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Recent climate change in Japan – spatial and temporal characteristics of trends of temperature

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Abstract. In this paper temperature series of Japan were statistically analysed in order to answer the question whether recent climate change can be proved for Japan; the results were compared and discussed with the global trends. The observations in Japan started for some stations in the 1870s, 59 stations are available since 1901, 136 stations since 1959. Modern statistical methods were applied, such as: Gaussian binominal low-pass filter (30 yr), trend analysis (linear regression model) including the trend-to-noise-ratio as measure of significance and the non-parametric, non-linear trend test according to MANN (MANN's Q).

According to the results of the analyses, climate change in Japan is clearly shown for temperature over the 100 yr (1901–2000): Annual mean temperatures increased at all stations from 0.35 (Hakodate) to 2.95°C (Tokyo). The magnitude of climate change is illustrated to increase over the recent period 1976–2000. Seasonally, the strongest warming trends were observed for winter temperatures and also increasing temperature trends prevailed in summer, with the exception of slightly decreasing trends at only four stations.

1 Introduction

“Global warming” and “climate change” are major keywords in the present-day global change discussion. Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere commonly recognized to affect the climate. The concentration of carbon dioxide in the atmosphere has increased by more than 30 percent since 1750. These developments have the potential of raising global surface temperatures and, in consequence, they impact other parts of the climate system. It is commonly accepted that

the global average surface air temperatures have risen by 0.74°C [0.56°C to 0.92°C] over the last 100 yr from 1906–2005 (IPCC, 2007). The corresponding trend for the observation period 1901–2000 is 0.6°C [0.4°C to 0.8°C] underlying the general strengthening of the warming trend during the last decades: Eleven of the last twelve years (1995–2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850) (IPCC, 2007). Although the temperature increase is widespread over the globe, spatial and temporal characteristics of temperature trends can be found with highest values in northern latitudes; additionally, land regions have warmed faster than the oceans (IPCC, 2007). Therefore, climate change and its impacts are an issue of a great and rapidly accelerating concern since the 1990s. Because of the spatial and temporal distinctions of temperature trends, it is very important to analyse station data for a better understanding of trend behaviours on regional and local scales.

So far, some studies have analysed temperature records in Japan in recent years: A general warming was found, for example by Yue and Hashino (2003) who showed increasing trends of monthly temperature in Japan for 46 stations from 1900–1996. Fujibe (1995) reported about rising temperature trends at 60 Japanese cities (1891–1992) and their relationship with urbanisation: Medium sized cities showed increasing minimum temperatures at a rate of about 1°C/100 years whereas large cities experienced a much stronger warming of 2–5°C/100 years. Maximum temperatures also increased but with a smaller magnitude. Kato (1996) applied principal component analysis to separate the impacts of urbanization from station data. According the analysis of the data of 51 stations (1920–1992) the urban increase counts 1.0–2.5°C/100 years.

In a recent paper Fujibe et al. (2007) reported about long-term changes of temperature extremes and the day-to-day variability in Japan by analysing the records of 17 climate stations (1931–2005). According to their study, minimum



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Fig. 1. Location of stations under study.

temperature shows a strong increase of temperature, especially for the monthly lowest value ($0.27^{\circ}\text{C}/\text{decade}$ for 1931–2005 and $0.51^{\circ}\text{C}/\text{decade}$ for 1981–2005). The day-to-day variability of minimum temperatures is decreasing. Maximum temperature shows increasing trends at a lower rate ($0.08^{\circ}\text{C}/\text{decade}$ for 1931–2005 and $0.4\text{--}0.5^{\circ}\text{C}/\text{decade}$ for 1981–2005); besides, there is no trend in the day-to-day variability (Fujibe et al., 2007).

In addition to the general warming in Japan articles about the role of external forcings can be found. The temperature after a great volcanic eruption (dust veil index >200) averages in summer $1.3 \pm 0.5^{\circ}\text{C}$ lower than in normal years, while in northern mid-latitude mean surface air temperature decrease about 0.2°C (Kondo, 1988). Kurihara (2000) reported of a quasi-six-year fluctuation of high summer temperatures in Japan which are related to the fluctuations of sea surface temperature in the North Pacific Ocean.

The aim of this paper is (1) to analyse mean temperature series of a dense network of stations in Japan in a detailed way in order to investigate the spatial and temporal characteristics of temperature change in Japan and (2) to compare and discuss the results with global trends.

2 Data and methods

Daily mean temperature series for 155 stations were provided by the National Climatic Data Center, USA (2006). The data have been quality checked by the National Climatic Data Center. According to Yue and Hashino (2003) no significant changes in the instrumentation of the stations or the observation practice have been observed. Instrumental observations started for some stations in the 1870s, 59 stations

are available since 1901 and 136 stations from 1959 onwards. Japan can be considered as ideal for climate change studies as sufficient and detailed (daily) temperature series are kept at diverse locations scattered across the islands (Fig. 1). The global temperature anomalies were taken for a comparison of the results with global temperature trends (Brohan et al., 2006). Three observation periods were investigated: 1901–2000 (100 yr), 1951–2000 (50 yr) and 1976–2000 (25 yr) in order to find out if the global observations of strengthened warming trends during the last decades can be confirmed for Japan. The periods were individually studied and compared with each other, applying the common international practice of climate change studies. Computations were carried out for annual, winter and summer data, referring to the following seasons:

- winter, December–February;
- spring, March–May;
- summer, June–August;
- autumn, September–November.

The following statistical methods of time series analysis were applied, which are commonly used for global climate change research in order to analyse the trends of spatial and temporal variabilities of temperature over Japan: As emphasised by the World Meteorological Organisation (Mitchell et al., 1966) the Gaussian binomial low-pass filter that suppresses high-frequency oscillations (30 yr) was applied to smooth the data. The linear trend analysis (the least square method) was computed to measure the magnitude of long-term linear trends. In this study, the linear regression model was applied for annual and seasonal data (for all three time periods under study: 1901–2000, 1951–2000, and 1976–2000); the regression coefficients are given in $^{\circ}\text{C}$. As a measure of significance the trend-to-noise-ratio (T/N) was calculated: The trend value is divided by the noise, where the noise is represented by the standard deviation of the data. T/N values >1.96 can be regarded as statistically significant (95%) (Sneyers, 1990). Additionally, the non-parametric, nonlinear trend test according to MANN (MANN's Q) was computed to detect all trends, no matter what form they have (Mann, 1945). This trend test was modified by Kendall (Kendall, 1970) and makes no assumption of a statistical distribution of the analysed data (Sneyers, 1990). MANN's Q values >1.96 can be regarded as significant (95%).

3 Results

3.1 The case study Tokyo

The official meteorological station Tokyo was taken for a case study because of its long observation period covering 125 yr from 1876–2000. Annual mean temperature shows

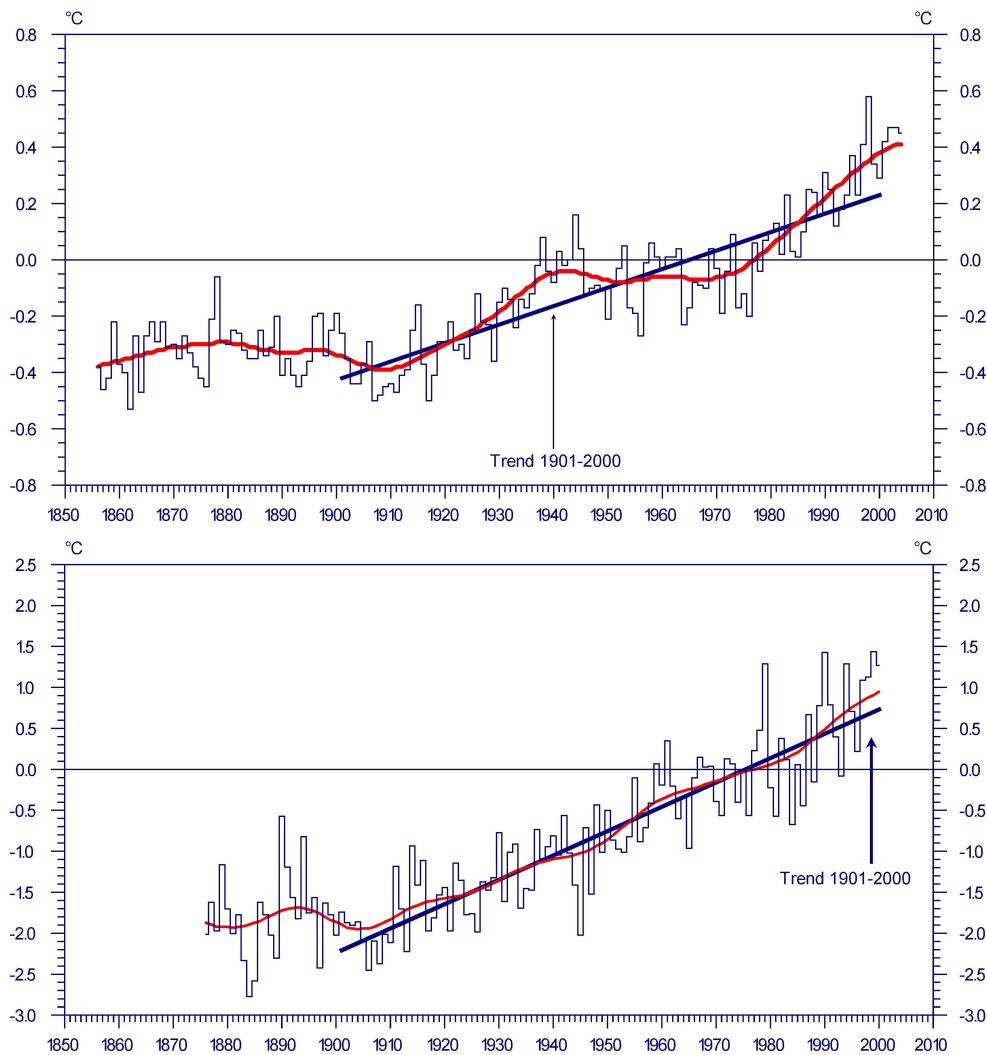


Fig. 2. Mean global temperature anomalies (top) and mean annual temperature anomalies at Tokyo (bottom) along with low-pass filtered values/30 yr (red curve) and trend lines, 1901–2000; notice different scales of the y-axis.

a strongly increasing trend during the last century with the 1990s as the warmest decade in the series (Fig. 2). The warmest year on record was 1999, with a temperature of 1.44°C over the long-term 1961–1990 mean. Most of the warmest years of the period under study (1876–2000) were experienced during the 1990s (Fig. 2). The trend line indicates an almost linear trend of the mean annual temperature over the 100 yr observation period 1901–2000 (Fig. 2). A general increase of the temperatures can be clearly manifested from about 1905 onwards; the slightly decreasing global temperatures from 1946–1975 can not be determined for Tokyo temperatures (Fig. 2). For the 125 yr (1876–2000), the warming trend in Tokyo is confirmed by the results of trend computation and can be quantified by an increasing trend at a rate of 2.93°C (or 0.24°C per decade), which is almost five times higher than the global trend (0.05°C per decade, see Table 1 and Fig. 2). According to the T/N -value

of 2.96 the linear trend can be taken as highly significant trend ($>99\%$). The warming trend of mean annual temperature continued and even strengthened in the last decades, which can be clearly shown by the computed trend values per decade increasing from 0.34°C to 0.52°C for the periods 1951–2000 and 1976–2000, respectively (Table 1). Strongly increasing trends of temperature can be manifested in seasonal respects with highest values for winter and autumn (Table 1). All computed seasonal temperature trends over the 125 yr study period (1876–2000) are linear ($T/N > 1.96$) and significant ($T/N > 1.96$; MANNs $Q > 1.96$). Warming of seasonal temperatures is also strengthened during the more recent times: The rate of warming of winter temperatures over the last 25 yr (1976–2000) is much higher than over the last 50 yr (1951–2000), namely 0.73°C vs. 0.52°C per decade (Table 1). At the same time, the T/N -values are slightly decreasing (Table 1). This means that the trends

Table 1. Annual and seasonal temperature trends per decade, the trend-to-noise-ratios (T/N) and MANNs Q (Q) in Tokyo (top) and for the global temperature anomalies (bottom); trends over the whole observation period are given in brackets.

	1901–2000			1951–2000			1976–2000		
Tokyo	Trend	T/N	Q	Trend	T/N	Q	Trend	T/N	Q
Annual	0.30 (2.95)	3.06	10.70	0.34 (1.67)	2.45	5.38	0.52 (1.24)	1.85	2.83
Winter	0.40 (3.96)	2.78	9.01	0.52 (2.59)	2.47	5.42	0.73 (1.82)	1.90	2.80
Spring	0.29 (2.86)	2.72	8.76	0.25 (1.24)	1.60	3.76	0.45 (1.07)	1.30	1.96
Summer	0.21 (2.13)	2.09	6.24	0.21 (1.05)	1.18	2.31	0.44 (1.07)	1.04	1.96
Autumn	0.30 (2.95)	2.66	8.71	0.42 (2.04)	2.20	4.98	0.60 (1.43)	1.61	2.64
Global	Trend	T/N	Q	Trend	T/N	Q	Trend	T/N	Q
Annual	0.07 (0.66)	2.91	9.92	0.10 (0.47)	2.57	5.78	0.18 (0.43)	2.65	4.46
Winter	0.07 (0.69)	2.64	8.46	0.11 (0.52)	2.28	5.01	0.20 (0.48)	2.51	4.16
Spring	0.07 (0.73)	2.88	9.84	0.11 (0.53)	2.58	6.01	0.19 (0.46)	2.60	4.61
Summer	0.06 (0.61)	2.81	9.46	0.09 (0.45)	2.50	5.74	0.19 (0.46)	2.57	4.31
Autumn	0.06 (0.59)	2.77	9.25	0.08 (0.40)	2.31	4.99	0.15 (0.36)	2.25	3.30

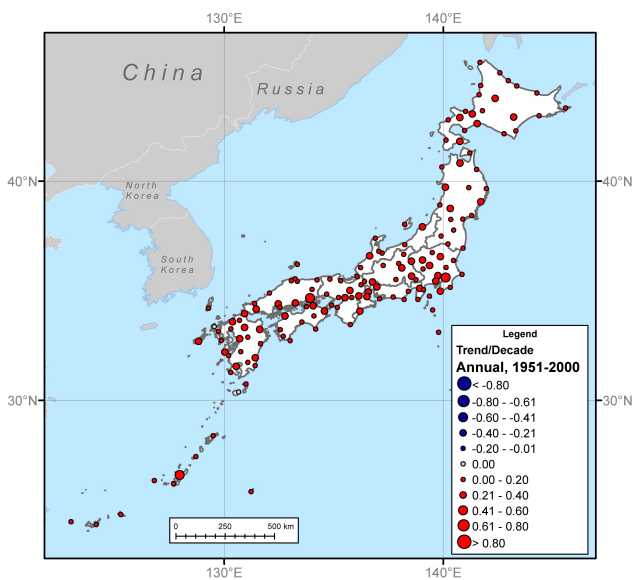


Fig. 3. Trends/decade of mean annual temperature [°C], 1951–2000.

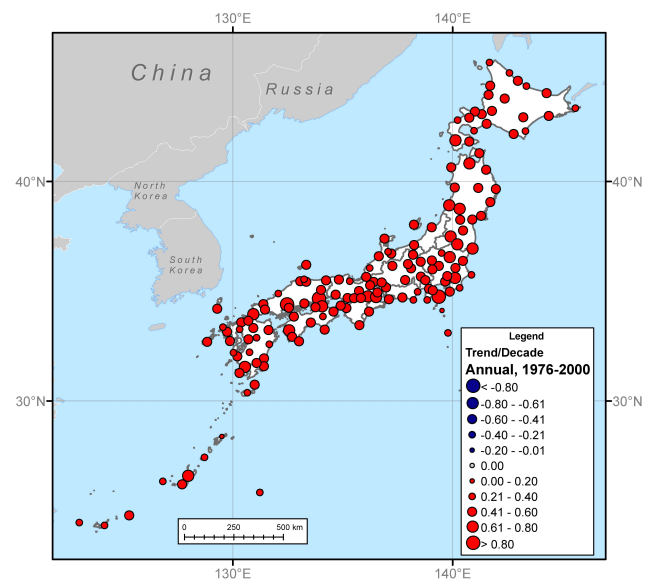


Fig. 4. Trends/decade of (mean) annual temperature [°C], 1976–2000.

are not strictly linear because of their high interannual variability. In any case, the trends are positive and significant (MANNs $Q > 1.96$). The computed seasonal temperature trends in Tokyo (1976–2000) are higher than the corresponding values of the global temperature anomalies, in case of winter and autumn even three times higher (Table 1). However, the computed trends for the more recent period (1976–2000) are not linear but significantly positive (Table 1). In summary, annual and seasonal temperatures in Tokyo have risen over the 125 yr study period (1876–2000) and also over the more recent periods (1951–2000 and 1976–2000, respectively). The warming trends in Tokyo are intensified in the last decades. Compared with global trends, general similari-

ties can be found: It can be observed that the highest positive temperature trends are experienced in winter, whereas the trends in summer are also positive but with a smaller magnitude. It is noticeable to mention that the magnitude of all temperature trends in Tokyo is much higher compared with the global temperature anomalies and the computed trends are significant linear over the total observation period (1876–2000).

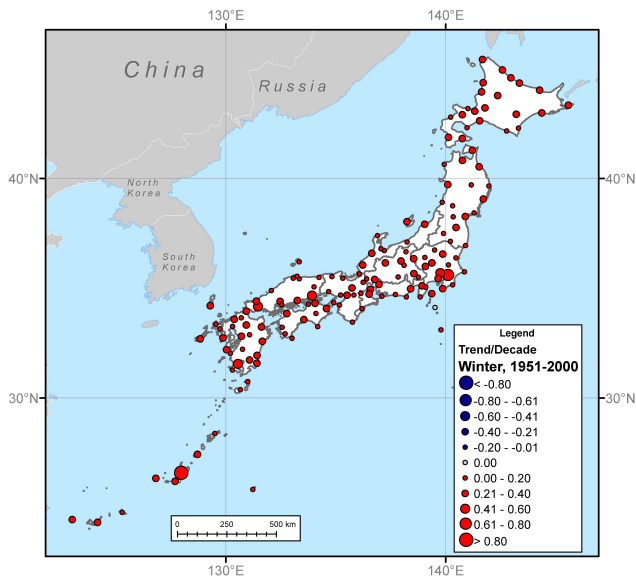


Fig. 5. Trends/decade of mean winter temperature [°C], 1951–2000.

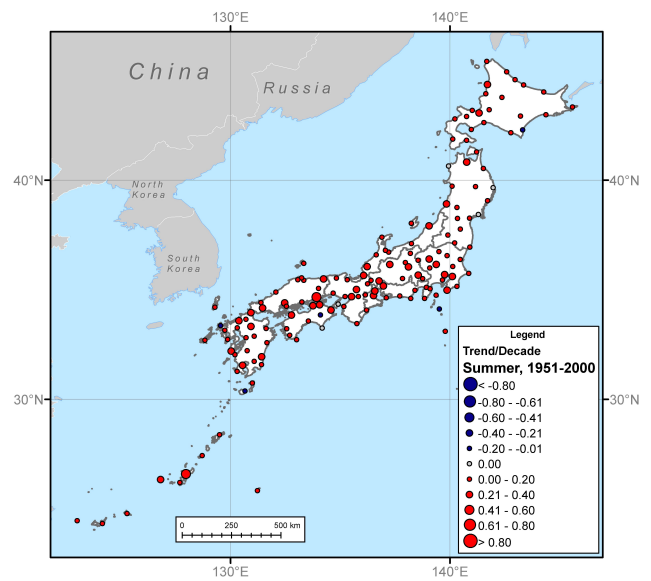


Fig. 7. Trends/decade of mean summer temperature [°C], 1951–2000.

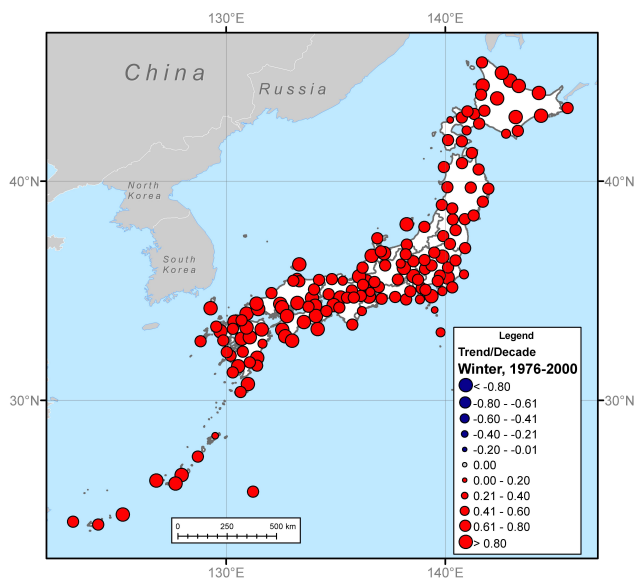


Fig. 6. Trends/decade of mean winter temperature [°C], 1976–2000.

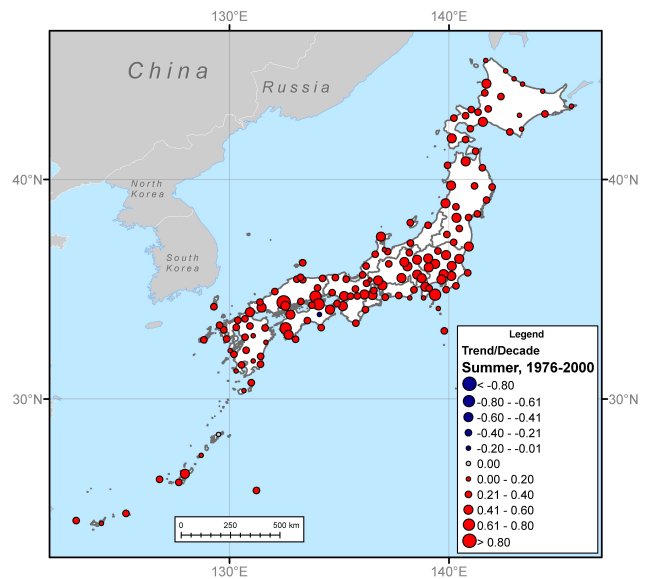


Fig. 8. Trends/decade of mean summer temperature [°C], 1976–2000.

3.2 Spatial and temporal characteristics of temperature trends in Japan

3.2.1 Mean annual temperature trends in Japan

According to the results of the trend computations for all stations under study, climate change in Japan is clearly shown for temperature over the past 100 yr (1901–2000): Annual mean temperatures increased at all (59) stations from 0.35 (Hakodate) to 2.95°C (Tokyo), or 0.04°C and 0.30°C/decade,

respectively. The trends are at 42 stations (or 70%) significantly linear (T/N -values > 1.96). However, the temperature rise is pronounced: 98% of the trends are significant positive (according to MANNs $Q > 1.96$). Positive trends of temperature prevail in Japan also for the 50 yr period (1951–2000; see Fig. 3): The highest temperature rise was observed in Okayama with 2.14°C (resp. 0.44°C/decade). 84% (or 114 out of 136 stations) of the trends are not strictly linear but 69% (or 94 stations) are significantly positive (according to the MANNs Q values > 1.96). For the

study period 1976–2000, positive temperature trends were observed at all stations under study and the magnitude of climate change is seen to increase (Fig. 4). The highest temperature warming was observed in Hiroshima with 2.35°C (resp. $0.98^{\circ}\text{C}/\text{decade}$), a value which is almost five times higher than the global trend. In any case, 34% of the computed trends are linear and 87% significantly positive. As far as annual temperatures are concerned, a distinct increase could be shown over the secular period (1901–2000) with a strong trend of warming over the recent period (1976–2000).

3.2.2 Mean winter temperature trends in Japan

Analysing seasonal trends (of mean temperatures) the strongest warming trends were observed in winter season corresponding with the global trends (Fig. 5). All computed trends were positive during the 50 yr period (1951–2000) showing even higher values than the trends of the annual temperature. Again, Tokyo shows the highest increasing trend with 2.46°C (resp. $0.50^{\circ}\text{C}/\text{decade}$). Although all computed trends are positive, only the computed trend at Tokyo is linear indicating however a high interannual variability. 46% of the trends are significant (according MANNs Q). The warming trend in winter is strengthened during the last decades (1976–2000) resulting in the highest computed temperature trends in this analysis (Fig. 6): Temperatures in Nago increased linear at a rate of 2.81°C (resp. $1.12^{\circ}\text{C}/\text{decade}$). Because of the high interannual variability only 6% of the computed trends are linear but 80% are significant (according to MANNs Q).

3.2.3 Mean summer temperature trends in Japan

In summer, increasing trends of temperature prevail at all stations, but also slightly decreasing trends were observed at five stations (1951–2000): Its magnitude varies between a decrease of -0.52°C (resp. $-0.11^{\circ}\text{C}/\text{decade}$) at Yakushima and 2.01°C (resp. $0.41^{\circ}\text{C}/\text{decade}$) at Okayama (Fig. 7). Due to the high interannual variability not all trends are significantly linear. The increasing trends of summer temperatures as already shown for the study period 1951–2000 are intensified during the period 1976–2000 (Fig. 8). Hiroshima experienced the highest positive trend at a rate of 2.36°C (resp. $0.98^{\circ}\text{C}/\text{decade}$). Only at four stations the computed trends were significantly linear and at most stations not significant (according to MANNs Q).

4 Discussion

The case study of Tokyo shows increasing trends of temperature over all periods of observation (1876–2000, 1901–2000, 1951–2000, 1976–2000). The mean annual temperature shows an increasing trend of 2.93°C (resp. $0.24^{\circ}\text{C}/\text{decade}$) during the period 1876–2000 whereas the trend for the global mean temperatures is 0.59°C (resp. $0.05^{\circ}\text{C}/\text{decade}$).

Strongly increasing trends can be observed during all seasons, with highest trends in winter (corresponding with global trends). The warming trends in Tokyo were intensified in the last decades. The trend for the annual temperature (1976–2000) in Tokyo ($0.52^{\circ}\text{C}/\text{decade}$) is almost three times higher than for the global temperature anomalies ($0.18^{\circ}\text{C}/\text{decade}$). The magnitude of all temperature trends in Tokyo is much higher compared with the global temperature anomalies.

For Japan as a whole, climate warming is clearly shown over all periods of observation (1901–2000, 1951–2000, 1976–2000). During the 100 yr (1901–2000) mean annual temperatures increased at all stations from 0.35 (Hakodate) to 2.95°C (Tokyo). Strongly increasing trends can be found in all seasons, with highest increasing trends in winter. The magnitude of climate change is illustrated to increase over the recent period 1976–2000, which can be clearly identified by the case of Tokyo and also for the other stations under study. The temperature series in Japan show remarkable correlations with the global temperature anomalies, explaining a great correspondence between the recent trends of warming in Japan with global warming underlining the highest values in winter. However, the magnitude of the computed trends in Japan is much higher than the global temperature anomalies. Increasing temperature trends can be observed in large parts of East Asia as shown in a detailed investigation for China for the observation period 1951–2000 (Schaefer, 2001; Domroes and Schaefer, 2003): Annual temperature trends increase mostly between 0.5 – 1.0°C (1951–2000) with the highest magnitudes over the northeastern and northwestern parts of China. Annual temperature increase results mainly from the marked increase in winter temperatures and the positive temperature trends in spring and summer, while slight decreases are experienced in summer. Thus the observations for China correspond with global trends, too. The fact that the temperature increase in China appears to be growing faster than the global temperatures corresponds with the marked warming in Japan.

The observations on recent climate change in Japan must be regarded with great concern on the human and natural environment. However, the observed warming in Japan might be superposed by other forcings like the urban heat island (Fujibe, 1995; Kato, 1996). It is from the statistical point of view difficult to filter out and quantify the urban heating effects out of the station data. Therefore, the separation of urban and global temperature signals remains as a subject of future studies (Fujibe et al., 2007). Even though the data have been quality checked by the National Climatic Data Center, possible inhomogeneities caused by station moves may influence trend (Mitchell et al., 1966; Fujibe, 1995; Pielke et al., 2007). Accordingly further investigations have to be carried out to deepen the observations and also to analyse the forcings of the observed increasing temperature trends in Japan.

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