, therefore, represents a region of the world where, if there were to be significant urban-related warming, it ought to be in this region and over recent decades. However, just as with the two European examples, many of the cities have been in their present positions for a long time, with some being large population centers for many centuries.

[11] Many papers have addressed possible urban-related warming trends in Chinese temperature data sets. We will discuss one of the first [*Jones et al.*, 1990] in more detail in section 3.1 later. Others in the early 1990s include *Wang et al.* [1990] and *Portman* [1993]. *Wang et al.* [1990] concluded that UHI intensity (based on a network of 42 sites) increased by 0.1°C over their analysis period of 1954–83 and also note the difficulty of designating sites as being truly rural. *Portman* [1993] using a similar network of stations concluded an urban-related warming trend of 0.15–0.26°C over 1954–83, the range depending on the city population size. The effects of site changes in both studies weren't explicitly considered, but both chose sites where the number of site changes based on station history information was few. *Portman* [1993] removed two sites from his analyses where the effects of site changes were clearly evident in time series plots.

[12] More recent papers have also addressed Chinese temperature series and looked at potential UHIs and urban-related warming [e.g., *Li et al.*, 2004a; *He et al.*, 2007; *Ren et al.*, 2007; *Ren et al.*, 2008]. Only two of these papers produce an estimate of the effect of urban-related warming for a large part of China through a direct comparison with less-affected "rural" sites. *Ren et al.* [2007] look at only two sites (Beijing and Wuhan), but only adjust the Beijing city center site for homogeneity. They consider, compared to rural sites, that both cities are seriously affected (expressed as 65–80% of the warming could be urban related over 1961–2000 and 40–61% over 1981–2000), but with marked seasonal

Table 2. Temperature Trends for Station Series in the Vienna Area

Station Name	Distance (km) and Direction from Central Vienna	Elevation (m)	Site Description	Temperature Trend (°C/10 years) for the Period 1910–2006	Temperature Trend (°C/10 years) for the Period 1961–2006
Wien (Hohe Warte)	5(N)	209	Urban	**0.16**[a]	**0.36**[a]
Grossenzersdorf	15 (E)	148	Rural	**0.16**[a]	**0.33**[a]

[a] Bold trend values indicate significance >95% level.

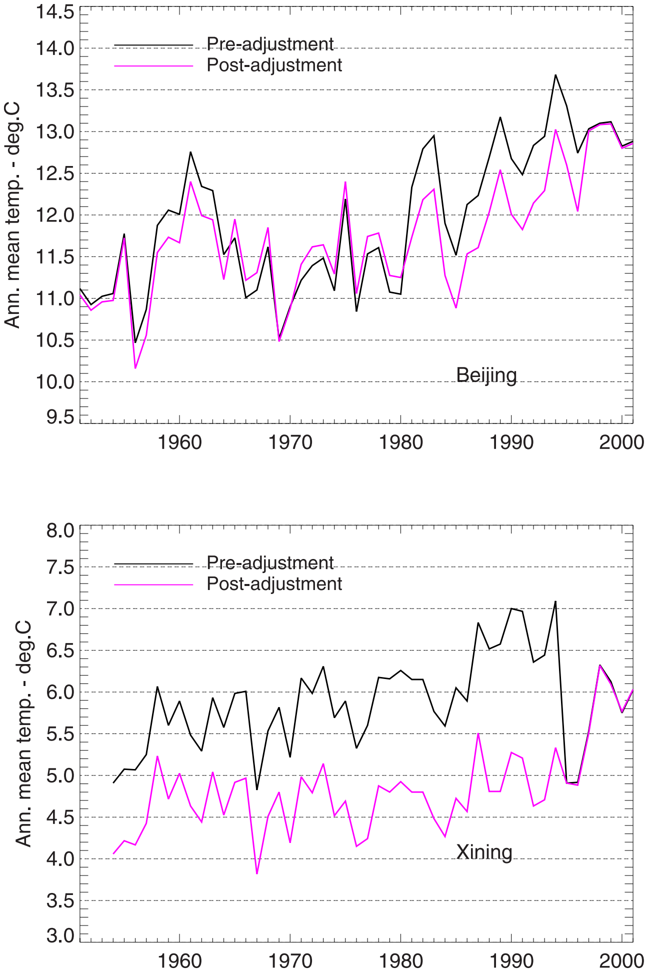

Figure 4. Raw annual temperature averages before adjustment (black) and after (purple), top (Beijing) and bottom (Xining). Adjustments are always made compared to the most recent years of the records.

differences (lowest percentages in winter and highest in summer). The ranges come from the two locations studied with Beijing always being the higher value except for summer for 1981–2000 where the Wuhan value is larger. The use of ratios to indicate urban-related warming can easily imply that the problem is much greater than it might appear (e.g., the city site could warm at 0.1°C decade^{-1} and the rural site 0.05°C decade^{-1}, but the percentage value of excess warming would be 100%). Excess warming may not be highest in summer, but expressed in percentage terms by *Ren et al.* [2007] it is. *He et al.* [2007] compare Chinese temperature series by land-use type, but again do not use fully homogeneous data. *Li et al.* [2004a] attempt to assess urban-related warming with "rural" sites, using homogeneity-adjusted data (principally site moves, using the approach used in *Li et al.* [2004b]). Their conclusion is that regional-averaged temperature trends with and without stations that are affected by urban-related warming is at most an effect of 0.06°C over the last 50 years (i.e., $\sim$0.01°C decade^{-1}). *Parker* [2004, 2006] who found no evidence of urban-related warming trends by comparing temperature trends on calm with windy nights, used 15 Chinese sites in his study of 270 stations worldwide.

[13] *Ren et al.* [2008] is the most comprehensive Chinese study looking at 282 sites across northern China (between 33° and 43°N by 108° and 120°E). The stations come from two different networks (93 National Stations, NSs, and 282 Ordinary Weather Stations, OWSs). Using networks of sites of different population sizes (from rural $<$50 K people, to metropolis $>$1 M people), the study shows that the rural network (63 sites) warms less than the NS average (93 sites) by 0.11°C decade^{-1} over the period from 1961–2000. The NS sites used have been homogenized by *Li et al.* [2004b], but the OWSs have not been adjusted.

[14] In China, all the climatological data available for research use have been collected by the Chinese Meteorological Administration (CMA), at least for the period from 1949. Data for the 1940s are sparse because of the political situation, but for earlier decades there are a more limited set of records from the late-19th century, principally for eastern China, which are available through CMA and a number of publications [see e.g., *Central Meteorological Bureau and Academica Sinica*, 1952; *Yan et al.*, 2001].

[15] An interesting feature of the post-1949 CMA records is that none are located at airports, the necessary data for airports being collected by another agency within China, and the records are not routinely exchanged with CMA. CMA records also tend to be located where people live in the towns and cities, so there are very few records located in National Parks and other areas that would probably have always been designated rural. It is thus extremely difficult to designate the temperature series into rural and urban, and researchers have more generally referred to networks of larger and smaller cities/towns (see discussion in *Li et al.* [2004a] and *Ren et al.* [2008]). This designation uses recent population figures. *Ren et al.* [2008], for example, use figures published for the population of villages, towns and districts in 2002. As the cities have grown rapidly over the last few decades, many of the series generally have at least one site move. Before urbanization can be considered it is important to adjust the records for the site moves. For 728 CMA records (the total number of NS sites across China) this has been undertaken by the process introduced by *Li et al.* [2004b] and *Li and Li* [2007], using the approaches of *Peterson and Easterling* [1994] and *Easterling and Peterson* [1995]. Using metadata information (site moves, instrument changes and changes to observation schedules), adjustments are made (see Figure 4 for two locations in China, before and after, from *Li and Li* [2007]). These adjust *solely* for known changes from metadata information,

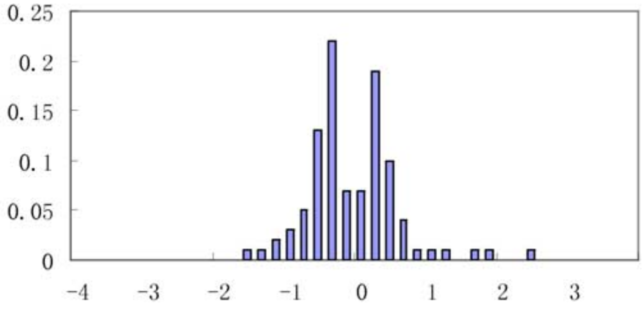

Figure 5. Distribution of annual station homogeneity adjustments (°C). The histogram is based on adjustments from 243 stations from *Li and Li* [2007].

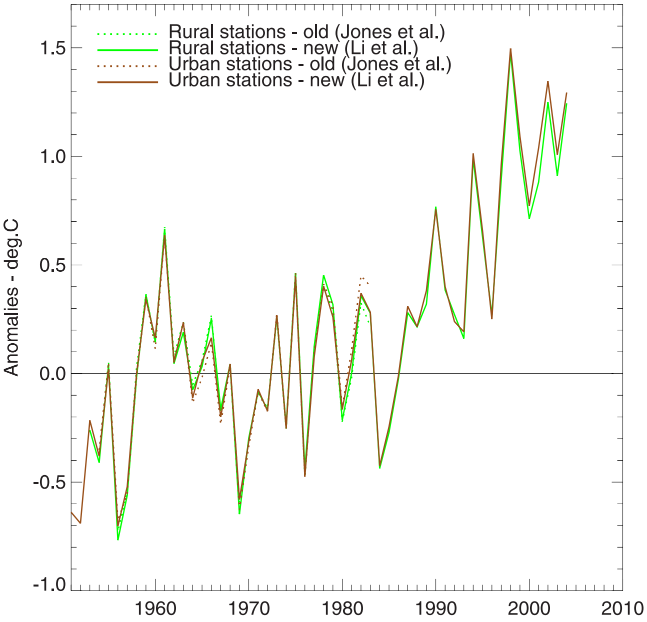

Figure 6. Annual temperature anomalies (with respect to 1954–1983) for the average of 42 rural and 42 urban sites used by *Jones et al.* [1990] and 42 rural and 40 urban sites after homogenization by *Li et al.* [2004a] and *Li and Li* [2007]. Rural averages are shown in green and urban in brown. The earlier data (which ends in 1983) are shown in dotted lines and the complete series (after homogenization) by the solid lines.

they do not remove or adjust for possible urban-related warming trends in the temperature series.

[16] An interesting way of looking at the adjustments applied by *Li et al.* [2004b] and *Li and Li* [2007] is to plot the annual adjustments as a histogram across all 243 sites that needed adjusting. Figure 5 shows that this exhibits a bi-modal distribution similar to that given by *Brohan et al.* [2006, their Figure 4] for stations around the world and by *Menne and Williams* [2008, their Figure 6] for the US Historic Climatological Network (HCN). The bi-modal distribution results from the inability of adjustment techniques to locate discontinuities near to zero (as one would expect), with the majority of adjustments being in the range ±(0.5 to 2.0°C). In all these examples of multiple station adjustments, the overall change to the "average" temperature across all sites is relatively close to zero. All three examples do show that the "average" is slightly negative, implying, as adjustments are always made relative to the latter parts of records, an adjustment that results in slight cooling of earlier records relative to those later in the record. The exception to this distribution of adjustments for land stations is biases that result from systematic changes across entire networks such as the time of observation biases in the United States [see *Karl et al.*, 1986; *Menne and Williams*, 2008]. As indicated in the latter paper, it is important to remove these biases before undertaking homogeneity adjustment.

[17] The effort involved in all three studies in the previous paragraph is considerable. Showing that the extensive adjustment procedures have little overall impact on trends averaged over large areas, therefore, warrants the question: why undertake the exercise at all? It is clearly necessary for individual sites to be homogeneity assessed and adjusted where necessary. They are likely to be needed for a whole range of studies in climatology and related sciences, all of which should be using the best (adjusted if necessary) data, and the great majority of users do not want to have to worry about homogeneity issues. As the scales increase however the overall impact of the homogeneity exercises on large-scale averages diminishes, especially when the number of stations incorporated into the average series is high. Later we will show this for a subset of the Chinese network of 728 stations. This aspect of homogeneity adjustment however *only* applies to the application of developing large-scale averages. Ideally, we would like all series to be homogeneity adjusted, so all the grid-box series were as homogeneous as possible. An excellent way of illustrating the need for local-scale homogeneity assessment is shown by *Caussinus and Mestre* [2004, their Figure 9] for France. This shows coherent and easily-contourable temperature trends for the period 1901–2000 for France after adjustment, but a pattern of abrupt spatial variations and bull's-eyes before. Thus homogeneity increases the confidence of both authors and readers in the results, at both local and larger scales.

[18] As mentioned in the Introduction, we do not consider monthly mean maximum and minimum temperature series as, in this study, we are interested in mean temperatures. As part of a global-scale analysis, *Vose et al.* [2005a] shows that for China, the diurnal temperature range (DTR, maximum minus minimum) has decreased for both periods analyzed, 1958–2004 and 1979–2004. Global land averages show a decrease in the DTR over the longer period, but for the shorter period the global land average no longer declines. The decrease in DTR likely resulted from local air pollution (sulphate aerosols in particular). When considered at large scales this has been referred to as "global dimming" [*Cohen et al.*, 2004] and is evident from the 1950s to the 1980s. This reduces solar radiation at the surface reducing maximum temperatures, so reducing DTR. Improvements in air quality in recent decades have led to no overall change in DTR, referred to as "brightening" in many areas [*Wild et al.*, 2005]. Continued decrease since 1979 in DTR across China is likely due to reduced daytime warming caused by continued high levels of air pollution from local sources limiting direct insolation reaching the surface.

3.1. Comparisons with the *Jones et al.* [1990] Analyses Over Eastern China

[19] *Jones et al.* [1990] analyzed the differences in trends between specifically selected rural station networks and the gridded land temperature products available in CRU at the time. Comparisons were carried out over western parts of the former USSR, eastern Australia and eastern China. The results showed little difference in trends between the rural and gridded regional temperature series. For China, the comparisons involved 42 station pairs (one designated "rural" and one "urban", but recall the issue discussed earlier of finding "rural" sites in China) for the period 1954–83. The decisions about the station pairs were made in 1990 attempting to choose sites with few station moves and where the then populations were mostly from small (<100 K for "rural") as opposed to the largest (>500 K for urban) Chinese cities according to the 1984

Table 3. Annual Temperature Trends in Station Area-Averaged Series for Eastern China

Series Name	Temperature Trend (°C/10 years) for the Period 1951–2004**	Temperature Trend (°C/10 years) for the Period 1954–1983	Temperature Trend (°C/10 years) for the Period 1981–2004
Li and Li - rural	**0.23**[a] actual period 1953–2004**	0.10	**0.56**[a]
Li and Li - urban	**0.25**[a]	0.10	**0.59**[a]

[a] Bold trend values indicate significance > 95% level.

population figures. It should be noted that this earlier designation of rural is different from that recently employed by *Ren et al.* [2008]. With the new 728 station data set of *Li and Li* [2007] it is possible to see what effect station moves had on the conclusions from 1990. At this point, it must be remembered that the adjustments made [*Li et al.*, 2004b; *Li and Li*, 2007] are *only* for discontinuities (site moves, observation time changes etc. known from metadata information) and not for possible urban-related trends. *Jones et al.* [1990] concluded that any possible urbanization influences were an order of magnitude smaller than the 0.5°C warming evident in global-scale averages. Such a value (0.05°) is comparable to that given by *Li et al.* [2004a] for eastern China.

[20] In the present study, it has not been possible to locate all 42 pairs within the CMA database. In this study, therefore, we use 40 of the original urban and all 42 "rural" sites. We cannot find a reason for the absence of the other two urban sites. It may be that they were not considered as their records stopped for some reason. Almost all the 728 series have records extending to the near present. In the 1990 paper, the comparison was undertaken by gridding the 42 site pairs (separately for "urban" and "rural") using the gridding technique used by CRU at the time (details in *Jones et al.* [1986a]). Here, we simplify the comparisons by just using a simple average of the stations (42 stations originally, but only 40 now for the urban set) but maintaining the urban/rural categories. Averages (without any area weighting) were calculated after first reducing each station series to anomalies from the 1954–83 period. The results are shown in Figure 6. For the 40/42 site groups (separately for urban and rural) the period covered is that used originally (1954–83), while for the updated station data the period is from 1951 until 2004. Both series are expressed as departures from the base period used in 1990 (i.e., 1954–83). The trends of the two sets of stations are listed in Table 3 for the periods 1954–83, 1951–2004 and 1981–2004. The latter period has been chosen to encompass the period of recent rapid economic development in China.

[21] Both Table 3 and Figure 6 show that there are hardly any differences between the urban/rural groups over any of the periods. This clearly indicates that the effects of the homogeneity adjustments tend to cancel when a reasonable number of stations are averaged together (here 40 and 42). This doesn't yet address the issue of whether the stations really are rural or urban, but it shows that accounting for site moves has no impact on the results given by *Jones et al.* [1990]. This result could easily have been expected from the earlier cited studies [in *Brohan et al.*, 2006; *Menne and Williams*, 2008; *Caussinus and Mestre*, 2004] which show that homogeneity adjustments tend to produce little overall change in the 'average over large spatial areas' of all the series assessed. The adjustment factors to reach this conclusion have been available for some time [*Jones et al.*, 1985, 1986b] but the bi-modal histogram (see Figure 5) way of illustrating this was first shown by *Brohan et al.* [2006]. This "cancelling" of adjustment factors has also been commented upon by *Easterling et al.* [1996].

3.2. Comparisons at the "China" Scale

[22] In this section, we compare the "China" average developed from the 728 series based on the *Li and Li* [2007] adjusted data with a "China" series developed from the CRUTEM3v land-only data set [*Brohan et al.*, 2006]. For the latter we use the 5° by 5° grid boxes within the two rectangles (40–50°N by 100–130°E and 20–40°N by 100–120°E). We choose this region to encompass most of eastern and northern China, where most of the observational stations are located. We omit the areas of western China where observations are scarce and only begin in the early 1950s. This region is also selected for two additional reasons: (1) we can extend the CRUTEM3v record back before 1950 to place the *Li and Li* [2007] series in a longer context and (2) we will later compare with a non-urban data set based on sea surface temperature (SST) data from the marine regions directly east of the Chinese landmass (also for a longer period). The choice of this particular region uses principally Chinese stations, but does bring in a few

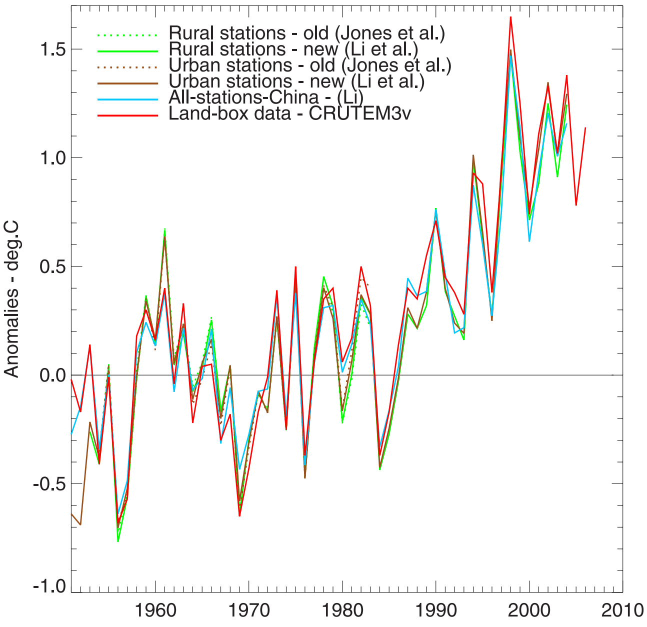

Figure 7. Annual temperature averages (as anomalies from 1954 to 1983) for the same four series as shown in Figure 6, together with the "China" series developed by *Li and Li* [2007], referred to in the text as CHINA-LI, and a China series developed from the gridded dataset, CRUTEM3v, for the region detailed in the text.

Table 4. Annual Temperature Trends in Areal-Averaged Series For Eastern China

Series Name	Temperature Trend (°C/10 years) for the Period 1951–2004	Temperature Trend (°C/10 years) for the Period 1954–1983	Temperature Trend (°C/10 years) for the Period 1981–2004
CRUTEM3v	**0.25**[a]	0.15	**0.57**[a]
Li and Li. −728	**0.22**[a]	0.12	**0.51**[a]

[a] Bold trend values indicate significance >95% level.

stations from Mongolia. The *Li and Li* [2007] database of 728 series (CHINA-LI) has been combined using the First Difference Method (FDM) introduced by *Peterson et al.* [1998]. *Vose et al.* [2005b] however have shown that the exact details of the gridding method are unimportant for large spatial scales.

[23] Figure 7 shows the two series (CHINA-LI, CRUTEM3v) as annual averages for the 1951–2004 period together with the original rural and urban networks of 42 sites [from *Jones et al.*, 1990] and the updated (and homogenized) site network from *Li and Li* [2007]. As the original (1990) network only extends over the period from 1954–1983, this plot uses the 1954–83 base period. As can be clearly seen, there are hardly any differences between the six series over their respective overlaps. This indicates that for a region of this size, the average can be constructed from a limited number of sites, implying that for the 728 station network there is considerable redundancy if the sole intention had been to develop an average series at the annual timescale. Table 4 shows trends for the two series for the same three periods used in Table 3. Over the three periods the trends from the three data sets (CHINA-LI, CRUTEM3v and the 42-station subsets) are essentially the same.

3.3. Comparisons with SST Data

[24] As it is difficult to develop a network of specifically rural sites in China, we now compare the CHINA-LI and CRUTEM3v series with one based on HadSST2 [*Rayner et al.*, 2006] for the region (20–45°N by 110–125°E) to the east of China. The HadSST2-based series extends back to the 19th century, but we show it here from 1901. The use of an SST series as a rural surrogate is very much an inferior choice to the more normal designation of a specifically-selected rural network. We would expect, a priori, the land series to warm more than the SST and if it were urban related we'd expect the warming to be gradual. We would also expect SST warming to be delayed compared to the land, because of the much greater thermal capacity of the coastal seas.

[25] Figure 8 shows the three series (CHINA-LI/CRUTEM3v, from 1951/1901 and HadSST2 from 1901) for the four climatological seasons and annual, together with smoothed series from a 10-year Gaussian data-adaptive filter. For this plot we are able to use the 1961–90 base period commonly used as a reference period. In the following discussion, readers should be mindful of the fact that temperatures for all curves have to average to zero for the 1961–90 period. Table 5 gives the trends of the series over the same three periods as earlier (1954–83, 1951–2004 and 1981–2004). Both land-based series warm relative to the SST series, but not as would be expected if increasing urban-related warming were the cause (e.g., for the post-1980 period of rapid economic growth the SSTs are warming faster, but the difference isn't statistically significant). The major warming of the land data relative to the SST occurs during a short period in the mid-1970s particularly evident during winter and to a lesser extent in spring and autumn. For summer, there is hardly any difference and no jump in the mid-1970s. Urban-related warming comparing the land series with HadSST2 for the longest period (1951–2004 and using annual averages) would imply a value between 0.08 and 0.11°C decade^{-1}, a value very similar to that derived by *Ren et al.* [2008] for the smaller area of northern China.

[26] CRUTEM3v and HadSST2 are less reliable (due to fewer stations over the land and sparser coverage from ships) before 1950. No trends have been calculated over this period, but the series are shown to consider SST/land trends and lags over a longer period. These two series show that in periods of relative warming, SST increases lag the land. The timing of the lag seems similar between the seasons, but a case could be made that the lag is greater during winter. As with the apparent divergence in the mid-1970s an earlier divergence of land warming relative to the marine data occurs in the late-1910s in spring and autumn and to a lesser extent in summer and winter. For all four series, the marine region warms relative to the land during the 1940s.

[27] Why are the apparent urban-related warming trends in the land records relatively small and not of the characteristic gradual increase that might be expected? The homogeneity adjustments cannot have removed some of the urban-related effects, as the raw temperature series have little difference from the homogeneity-adjusted data, when they are area-averaged. Second, it is important to bear in mind possible circulation influences. The dramatic change in the mid-1970s may be related to the 1976/77 climate shift noted by many authors [see, e.g., *Trenberth and Hurrell*, 1994]. The use of SST as a rural surrogate is probably only useful at the annual timescale and little emphasis should be placed on differences in seasonal trends between land and SST. Thirdly, in some larger Chinese cities, urban-related warming (leading to a UHI) may have occurred earlier than the period we are considering.

[28] In summary, the various China terrestrial series when compared with SST do show relative warming of the land series, but in periods of strong warming this would be expected, because of the markedly greater thermal inertia of the oceans. The character of the difference series is not a gradual warming but is abrupt and mostly occurs in the mid-1970s and the annual SST series warms (albeit slightly) compared to both China terrestrial series over the 1981–2004 period of rapid economic growth and development. Despite the above, trends using annual averages between 1951 and 2004 give an urban related warming between 0.08 and 0.11°C decade^{-1}. Over the period 1951–2004 (assuming an urban-related warming of 0.1°C decade^{-1}) this still leaves a warming over China (using CRUTEM3v) of

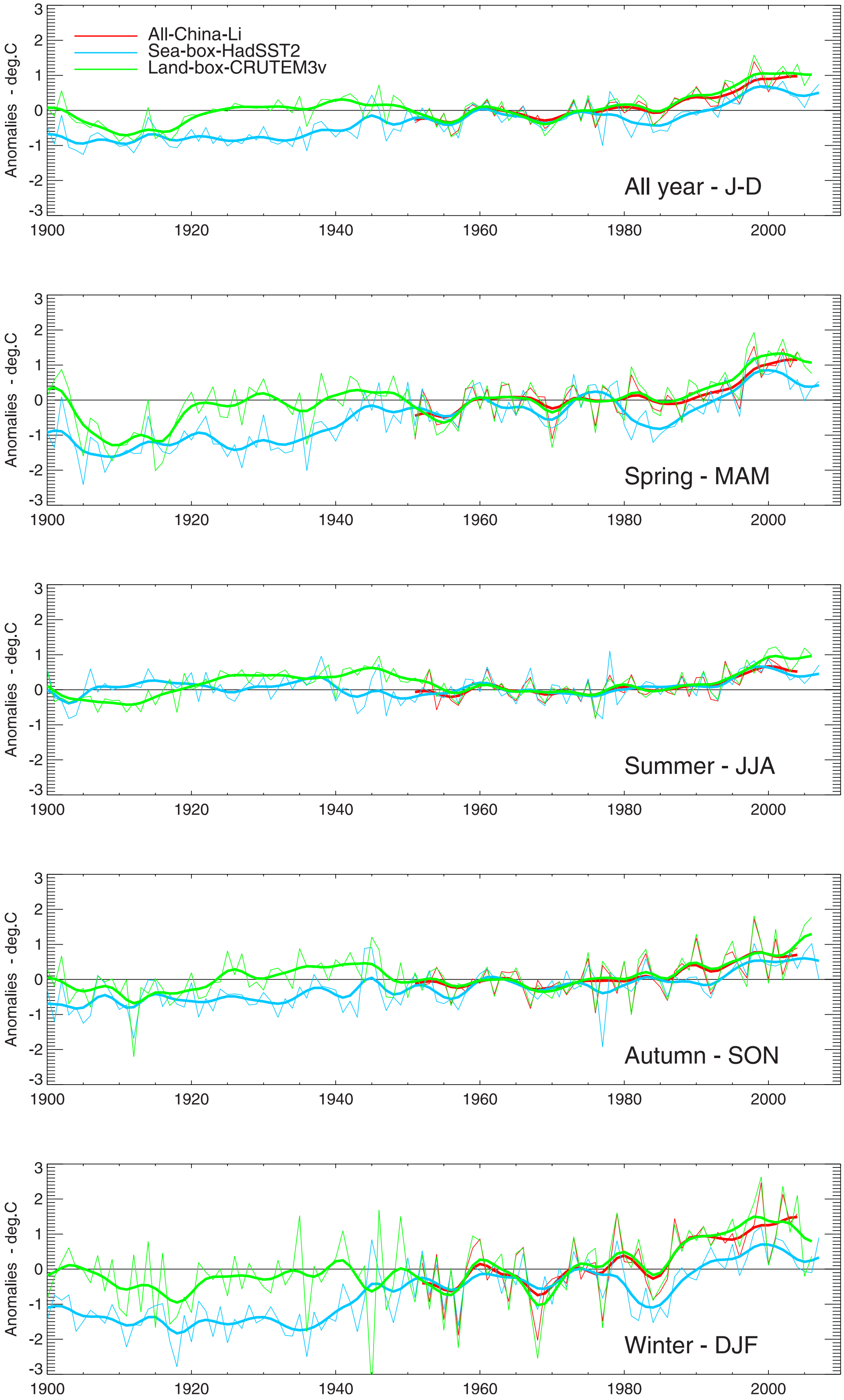

Figure 8. Annual and seasonal temperature averages (as anomalies from 1961 to 1990) for three series: CHINA-LI (red) and the gridded datasets (CRUTEM3v, green and HadSST2, blue). The regions used from the gridded products are given in the text.

Table 5. Annual and Seasonal Temperature Trends for Areal-Averaged Series (Including An SST Series) For Eastern China

Series Name	Temperature Trend (°C/10 years) for the Period 1951–2004					Temperature Trend (°C/10 years) for the Period 1954–1983					Temperature Trend (°C/10 years) for the Period 1981–2004				
	Yr	MAM	JJA	SON	DJF	Yr	MAM	JJA	SON	DJF	Yr	MAM	JJA	SON	DJF
CRUTEM3v	**0.25**[a]	**0.29**[a]	**0.13**[a]	**0.17**[a]	**0.42**[a]	0.15	0.21	0.02	0.09	0.27	**0.57**[a]	**0.64**[a]	**0.47**[a]	**0.38**[a]	**0.81**[a]
Li and Li -728	**0.22**[a]	**0.22**[a]	**0.11**[a]	**0.17**[a]	**0.37**[a]	0.12	0.16	0.05	0.06	0.20	**0.51**[a]	0.57	**0.31**[a]	**0.43**[a]	**0.74**[a]
HadSST2	**0.14**[a]	0.15	**0.11**[a]	**0.13**[a]	0.16	0.02	0.03	−0.01	0.11	−0.03	**0.60**[a]	**0.89**[a]	0.26	**0.32**[a]	**0.92**[a]

[a] Bold trend values indicate significance >95% level.

0.81°C over this period and 1.13°C between 1981 and 2004. The first number (see Figure 7 and Table 5) is slightly more than *Ren et al.* [2008] whose trend is less because of the warm years in the early 1960s. The agreement of the urban-related warming trends reinforces the *Ren et al.* [2008] study.

[29] An urban-related warming trend of 0.1°C decade^{-1} is almost an order of magnitude larger than that given by *Jones et al.* [1990] and *Li et al.* [2004b]. Possible reasons for the differences include: (1) different periods of analysis (e.g., 1954–1983 for *Jones et al.* [1990] versus the longer period from 1951–2004 used in this paper and 1961–2000 in *Ren et al.* [2008]) and (2) different regions of China (eastern in *Jones et al.* [1990], northern in *Ren et al.* [2008] and all except the far west in this study). The differences in periods are potentially the more important. Splitting the *Ren et al.* [2008] analysis into two halves (1961–80 and 1981–2000 and using the panels in their Figure 3) gives an urban-related warming trends of 0.06 and 0.14°C decade^{-1} respectively, highlighting that this component of the trend is greater in the last two decades. Despite the differences in urban-related warming estimates and assuming the larger estimate is correct, the remaining climatic warming (in CRUTEM3v) is 60% of the measured warming over 1951–2004 and 82% over 1981–2004.

3.4. Comparisons with ERA-40 Reanalyses

[30] Two studies [*Kalnay and Cai*, 2003; *Zhou et al.*, 2004] have compared the National Centers for Environmental Prediction (NCEP) Reanalyses with "raw" (i.e., as measured) surface temperatures over the eastern half of the United States and southern China respectively. They attempted to show from the comparisons, that observed surface temperature data are affected by land-use/land-cover changes (including urbanization). The former study has been extensively criticized for a number of reasons (e.g., use of unadjusted surface temperature data and NCEP Reanalyses not considering changes in forcing of the climate system from both anthropogenic and natural sources over the period of analyses, see, e.g., *Vose et al.* [2004] and *Trenberth* [2004] and these same criticisms are also implicit with the *Zhou et al.* [2004] study. In a later study, *Simmons et al.* [2004] compared the earlier CRU analysis [CRUTEM2v, *Jones and Moberg*, 2003] with the ERA-40 Reanalysis [*Uppala et al.*, 2005] for hemispheric averages and a number of large continental areas (Europe, North America and Australia). ERA-40 is a second generation Reanalysis [*Santer et al.*, 2004] that uses both improved and more satellite data as well as measured surface temperature/humidity. Observed surface temperature and humidity are not assimilated in the same way as upper air measurements and surface pressure. Instead, surface temperature and humidity do not affect atmospheric fields at model levels, but influence the background forecast (at 2m) for the next analysis, through adjustments to the model's soil temperature and moisture fields [*Simmons et al.*, 2004]. *Santer et al.* [2004] show that for a number of tropospheric metrics that ERA-40 is markedly superior to NCEP. The improvements stem from learning from mistakes made in the NCEP Reanalyses, but also from the use of more satellite and surface data [see *Simmons et al.*, 2004].

[31] Here we compare the results (Figure 9) for our defined "China" region (40–50°N by 100–130°E and 20–40°N by 100–120°E) against CRUTEM3v. As in *Simmons et al.* [2004], we plot the series with respect to 1987–2001, the period for which ERA-40 is believed to be best. Trends over the period 1958/79–2001 are given in Table 6. There is little difference between the trends over the period since 1979. Since 1958, CRUTEM3v warms more, but no more than expected from the other regions for reasons discussed earlier by *Simmons et al.* [2004]. We can also infer from *Simmons et al.* [2004] that the NCEP Reanalyses would also warm by a similar amount to CRUTEM3v over the 1979–2001 period.

4. Conclusions

[32] In this paper we have considered two different and clearly distinct issues: the size of possible UHIs in two European cities and the possible influence from urban-

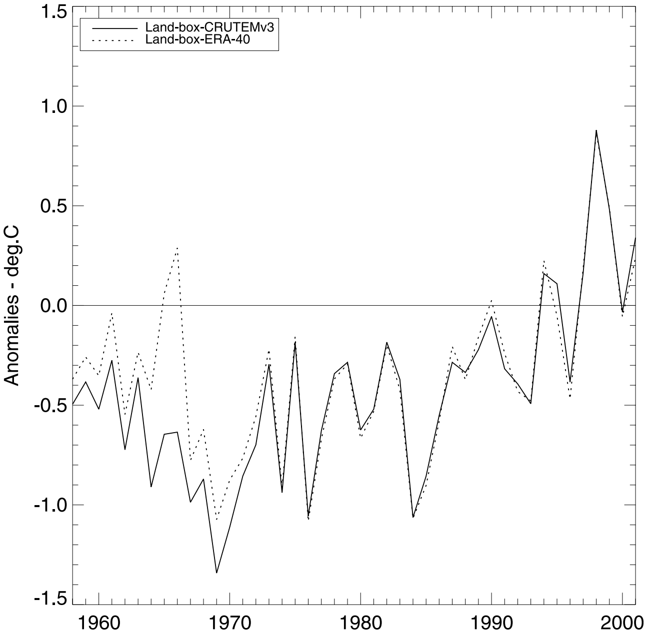

Figure 9. Annual temperature averages (as anomalies from 1987 to 2001) for CRUTEM3v (solid) and for ERA-40 (dotted). The regions used from the two gridded datasets are the same and details are given in the text.

Table 6. Annual Temperature Trends – Area-Averaged and Reanalysis Series for Eastern China

Series Name	Temperature Trend (°C/10 years) for the Period 1958–2001	Temperature Trend (°C/10 years) for the Period 1979–2001
CRUTEM3v	**0.21**[a]	0.44
ERA-40	0.12	0.43

[a] Bold trend values indicate significance >95% level.

related factors in large-scale temperature trends. With the first issue, there is a clear UHI influence in temperature records from centrally-located sites in London and Vienna of 1.5° and 0.3°C, respectively. The effect of this excess warmth (due to the city being there) however is irrelevant to temperature trends, for the periods studied. With data expressed as anomalies from 1961 to 90, trends for the city center and rural locations are very similar, so in this form the anomalies can be used in gridded temperature products (such as CRUTEM3v). These results only apply to these two cities, and clearly any effect on other cities can only be judged through similar analyses comparing city center and rural temperature time series.

[33] In the main part of the paper, we assessed the effect of the second of the two issues on temperature records from China. We first compared recently homogenized temperature series [from *Li and Li*, 2007] with earlier work undertaken by *Jones et al.* [1990] and showed that the homogeneity assessments have no impact on average 'Eastern Chinese' temperature series developed from the 42 sites used in 1990 (see Figure 6). We then compared two "China" averages [CHINA-LI from *Li and Li*, 2007, and from the gridded data, CRUTEM3v, *Brohan et al.*, 2006]. All series essentially show the same trends and interannual variability. We conclude from this that when sufficient temperature series are averaged over a relatively large area, the effect of homogeneity adjustments is negligible (see Figure 7). We caution that such a conclusion is only relevant for this one application. In order to produce detailed spatial patterns of temperature change (and almost all other possible applications) it is essential to adjust, where necessary, station temperature series for homogeneity.

[34] Finally, we assessed the Chinese data for the second issue (possible urban-related warming). This is difficult in China, as there are few specifically designated rural sites. Instead, we used SST data from the seas to the east of China, as we can guarantee that these data are unaffected by urban-related warming. We admit that SST is a poor surrogate for a "rural" network and, a priori, expect the land data sets to warm with respect to the SST series. We show trends of temperature by season for three different periods (1951–2004, 1954–1983 and 1981–2004). The two land series do warm relative to the SST over the periods from 1951 and 1954, but this mostly occurs during the mid-1970s. Over the most recent period (1981–2004), when economic development and growth have been most rapid, the SST series warms very slightly relative to the two "China" land series. Taking the annual data for the longest period (1951–2004) implies a relative warming of the land relative to the SST series of about 0.1°C decade^{-1} in agreement with the recent *Ren et al.* [2008] study. Allowing for this urban-related warming component (in CRUTEM3v) still leaves a warming over China of 0.81°C over the 1951–2004 period and 1.13°C between 1981 and 2004.

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References

Böhm, R. (1998), Urban bias in temperature series — A case study for the city of Vienna, *Clim Change*, *38*, 113–128.

Brohan, P., J. Kennedy, I. Harris, S. F. B. Tett, and P. D. Jones (2006), Uncertainty estimates in regional and global observed temperature changes: A new dataset from 1850, *J. Geophys. Res.*, *111*, D12106, doi:10.1029/2005JD006548.

Caussinus, H., and O. Mestre (2004), Detection and correction of artificial shifts in climate series, *Appl Stat*, *53*, 405–425.

Central Meteorological Bureau and Academica Sinica (1952), Rainfall and temperature data in China, report, Institute of Geophysical Research, Beijing.

Cohen, S., B. Liepert, and G. Stanhill (2004), Global dimming comes of age, *Eos, Trans. Am. Geophys. Union*, *85*, 362.

Easterling, D. R., and T. C. Peterson (1995), A new method for detecting and adjusting undocumented discontinuities in climatological time series, *Int. J. Climatol.*, *15*, 369–377.

Easterling, D. R., T. C. Peterson, and T. R. Karl (1996), On the development and use of homogenized climate datasets, *J. Clim.*, *9*, 1429–1434.

Gaffin, S. R., C. Rosenzweig, R. Khanbilvardi, L. Parshall, S. Mahani, H. Glickman, R. Goldberg, R. Blake, R. B. Slosberg, and D. Hillel (2008), Variations in New York city's urban heat island strength over time and space, *Theor. Appl. Climatol*, doi:10.1007/s00704-007-0368-3.

He, J. F., J. Y. Liu, D. F. Zhuang, W. Zhang, and M. L. Liu (2007), Assessing the effect of land use/land cover change on the change of urban heat island intensity, *Theor. Appl. Climatol.*, *90*, 217–226.

Howard, L. (1833), *The climate of London: deduced from meteorological observations made in the metropolis and at various places around it*, edited by J. Harvey and Darton and A. Arch, Longman, Hatchard, S. Highley and R. Hunter, London.

Jones, P. D., and A. Moberg (2003), Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001, *J. Clim.*, *16*, 206–223.

Jones, P. D., S. C. B. Raper, B. D. Santer, B. S. G. Cherry, C. M. Goodess, P. M. Kelly, T. M. L. Wigley, R. S. Bradley, and H. F. Diaz (1985), A Grid Point Surface Air Temperature Data Set for the Northern Hemisphere, U.S. Dept. of Energy, Carbon Dioxide Research Division, *Technical Report TRO22*, 251 pp.

Jones, P. D., S. C. B. Raper, R. S. Bradley, H. F. Diaz, P. M. Kelly, and T. M. L. Wigley (1986a), Northern Hemisphere surface air temperature variations: 1851–1984, *J. Clim. Appl. Meteorol.*, *25*, 161–179.

Jones, P. D., S. C. B. Raper, B. S. G. Cherry, C. M. Goodess and T. M. L. Wigley (1986b), A Grid Point Surface Air Temperature Data Set for the Southern Hemisphere, 1851–1984, U.S. Dept. of Energy, Carbon Dioxide Research Division, *Technical Report TR027*, 73 pp.

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

Kalnay, E., and M. Cai (2003), Impact of urbanization and land-use change on climate, *Nature*, *423*, 528–531.

Karl, T. R., C. N. Williams Jr., P. J. Young, and W. M. Wendland (1986), A model to estimate the time of observation bias associated with monthly mean maximum, minimum and mean temperature for the United States, *J. Appl. Meteorol.*, *25*, 145–160.

Li, Q., A. Zhang, X. Liu, and J. Huang (2004a), Urban heat island effect on annual mean temperature during the last 50 years in China, *Theor. Appl. Climatol.*, *79*, 165–174.

Li, Q., X. Liu, H. Zhang, T. C. Peterson, and D. R. Easterling (2004b), Detecting and adjusting temporal inhomogeneity in Chinese mean surface air temperature data, *Adv. Atmos. Sci.*, *21*, 260–268.

Li, Q., and W. Li (2007), Development of the gridded historic temperature dataset over China during recent half century, *Acta Met. Sinica*, *65*, 293–299, (In Chinese).

Menne, M. J., and C. N. Williams Jr. (2008), Homogenization of temperature series via pairwise comparisons, *J. Clim.*, in press.

Oke, T. R. (2004), *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites*, Instruments and Methods of Observation Program, IOM Report No. 81, WMO/TD 1250, World Meteorological Organization, Geneva.

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

Parker, D. E. (2006), A demonstration that large-scale warming is not urban, *J. Clim.*, *19*, 2882–2895.

Parker, D. E., T. P. Legg, and C. K. Folland (1992), A new daily Central England temperature series, 1772–1991, *Int. J. Climatol.*, *12*, 317–342.

Peterson, T. C., and D. R. Easterling (1994), Creation of homogeneous composite climatological reference series, *Int. J. Climatol.*, *14*, 671–679.

Peterson, T. C. (2003), Assessment of urban versus rural in situ surface temperatures in the contiguous United States: no difference found, *J. Clim.*, *16*, 2941–2959.

Peterson, T. C., and T. W. Owen (2005), Urban heat island assessment: Metadata are important, *J. Clim.*, *18*, 2637–2646.

Peterson, T. C., T. R. Karl, P. F. Jamason, R. Knight, and D. R. Easterling (1998), The first difference method: Maximizing station density for the calculation of long-term global temperature change, *J. Geophys. Res.*, *103*, 25,967–25,974.

Portman, D. A. (1993), Identifying and correcting urban biases in regional time series: Surface temperature in China's Northern Plains, *J. Clim.*, *6*, 2298–2308.

Rayner, N. A., et al. (2006), Improved analyses of changes and uncertainties in sea surface temperature measured in situ since the mid-nineteenth century: the HadSST2 dataset, *J. Clim.*, *19*, 446–469.

Ren, G. Y., Z. Y. Chu, Z. H. Chen, and Y. Y. Ren (2007), Implications of temporal change in urban heat island intensity observed at Beijing and Wuhan stations, *Geophys. Res. Lett.*, *34*, L05711, doi:10.1029/2006GL027927.

Ren, G. Y., Y. Zhou, Z. Chu, J. Zhou, A. Zhang, J. Guo, and X. Liu (2008), Urbanization effects on observed surface air temperature trends in North China, *J. Clim.*, *21*, 1333–1348.

Santer, B. D., et al. (2004), Identification of anthropogenic climate change using a second-generation reanalysis, *J. Geophys. Res.*, *109*, D21104, doi:10.1029/2004JD005075.

Simmons, A. J., P. D. Jones, V. da Costa Bechtold, A. C. M. Beljaars, P. W. Kållberg, S. Saarinen, S. M. Uppala, P. Viterbo, and N. Wedi (2004), Comparison of trends and low-frequency variability in CRU, ERA-40 and NCEP/NCAR analyses of surface air temperature, *J. Geophys. Res.*, *109*, D24115, doi:10.1029/2004JD006306.

Trenberth, K. E. (2004), Rural land-use change and climate, *Nature*, *427*, 213.

Trenberth, K. E., and J. W. Hurrell (1994), Decadal atmosphere-ocean variations in the Pacific, *Clim. Dyn.*, *9*, 303–319.

Uppala, S. M., et al. (2005), The ERA-40 reanalysis, *Q. J. R. Meteorol. Soc.*, *131*, 2961–3012.

Vose, R. S., et al. (2004), Impact of land-use change on climate, *Nature*, *427*, 213–214.

Vose, R. S., D. R. Easterling, and B. Gleason (2005a), Maximum and minimum temperature trends for the globe: An update through 2004, *Geophys. Res. Lett.*, *32*, L23822, doi:10.1029/2004GL024379.

Vose, R. S., D. Wuertz, T. C. Peterson, and P. D. Jones (2005b), An intercomparison of trends in surface air temperature analyses at the global, hemispheric and grid-box scale, *Geophys. Res. Lett.*, *32*, L18718, doi:10.1029/2005GL023502.

Wang, W.-C., A. Zeng, and T. R. Karl (1990), Urban Heat Islands in China, *Geophys. Res. Lett.*, *17*, 2377–2380.

Wilby, R. L. (2003), Past and projected trends in London's urban heat island, *Weather*, *58*, 251–260.

Wild, M., H. Gilgen, A. Roesch, A. Ohmura, C. N. Long, E. G. Dutton, B. Forgan, A. Kallis, V. Russak, and A. Tsvetkov (2005), From dimming to brightening: Decadal changes in solar radiation at Earth's surface, *Science*, *308*, 847–850.

Yan, Z., C. Yang, and P. D. Jones (2001), Influence of inhomogeneity on the estimation of mean and extreme temperature trends in Beijing and Shanghai, *Adv. Atmos. Sci.*, *18*, 309–322.

Zhou, L. M., R. E. Dickinson, Y. H. Tian, J. Y. Fang, Q. X. Li, and R. K. Kaufmann (2004), Evidence for a significant urbanization effect on climate in China, *Proc. Natl. Acad. Sci. U.S.A.*, *101*, 9540–9544.

P. D. Jones and D. H. Lister, Climatic Research Unit, University of East Anglia, Norwich NR4 7TJ, UK. (p.jones@uea.ac.uk)

Q. Li, National Meteorological Information Center, China Meteorological Administration, Beijing 100081, China.