ATMOSPHERIC SCIENCE LETTERS
Atmos. Sci. Let. (2011)
Published online in Wiley Online Library
(wileyonlinelibrary.com) **DOI:** 10.1002/asl.350

Centennial scale warming over Japan: are the rural stations really rural?

L. Das,[1,2]*† J. D. Annan,[1] J. C. Hargreaves[1] and S. Emori[3]
[1] *RIGC/JAMSTEC, 3173-25 Showamachi, Kanazawa-ku Yokohama City, Kanagawa 236-0001, Japan*
[2] *Department of Agricultural Meteorology and Physics, BCKV, Mohanpur, Nadia 741-252, India*
[3] *National Institutes for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan*

**Correspondence to: L. Das, Research Institute for Global Change, JAMSTEC, GCPRP-IPCC, 3173-25 Showamachi, Kanazawa-ku, Yokohama City, Kanazawa-ku 236-0001, Japan. E-mail: daslalu@yahoo.co.in; daslalu@jamstec.go.jp*

† Present address: Department of Agricultural Meteorology and Physics, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, Pin 741 252, India.

Received: 9 November 2010
Revised: 13 April 2011
Accepted: 3 May 2011

Abstract

In this study, we used two novel methods to estimate urban contamination in the Japanese temperature record of the last century. First, we tested different criteria for choosing the rural stations, and found little sensitivity to the method, though the presence of a decreasing local population trend appeared to be a useful indicator. Second, we investigated the relationship between the regional sea surface temperature (SST) and surface air temperature over land, and found a very strong relationship across the coupled model intercomparison project phase 3 multi-model ensemble. Applying this relationship to observational SST data indicates little or no contamination of the trends from the stations identified as rural.

Keywords: **urban heat island; global warming; CMIP3**

1. Introduction

The recent report of the Intergovernmental Panel on Climate Change (IPCC, 2007) has stated that the warming in the climate system is unequivocal, with an increase in global mean temperature of 0.74 °C during 1906–2005. The amount of warming varies over the globe. Urban areas generally have a warm bias relative to the surrounding rural region, termed the urban heat island effect. Thus the trend calculated from met station data may have a warming bias due to increasing urbanisation (Kukla *et al*., 1986; Ren *et al*., 2008; Parker *et al*., 2010). Accurate estimation of the urban influence on the long-term trend is a challenging task, particularly in densely populated, highly developed countries such as Japan, as it is difficult to find stations that are not influenced by urbanisation. Several US-based studies (i.e., Peterson, 2003; Peterson and Owen, 2005; Parker, 2006; Stone, 2007) found only a small urban bias in their analysis, but significant urban bias (∼0.11 °C/decade) was reported in north and northeast China, mostly after the 1950s (Jones *et al*., 2008; Ren *et al*., 2008). A series of studies over Japan (Fujibe, 1995, 2009, 2011 and references therein; Kato, 1996; JMA, 2009) based on temperature and population data focused on how to effectively detect and quantitatively estimate the urban bias in the trends of the last few decades to centennial scale. Although none of the studies in Japan looked for evidence of residual urban bias in the stations that were classified as rural, it was found that the warming rate across Japan varied widely, from 0.35 to 2.95 °C/century (Schaefer and Domroes, 2009) during 1901–2000. The average trend for all 60 Japanese stations is 1.41 °C during 1900–1999. This value is higher than many of the estimates of mean average warming that have been made for other countries: for example, the United States (∼0.4 °C/century, Knappenberger *et al*., 2001), United Kingdom (0.64–0.77 °C during 1861–2000, http://www.metoffice.gov.uk/climate/uk/about/UK_climate_trends.pdf), Spanish Mediterranean (0.9 °C for the period 1870–1996, Quereda Sala *et al*., 2000), and rapidly developing countries like India (∼0.7 °C/century, Dash *et al*., 2007) and North China (1.16 °C during 1961–2000, Ren *et al*., 2008).

Urban bias on the country scale is normally estimated through the difference in regionally averaged warming between urban and rural sites, so it is important that the urban and rural stations are classified correctly. There is, however, no robust method which selects rural stations with a high level of confidence to eliminate urban influence completely. For monitoring background warming in Japan, the Japan Meteorological Agency (JMA) selected 17 rural stations, hereafter denoted by 17_JMA, that were considered to have not been highly influenced by urbanisation

(JMA, 2009). The average warming of these stations was 1.13 °C during 1898–2009, still relatively high compared to global warming and it has been suspected that these 17 stations, some of which have population over 100 000, were not entirely free from the influence of urbanisation (Fujibe, 2009). In this study, we consider alternative methods for choosing rural stations and compare the chosen stations to 17_JMA. We also present possibly the first independent attempt to objectively quantify the extent of the residual urban bias in the rural set of 17_JMA. This estimate is formed by analysing the current generation climate model simulations which contributed to the World Climate Research Programme's coupled model intercomparison project phase 3 (CMIP3) together with observations of warming of the neighbouring ocean region, which is explained in more detail in Section 4. In addition, using this ensemble as a baseline, an estimate is made of the urban contamination in the highly populated metropolitan cities and rapidly growing suburban cities.

2. Data and models

The mean annual air temperature, from 1900 to 1999, for the synoptic stations of JMA (http://www.data.jma.go.jp/obd/stats/data/en/smp/index.html) was analysed. The JMA quality control procedure produces three categories of stations: reliable; 'quasi-reliable', missing a few values; and incomplete, missing many values. Here, data from the 60 stations of the first two types were used. For the quasi-reliable data, the missing values were replaced by the mean of 10-year data centred on the missing points (previous 5 years and following 5 years). In general, the observational data have not been adjusted for homogeneity and therefore may exhibit small changes due to changes of sites (Kato, 1996), changes in observational practice, or in the instrumentation (Fujibe, 1995). Yue and Hashino (2003) found insignificant changes in the homogeneity by analysing long-term annual, seasonal and monthly temperature records of JMA. The population data of each station for the years 1995, 2000, 2005 and 2008, taken from the Japanese national census, and compiled by the Statistics Bureau of Japan were obtained via the URL: http://www.citypopulation.de/Japan.html.

The monthly mean global SST from 1900 to 1999 with $1 \times 1°$ horizontal resolution archived as COBE-SST by JMA (Ishii *et al.*, 2005) were considered over a domain extending 25–50 °N and 120–150 °E. A significant abrupt drop (∼0.3 °C) of global SST in 1945 is the apparent result of uncorrected instrumental biases (Thompson *et al.*, 2008), but a similar drop is not found in the regional scale analysis of SST in the surrounding ocean over Japan, possibly because of larger year-to-year variation than that of global average or perhaps inhomogeneity in observing practices. The '20th century climate simulations' (20C3M) were analysed for 19 CMIP3 models.

3. Selecting rural and urban stations

Since 1996, JMA has been issued an annual Climate Change Monitoring Report (CCMR). According to the report published in 2003 (CCMR2003), JMA has been using 17 rural stations (known as 17_JMA, Table I) since 2001 to monitor Japan climate change. The present study considered those 17 stations as one of the rural set which is considered to be free from urbanisation effect. The second set of rural stations was selected through a subjective identification using Google Maps' satellite images. This selection was made purely visually by two researchers (authors J. D. A and J. C. H) who did not have the knowledge of the temperature changes at the stations, selecting for stations with evidence of countryside, agriculture or water, and general lack of nearby buildings. This resulted in the identification of 12 rural stations, hereafter referred to as '12_SAT' (Table I).

A third set of rural stations was classified according to population data from the last four censuses. First, as shown in Figure 1, depending on the mean population, the 60 meteorological stations were classified into three distinct categories (a) megacities (population >1 000 000), (b) suburban cities (population >200 000 and <1 000 000) and (c) rural cities/towns (population <200 000). There are 9 megacities with population of more than 1 million and long-term temperature data since 1900, while 18 stations have a mean population of less than 200 000, which seems to be good candidate for rural stations. Second, we considered the population trend calculated from the city population data of last four censuses, as a decreasing trend should in principle also indicate a site with little urbanisation. However, it must be noted that our population data only covers the last part of period of interest and cannot inform on earlier changes. Of the 15 stations, with a mean population of below 200 000 and a decreasing trend, one station, Obihiro, was highlighted by Fujibe (2011) as an ideal example of a site that has changed drastically from uncultivated fields, with a small number of inhabitants at the early stage of the 20th century, to a medium size city later in the century, and suggests, therefore, that the large temperature increase at this site contains an urban bias. So we exclude Obihiro from the rural stations, leaving 14 stations, which we refer to as '14_OUR' (Table I). In this paper, we finally define the suburban city (SUC) to be the 37 stations with population less than 1 000 000 that are not included in the 14_OUR stations. Figure 1 also shows that roughly half of the 37 semi-urban cities have increased in population whereas the other half have decreased in population in the last four censuses. On the other hand, almost all megacities (MC; Table I) show increasing trend of

Table I. List of stations selected for different categories indicated by √.

Station name	Latitude	Longitude	MC	17_JMA	14_OUR	12_SAT
Abashiri	44.02	144.28		√	√	
Sapporo	43.06	141.33	√			
Nemuro	43.33	145.59		√	√	
Suttsu	42.8	140.22		√	√	√
Miyako	39.65	141.97			√	√
Yamagata	38.26	140.35		√		
Ishinomaki	38.43	141.3		√	√	√
Fushiki	36.79	137.06		√	√	
Nagano	36.66	138.19		√		
Utsunomiya	36.55	139.17				√
Takayama	36.16	137.25			√	√
Matsumoto	36.25	137.97				√
Mito	36.38	140.47		√		
Nagoya	35.17	136.97	√			
Iida	35.52	137.82		√	√	
Choshi	35.74	140.86		√	√	
Tokyo	35.69	139.76	√			
Yokohama	35.44	139.65	√			
Sakai	35.54	133.24		√	√	
Hamada	34.9	132.07		√	√	√√
Kyoto	35.02	135.73	√			
Hikone	35.28	136.24		√		√
Hiroshima	34.4	132.46	√			
Kure	34.24	132.55				√
Kobe	34.7	135.21	√			
Osaka	34.68	135.52	√			
Izuhara	34.2	129.29			√	√
Fukuoka	33.58	130.38	√			
Saga	33.27	130.31				√
Miyazaki	31.94	131.41		√		
Tadotsu	34.28	133.75		√	√	
Naze	28.38	129.5		√	√	√
Ishigakijima	24.34	124.16		√		

MC, population-based 9 megacities; 17_JMA, JMA's 17 rural stations; 14_OUR, population-based 14 rural stations; 12_SAT, satellite pictures-based 12 rural stations.

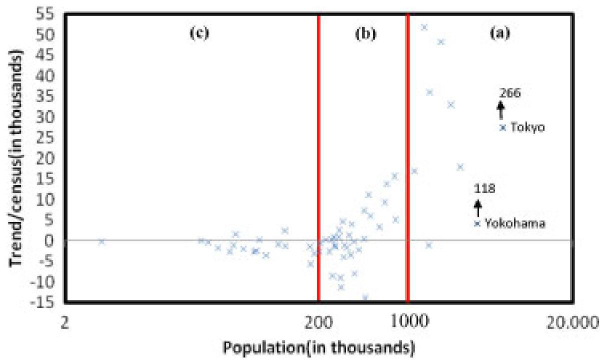

Figure 1. The mean population and population change during 1995–2008 from the Japanese census data. The red lines indicate a general categorisation into (a) megacities, (b) suburban cities and (c) rural stations. Tokyo and Yokohama have very large population changing trends and so are displayed in reduced *y*-axis scale with the actual values of their population trend being written on the plot.

Table II. Linear trends in annual mean temperature for different categories of Japanese cities during 1900–1999.

Sl. no.	Category	Trend (°C/century)
1	MC	1.99
2	SUC	1.43
3	MPSC	1.54
4	17_JMA	1.02
5	14_OUR	0.98
6	12_SAT	1.12
7	COBE_SST	0.80
8	60_JAPAN	1.41

MC, set of 9 megacities; SUC, set of 37 suburban cities; MPSC, set of 46 mega plus suburban cities; 17_JMA, set of JMA selected 17 rural stations; 14_OUR, set of authors selected 14 rural stations on the basis of city population; 12_SAT, set of authors selected 12 rural stations on the basis of Google Maps satellite images; COBE_SST, observed SST archived as COBE-SST by JMA; 60_JAPAN, set of the 60 meteorological stations over Japan.
Trends are significant at the 95% level.

population with only Kyoto showing a slight decline (Figure 1).

The average warming for each category is given in Table II. Even for the rural stations, the average warming (0.98–1.08 °C for the three sets) is rather high compared to studies in some other countries (Section 1). What is not known is the extent to which this observed warming in Japan may be due to residual urban effects remaining in the rural stations, or whether Japan has in fact experienced relatively large underlying warming compared to other regions. We now consider this in more detail in the following section.

4. Effects of urbanisation in the observed trends

The difference between urban and rural trends may, on the assumption that the stations classified as rural have no remaining urban contamination, be considered a measure of urbanisation effect in the urban areas, and can be estimated from Table II. For example, the urban contamination of the warming trends for the nine megacities, estimated assuming the rural stations represent the underlying warming, are 0.97 °C/century, 1.01 °C/century and 0.91 °C/century for 17_JMA, 14_OUR and 12_SAT, respectively. These results are consistent with Jones *et al*. (2008) who estimated urban-related warming in China in the range of 0.08–0.11 °C/decade, although they used a relatively shorter time period (1951–2004) compared with our longer time span of 100 years. But the estimated bias over Japan is higher than estimated in US cities (0.05 °C/decade during 1951–2000; Stone, 2007).

These calculations, however, depend heavily on the assumption that the rural stations are not themselves contaminated by urbanisation. In order to test this assumption, we use results from coupled climate models to link the warming over land and the surrounding ocean region. The sea surface temperature (SST) of the surrounding ocean region has been observed to warm over the 20th century, but by a lesser amount than the met stations. Although the SST observations are clearly not affected by urbanisation, we cannot assume that these observations directly indicate the rural warming over land, because the anthropogenically forced warming rate over land and ocean is known to differ, although the ratio of warming rates is uncertain at the global scale (Sutton *et al*., 2007). Therefore, we use the CMIP3 multi-model ensemble to link land and ocean. We hypothesise that although these models cannot be expected to directly replicate the actual observed rural warming (due to the strong effects of internal variability over such a small region), they should indicate the relationship, if any, between land and adjacent ocean regions.

We analysed the 20th century experiments (20C3M) for the CMIP3 climate model simulations for the domain extending 25–50 °N and 120–150 °E. In these simulations, the urbanisation effect was not represented but various other anthropogenic forcings were included. The variable used is the 2-m air temperature denoted by LSAT (land surface air temperature) over land and OSAT (ocean surface air temperature) over ocean region surrounding Japan. Using land area fraction (slftf) data for each model, we applied 90% ocean and 90% land masks in order to focus on areas with miminal cross-contamination of sea and land. This resulted in only 19 models providing suitable data. The linear least square trend from 1900 to 1999 of each model was calculated for both variables LSAT

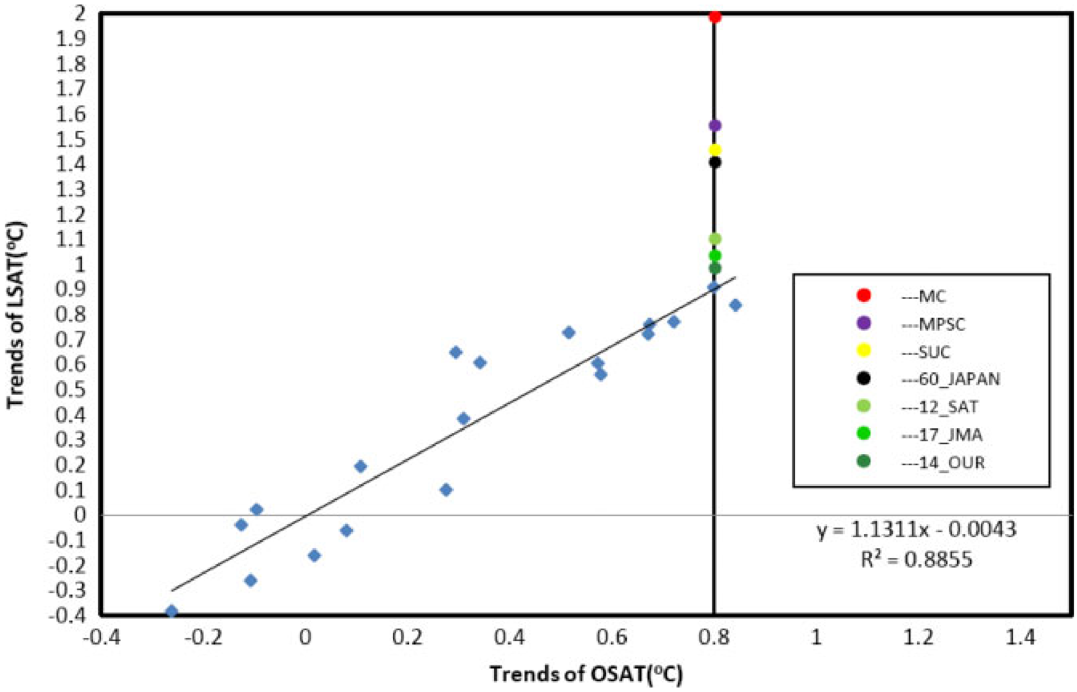

Figure 2. The blue diamonds are the centennial linear temperature trends over land and ocean for the Japan region, from the simulations of 19 CMIP3 models. The vertical line crossing the *x*-axis at 0.8 °C illustrates the observed trend of COBE-SST and cuts the trend line through the CMIP3 results at 0.90 °C. The *y*-axis values for the coloured dots along this vertical line are the observed trends from the terrestrial Japanese station data. The red dot is the average trend of the 9 megacities, the purple dot is the average of the 46 mega plus suburban cities, yellow dot is the average trend of 37 suburban cities, the green dots are the average trends for the various sets of rural stations and the black dot is the average for all the 60 stations.

and OSAT and the results for 19 models were plotted in Figure 2. The trends of LSAT and OSAT cover a large range, including negative values, although all are positive on the global scale (not shown). There is a strong relationship between trends of LSAT and OSAT which can be represented by the regression equation: $Y_{\mathrm{LSAT}} = 1.1311X_{\mathrm{OSAT}} - 0.0043$ which explains 89% of the variance in these data. Thus, although there is a substantial range in the modelled trends (due to internal variability and/or forcing differences between the simulations), there is a very strong relationship between the land and ocean warming in this region, such that ocean temperature trend can be used as a predictor of the warming over land. This is a physically reasonable result because temperature anomalies are expected to be strongly correlated over such a small domain, modified by the small amplification seen over land. The vertical line shown in Figure 2 indicates the value of the observed COBE-SST trend (0.80 °C) from 1900 to 1999 over the seas adjacent to Japan, and the dots show the surface air temperature (SAT) trends from the various categories of Japanese station data, from Table II. The observed SAT over the ocean is very close to the upper limit of the model range, which may be due to model limitations but may simply indicate that natural variability has caused a relatively large temperature change around Japan in this period. The observed SAT for all three sets of rural stations are outside the model range in absolute terms, but inside the uncertainty of the regression relationship for the observed SST. One may perhaps consider the 14_OUR set of rural stations to be preferred as they lie closer to the expected value of 0.90 °C calculated from the COBE-SST trend and the regression line. It is also very clear from Figure 2 that the suburban and megacities have very clear signals of urban bias in their trends.

5. Discussion and conclusion

Many of the meteorological stations in the Japan of the early 1870s were installed in locations that are today in the heart of major cities, so obtaining century-scale observations of the underlying warming over Japan is not straightforward, and the effect of urbanisation on the trend must be taken into account. Even for rural stations, the trend has been found to be quite high, leading to suspicion of remaining urban bias.

We used two novel methods to approach this problem. First, we experimented with two different criteria for choosing the rural stations, and compared the results to those for the 17 rural stations as defined previously by JMA. These approaches produced relatively small differences in the trend, although there is some indication that considering the population trend as well as the total population may be helpful. Second, we compared the observed SST and SAT over land with the results from 19 members of the CMIP3 multi-model ensemble. This indicates that while the results for Japan are towards the high end of the multi-model range, there is little evidence that the trends from the stations identified as rural are strongly contaminated by urbanisation. Rather, the indication is that natural variability has caused there to be a generally large warming over the Japan region relative to the globe as a whole, which is also reflected in the rise in the SST of the surrounding region. Thus, there is little evidence of urban contamination in the rural stations, and this result should strengthen confidence in the use of the JMA_17 stations as an indication of rural warming reasonably free from urban contamination. It is, however, very clear that the temperature trends in the larger cities in Japan are very influenced by urbanisation, to the extent that the megacities have warmed twice as much over the last century as the rural stations.

While the current study shows no clear evidence of urbanisation in the rural stations, it considers the period 1900–1999, and it is possible that increasing urbanisation could have further influenced these stations over the last decade. In addition, further improvements in models may increase confidence in the models, so we suggest that an up-to-date analysis be performed when new model results and observational data become available.

Acknowledgements

This work was supported by the S-5-1 project of the MoE, Japan, and by the Kakushin Program of MEXT, Japan. We acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, US Department of Energy. L. D. acknowledges the authority of Bidhan Chandra Krishi Viswavidyalaya, West Bengal, for approving a period of leave during which the work was carried out.

References

Dash SK, Jenamani RK, Kalsi SR, Panda SK. 2007. Some evidence of climate change in twentieth-century India. *Climatic Change* **85**: 299–321.

Fujibe F. 1995. Temperature rising trends at Japanese cities during the last hundred years and their relationships with population, population increasing rates and daily temperature ranges. *Papers in Meteorology and Geophysics* **46**: 35–55.

Fujibe F. 2009. Detection of urban warming in recent temperature trends in Japan. *International Journal of Climatology* **29**: 1811–1822. DOI: 10.1002/joc.1822.

Fujibe F. 2011. Urban warming in Japanese cities and its relation to climate change monitoring. *International Journal of Climatology* **31**: 162–173. DOI: 10.1002/joc.2142.

IPCC. 2007. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller HL (eds). Cambridge University Press: New York.

Ishii M, Shoji S, Sugimoto S, Matsumoto T. 2005. Objective analysis of SST and marine meteorological variables for the 20th century using ICOADS and Kobe collection. *International Journal of Climatology* **25**: 865–879.

JMA. 2009. Climate change monitoring report 2009, Japan Meteorological Agency. (Available from http://ds.data.jma.go.jp/tcc/tcc/products/gwp/gwp.html).

Jones PD, Lister DH, Li Q. 2008. Urbanization effects in large-scale temperature records, with an emphasis on China. *Journal of Geophysical Research* **113**: D16122. DOI: 10.1029/2008JD009916.

Kato H. 1996. A statistical method for separating urban effect trends from observed temperature data and its application to Japanese temperature records. *Journal of the Meteorological Society of Japan* **74**: 639–653.

Knappenberger PC, Michaels PJ, Davis RE. 2001. Nature of observed temperature changes across the United States during 20th century. *Climate Research* **17**: 45–53.

Kukla G, Gavin J, Karl R. 1986. Urban warming. *Journal of Climate and Applied Meteorology* **25**: 1265–1270.

Parker DE. 2006. A demonstration that large-scale warming is not urban. *Journal of Climate* **19**: 2882–2895.

Parker DE. 2010. Urban heat island effects on estimates of observed climate change. *Wiley Interdisciplinary Reviews Climate Change* **1**: 123–133.

Peterson TC. 2003. Assessment of urban versus rural in situ surface temperature in the contiguous United States: no difference found. *Journal of Climate* **16**: 2941–2959.

Peterson TC, Owen TW. 2005. Urban heat island assessment: metadata are important. *Journal of Climate* **18**: 2637–2646. DOI: 10.1175/JCLI3431.1.

Quereda Sala J, Gil Olcina A, Perez Cuevas A, Olcina Canton J, Rico Amoros A, Monton Chiva E. 2000. Climatic warming in the Spanish Mediterranean: natural trends or urban effect. *Climatic Change* **46**: 473–483.

Ren GY, Zhou Y, Chu Z, Zhou J, Zhang A, Guo J, Liu X. 2008. Urbanization effects on observed surface air temperature trends in North China. *Journal of Climate* **21**: 1333–1348.

Schaefer D, Domroes M. 2009. Recent climate change in Japan – spatial and temporal characteristics of trends of temperature. *Climate of the Past* **5**: 13–19.

Stone B, Jr. 2007. Urban and rural temperature trends in proximity to large US cities: 1951–2000. *International Journal of Climatology* **27**: 1801–1807.

Sutton RT, Bong B, Gregory JM. 2007. Land sea warming ratio in response to climate change: IPCC AR4 model results and comparison with observations. *Geophysical Research Letter* **34**: L02701. DOI: 10.1029/2006GL028164.

Thompson DWJ, Kennedy JJ, Wallace JM, Jones PD. 2008. A large discontinuity in the mid-twentieth century in observed global-mean surface temperature. *Nature* **453**: 646–650, DOI: 10.1038/nature06982.

Yue S, Hashino M. 2003. Temperature trends in Japan, 1900–1996. *Theoretical and Applied Climatology* **75**: 15–27.

