Assessment of urbanization effects in time series of surface air temperature over land

P. D. Jones*, P. Ya. Groisman†, M. Coughlan‡, N. Plummer‡, W-C. Wang§ & T. R. Karl||

* Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK
† State Hydrological Institute, Leningrad, USSR
‡ Bureau of Meteorology, Melbourne, Australia
§ Atmospheric Sciences Research Center, State University of New York, Albany, New York 12205, USA
|| National Climate Data Center, Asheville, North Carolina 28801, USA

RECORDS of hemispheric average temperatures from land regions for the past 100 years provide crucial input to the debate over global warming[1–4]. Despite careful use of the basic station data in some of these compilations of hemispheric temperature[1,2,4–6], there have been suggestions[7,8] that a proportion of the 0.5 °C warming seen on a century timescale may be related to urbanization influences—local warming caused by the effects of urban development. We examine here an extensive set of rural-station temperature data for three regions of the world: European parts of the Soviet Union, eastern Australia and eastern China. When combined with similar analyses for the contiguous United States[9,10], the results are representative of 20% of the land area of the Northern Hemisphere and 10% of the Southern Hemisphere. The results show that the urbanization influence in two of the most widely used hemispheric data sets[1,2,4] is, at most, an order of magnitude less than the warming seen on a century timescale.

Significant urbanization effects have been noted at many cities[7,11]. Two factors must be considered, however, when comparing individual city 'heat island' magnitudes with hemispheric warming trends. First, many of the extreme urban biases that have been quoted are the largest daily occurrences, perhaps happening during still evenings or intense inversions. The effect on station monthly mean temperatures is sure to be considerably smaller. Second, in any gridded temperature data set, a single affected station is unlikely to have a large influence on the time series of the nearest grid-point, because this is generally a weighted average of between 5 and 20 station records[1,2].

The most comprehensive attempt to assess the significance of urbanization on large-scale temperature trends has been made for the contiguous United States by Karl *et al.*[12]. In this analysis the Historical Climate Network (HCN)[13] of 1,219 stations was used to assign stations to pairs of rural and urban sites. Karl *et al.* showed that an urbanization influence could be detected in many records, with the urban bias being a nonlinear function of population. To assess the influence of urbanization on regional averages developed from the gridded data sets[1-3], the average for the contiguous United States derived from the HCN data set of principally rural stations was compared with the gridded series. The gridded series make use of some of the temperature data that have been assembled over the present century from sources such as World Weather Records and Monthly Climatic Data for the World (see ref. 5 for details of these sources). Some of these records come from large cities and could be affected by urbanization-related trends. Comparison of the gridded and the HCN series revealed that the gridded time series shows a warming of ~0.1 °C over the period 1901-84[9]. It can be argued[10], however, that the rate of urbanization growth in the United States is atypical compared with many other parts of the world. We have therefore attempted to assess the urbanization influence in other regions of the world using specially developed rural-station temperature series.

Western Soviet Union. For the western part of the Soviet Union we selected a network of 38 stations from sites in non-urbanized areas with long records (Fig. 1*a*). The sites include isolated meteorological stations, lighthouses, villages and other small settlements. The largest populated sites are nine towns with populations of the order of 10,000 people. All nine towns are located at least 80 km away from major cities. All the site records were assessed for artefacts due to factors such as site moves or changing methods used to calculate monthly mean temperatures. At twelve sites the observing station was moved slightly. Comparisons with neighbouring sites were made before and after each change, and where necessary, corrections were made to ensure homogeneity of the rural-station record. No corrections were deemed necessary for the remaining 26 stations, where no station moves were reported.

Data from the 38 stations were then converted to anomalies from the 1951-75 average and combined using the inverse-distance weighting gridding scheme used in ref. 1. By using the same averaging scheme as for the gridded data, any differences between this average and the gridded average will be the result of data differences and not due to differing interpolation methods. The resulting series (RUSSR, Fig. 2*a*) is an average for the European part of the Soviet Union, parts of western Siberia and Kazakhstan.

Using the gridded data from ref. 1, we developed a regional time series (JUSSR) for the region using 22 gridpoints (see Fig. 1*a*). Similarly, we developed a regional time series (VUSSR) for this region using the hemispheric data set from ref. 4. An optimum interpolation procedure was employed by Vinnikov *et al.*[4] to produce their annual hemispheric average time series, using about one-third the number of stations that were used in ref. 1. In this procedure, interpolation of station data to grid points was not undertaken, the published data being available only as annual hemispheric averages. For our study, regional time series were constructed from the data of ref. 4 using this

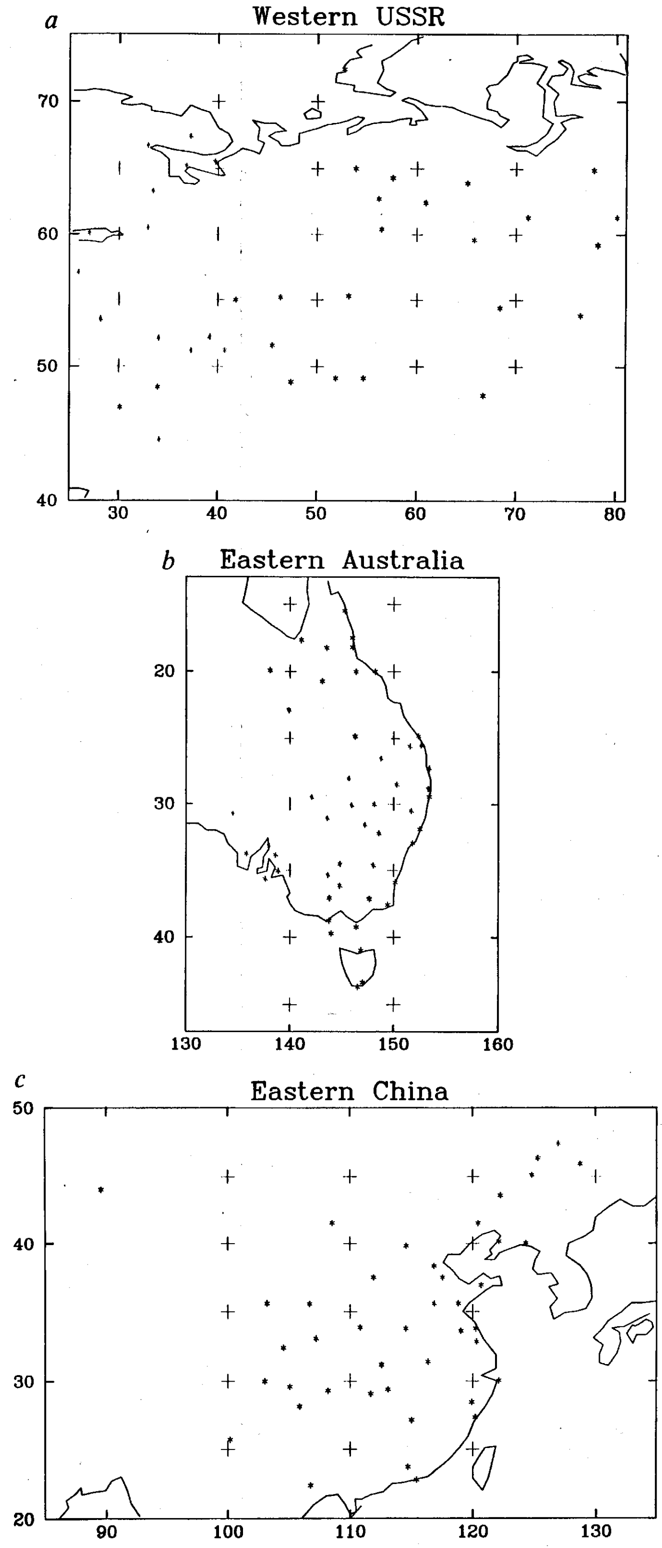

FIG. 1 Study regions, showing the rural stations (*) and the grid points (+). *a*, Western USSR; *b*, Eastern Australia; *c*, Eastern China. Details of the rural station networks are included in the text. The grid points are taken from the data set of refs 1 and 2, which interpolate station data onto a 5° latitude by 10° longitude grid. Station data used in the gridding extend 2.5° of latitude and 5° of longitude away from each grid point. For the western USSR, 60 station records were used to construct the grid-point series. There were 25 stations in operation by 1901 and 32 were operating in 1987. For eastern Australia 20 stations were used, 7 of which were operating during the 1930s and 15 of which were operating in 1988. For eastern China 38 stations were used, all of which were in operation in 1954, whereas only 29 were still operating in 1983. For the western USSR region only, there are four stations common to the grid-point and rural time series.

same optimum interpolation scheme. The stations used extend beyond the bounds of the rural network, unlike those used in ref. 1.

The rural-network average was compared with the two gridded data series over two periods, 1901–87 and 1930–87. Intercorrelation between the three series over these two periods is exceedingly high, with all correlations between 0.98 and 0.99. Comparisons of the standard deviation and linear trend are given in Table 1. The similarity between the statistics for all three series over both periods is remarkable. Over the 1930–87 period, a cooling of ~0.2 °C in RUSSR is observed. This cooling is about 0.1 °C smaller in JUSSR, but there are no statistically significant differences between the two series. Given that all three data sets make use of different station networks, slight differences between the time series and their trends are to be expected.

Eastern Australia. We assembled a network of 49 stations in the eastern half of Australia, from the states of Queensland, New South Wales, Victoria and the southeastern quarter of South Australia (Fig. 1*b*). All stations are rural or small village sites and all encompass the period 1930–88. The average population of the stations is 5,775; the maximum population is 33,368 and there were seven lighthouse sites which were assumed to have a negligible population. The series from all stations were reduced to anomalies from the 1951–80 period before being combined into a regional series (RAUS, Fig. 2*b*) using the same inverse-distance gridding scheme.

A regional time series (JAUS) was developed for this region from ref. 2, using grid points (Fig. 1*b*). We also used the data in ref. 4 to derive a regional series (VAUS) for the region, which incorporated between 7 and 27 stations.

The correlation coefficients between the RAUS, JAUS and VAUS series over the 1930–88 period are all between 0.95 and 0.96. Comparisons of the standard deviation and linear trend are shown in Table 1. The results indicate that neither JAUS nor VAUS differ significantly from the rural time series RAUS. For VAUS, the warming over the region is similar to that from the rural series. In all three series, warming over the 59-year period is statistically significant at the 5% level.

The rural data set for Australia can be split into time series based on maximum and minimum temperatures. Calculation of trends for these series shows that the 1930–88 warming is greater for the minimum temperatures (a 0.81 °C rise) than for the maximum temperatures (a 0.30 °C rise). This result indicates a reduction in the daily temperature range from this region, a feature noted for the United States by Karl *et al.*[14]. It is unfortunate that separate maximum and minimum temperature data sets are not more widely available. Many countries calculate mean monthly temperatures using observations from a number of fixed hours per day, without recording the daily maximum and minimum temperatures.

Eastern China. We assembled a network of 42 station pairs of rural and urban sites in the eastern half of China (Fig. 1*c*). The data cover the period 1954–83. The 84 stations were selected from a 260-station temperature set recently compiled under the US Department of Energy and People's Republic of China Academy of Sciences Joint Project on the Greenhouse Effect[15]. The stations were selected on the basis of station history: we chose those with few, if any, changes in instrumentation, location or observation times. All 84 records were complete for the 30-year period. The urban stations were in regions with populations of over 0.5 million, whereas for the rural stations populations mostly less than 0.1 million (according to 1984 population statistics). From the 42-station rural network, we formed an average (RCHI, Fig. 2*c*) for eastern China using the inverse-weighting gridding scheme. The 42-station urban network (UCHI) was averaged in the same way. Using the gridded data from ref. 1, a regional time series (JCHI) was developed for the region encompassing 15 grid points (see Fig. 1*c*). An average series (VCHI) for the region, making use of 32 stations, was developed from the data in ref. 4.

The correlation between the RCHI and JCHI series over the 1954–83 period is 0.90, and there is a lower correlation of 0.81 between RCHI and VCHI. Comparisons of the standard deviation and linear trend are shown in Table 1. Although the results indicate that both gridded series show a slight cooling relative to the Chinese rural network (RCHI) over the 30-year period, differences between all three series are not statistically significant. Slight differences are to be expected given that the various series make use of different sets of raw station data. The

TABLE 1 Comparison of temperature trends

Series	Period	Standard deviation (°C)	Linear trend (°C over period)
Western USSR			
RUSSR (rural)	1901–1987	0.82	0.38
JUSSR	1901–1987	0.79	0.38
VUSSR	1901–1987	0.81	0.31
RUSSR (rural)	1930–1987	0.84	−0.21
JUSSR	1930–1987	0.82	−0.09
VUSSR	1930–1987	0.85	−0.20
Eastern Australia			
RAUS (rural)	1930–1988	0.31	0.56*
JAUS	1930–1988	0.31	0.60*
VAUS	1930–1987	0.34	0.55*
Eastern China			
RCHI (rural)	1954–1983	0.30	0.23
JCHI	1954–1983	0.27	0.19
VCHI	1954–1983	0.37	0.13
UCHI	1954–1983	0.32	0.39*
Contiguous United States			
Rural[9,10]	1901–1984	0.42	0.16
Grid[9,10]	1901–1984	0.39	0.31

* Significant trend at the 5% level.

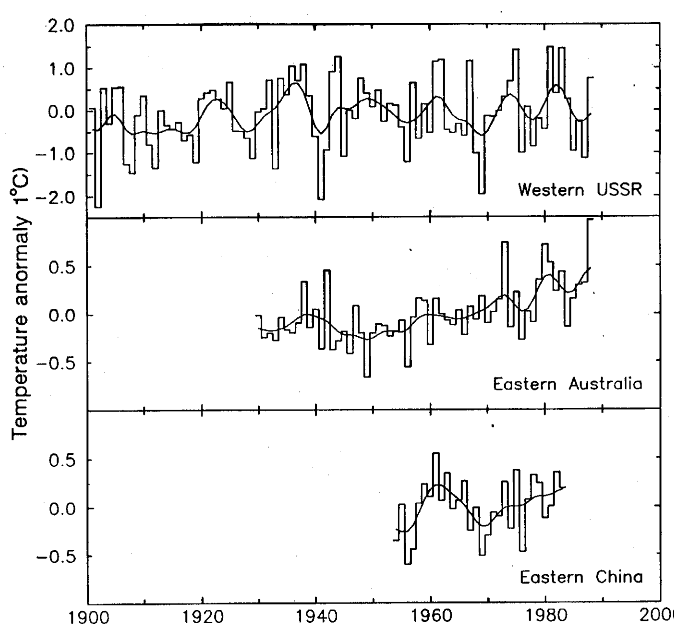

FIG. 2 Time series of annual temperature anomalies for the three regions: *a*, Western USSR (1901–88); *b*, Eastern Australia (1930–88); *c*, Eastern China (1954–83). The smooth curves were obtained using a gaussian filter designed to suppress variations on timescales of less than 10 years. The base periods for the three regions are 1951–75, 1951–80 and 1954–83, respectively. For the Chinese region all the rural stations are available for every year. For Eastern Australia, 3% of the annual station values are missing. For the Soviet series, there were only 20 of the 38 stations contributing in 1901. Seven stations began recording after 1930. Over 1930–87, the number of missing values amounts to 8% of the total. Most of these missing values were between 1930 and 1945.

warming in UCHI is 0.39 °C, considerably higher than that in RCHI. For this region, UCHI is the only series for which warming is statistically significant. The Chinese results may, at first glance, seem somewhat surprising, as 24 of the stations used in ref. 1 are among the 42 urban sites. In refs 1 and 4, average temperatures for these sites generally come from airport sites, which may be in rural areas. In many parts of the world, city-centre observatories were relocated to airport sites during the 1950s and 1960s. That temperature records from many sites are a combination of information from various locations within a city or town emphasizes the need to assess the homogeneity of individual site records[5,6].

In none of the three regions studied here is there any indication of significant urban influence in either of the two gridded series[1,2,4] relative to the rural series. Earlier work on the contiguous United States[9,10] showed an urban influence of 0.15 °C over the period 1901-84. (The results of this work are summarized in Table 1.) The United States result therefore does seem to be somewhat atypical compared with other industrialized regions of the world. The results from the United States clearly represent an upper limit to the urban influence on hemispheric temperature trends.

In total, the three regions and the contiguous United States encompass 82 grid points (22 over the western USSR, 14 over eastern Australia, 16 over eastern China and 30 over the contiguous United States) on a resolution of 5° latitude by 10° longitude. The three Northern Hemisphere regions in total comprise about 20% of the landmass of the hemisphere, and the eastern Australian region comprises 10% of the landmass in the Southern Hemisphere. Thus there seems to be little urbanization influence in three regions of the world that, when taken together, are twice the size of the contiguous United States.

It is unlikely that the remaining unsampled areas of the developing countries in tropical climates, or other highly populated parts of Europe, could significantly increase the overall urban bias above 0.05 °C during the twentieth century. A bias of this order is an order of magnitude smaller than the hemispheric and global-scale warming trend observed over the last 100 years. The bias will be further halved in hemispheric and global temperature estimates that incorporate marine as well as land temperatures.

We emphasize, however, that our results do not imply that urban warming influences in observations of local temperature will remain inconsequential in global averages in the future. Indeed, careful selection, inspection and monitoring for urbanization influences in the climate record will be required. This concern could be greatly lessened by an international effort to monitor and place observing stations outside urban areas. □

Received 5 April; accepted 24 July 1990.

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ACKNOWLEDGEMENTS. This work was funded partly by the US Department of Energy, Carbon Dioxide Research Division and through NOAA/DOE Interagency Agreement. The collaboration of the many individuals in this work was initiated by a meeting of one of the subgroups of Working Group 1 (WG1) of the Intergovernmental Panel on Climatic Change (IPCC) in December 1989.