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Hydro-climatic Change in Japan (1906–2005): Impacts of Global Warming and Urbanization

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ABSTRACT: Hydro-climatic change in Japan from 1906 to 2005 has been analyzed using local climate data from four large metropolitan areas, four cities, and eight rural areas. Mean annual and seasonal air temperature records (Japan Meteorological Agency, JMA) show linear warming trends at all 16 study sites with a strong dependence on population (density). Over the 100 year period investigated, the average warming has been the least (1.06°C) at the rural sites, higher (1.77°C) in the urban areas and cities, and highest (2.70°C) in the large metropolitan areas. The more sparsely populated rural sites had warming trends from 0.73 to 1.24°C per 100 years. In the business district of Tokyo, an average warming of 3.07°C in 100 years was recorded. Warming in Japan has been higher in winter than in summer, and has accelerated significantly since 1981. Average warming at all 16 stations was 3.1 times higher in the recent 25 years (1981–2005) than in the last century (1906–2005). The 1906–2005 average warming at the rural sites (1.06°C) was higher than the global warming reported by the IPCC (0.74°C).

Mean annual precipitation has decreased, on average, by 3% (60 mm) number of days with precipitation by 8% (29 days) at the 16 study sites in 100 years (1906–2005), and average daily precipitation intensity has increased by 4%. Annual precipitation amounts have changed the most (7%) in medium sized cities, and the least (2%) at rural study sites; they have also been higher in the warmer south (8%) than in the cooler north (1%) of Japan. Precipitation intensity increases are uncorrelated with air temperatures or their increases. Changes in precipitation from 1906 to 2005 in Japan are more likely caused by global climate change rather than by local urban heat island effects.

KEYWORDS: air temperature, climate change, Japan, precipitation, trends, urban heat islands

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Introduction

Information on hydro-climate is essential for water resources projects, and climate change raises the uncertainty in the planning and operation of such projects. It is not surprising, therefore, that the recent hydrologic and engineering literature deals with climate change and its impact on water resources. Examples, among the many available, can be found in a special issue of *Hydrologic Engineering*,[1] and in recent articles by Hossain et al[2] on climate feedback-based dam design and operations; by Kang and Ramírez[3] on the response of stream flow to weather variability under climate change; by Aral et al[4,31] on sea level rise; and by Berggren et al,[5] as well as Forsee and Ahmad,[6] on the impact of climate change on urban storm-water infrastructure.

Hydro-climate change at the global scale has been studied by the Intergovernmental Panel on Climate Change.[7] The change in global average surface air temperatures over the past century (1906–2005) shows a weak warming trend of 0.0074°C/year.[8] This linear warming trend integrates geographic factors, natural variability, and human activities including emission of greenhouse gases and urban growth over the entire globe. A recent finding based on observed changes in surface air temperatures for windy and calm conditions suggests that urban warming has not introduced significant bias into estimates of global warming.[9,10] This appears to be also the IPCC[7] position. However, changes in surface air temperatures and precipitation on a local or regional scale, integrate the global warming of the atmosphere by the global greenhouse effect, and the local urban heat island (UHI) effect.

Urban climate is the subject of a book with this title by Landsberg,[11] and a book chapter on UHIs by Voogt.[12] The effect of UHIs on global climate change is still a subject of much discussion and interpretation but it is not the subject of this paper. We merely determine local trends in Japan and compare them to each other and to the global record.

Air temperature change in Japan has previously been analyzed by Fujibe.[13–15] Recently Das et al[16] discussed urban bias in the centennial scale temperature trends at the Japan Meteorological Agency (JMA) stations. For precipitation, Fujibe also documented the change at 51 stations in Japan since 1901, including a decrease in precipitation days over the last century.

The main objective of this paper is to give an overview of hydro-climatic changes in urban and rural areas of the northern and southern regions of Japan, and the acceleration of atmospheric warming in Japan in recent decades. The main part of the paper is preceded by a brief summary of the climate of Japan.

The results to be presented will show how global warming and UHIs have affected the increase in the surface air temperature and changes in precipitation on local and regional scales in Japan in the last 100 years. Taking into account the location and the degree of progressive urbanization, several cities and rural areas are chosen as study sites. Data collected by the JMA are used in the study.

In this paper we analyze the features of climate change at 16 climate observatories in Japan over the 1906–2005 (100 year) period. Changes in air temperature and precipitation in urban and rural locations are determined separately, and trends over the most recent 25, 50, and 100 years are presented.

Climate of Japan

Japan stretches over 20° of latitude, from 25° to 45°N, and has extreme elevations from 0 to 3776 m (Mount Fuji). The terrain ascends from sea level to up to 1500 m on the Sea of Japan. The interior region's altitude is 1500–3000 m. The total land area is 377,800 km^2 and the length of the coastline is 29,750 km. About 75% of Japan's land area is mountainous, and about 25% is coastal plains and basins. Only 11% is arable land, a much larger portion is forests. Japan's population is concentrated on the coast. Over 35 million people live in the Greater Tokyo area. There are several other large urban metropolitan areas with populations of several millions.

The climate of Japan is highly diverse and varies from sub-tropical in the south to cool temperate and sub-arctic in the north. Mean monthly and other weather information is provided by the JMA, 1-3-4 Otemachi, Chiyoda-ku, Tokyo, Japan.

Japan's climate is governed by seasonal winds and therefore characterized as monsoonal. The neighboring Asian landmass, the surrounding oceans, and the country's latitudinal extent, have great influence on Japan's climate. The highly diverse topography causes numerous local climate variations. From late September to late March, an eastward flow of cold air is typically produced by high pressure over eastern Siberia and low pressure over the western Pacific. This winter monsoon picks up moisture over the Sea of Japan, deposits it as precipitation (rain or snow) on the western (Sea of Japan) landside of Japan, and brings dry, windy weather to the eastern (Pacific) landside. From about mid-April to early September, the atmospheric pressure system is reversed and warm moist air flows typically from southeast to northwest across the islands of Japan. This summer monsoon brings warmer temperatures in addition to rain. In late summer and early fall, destructive typhoons occur frequently, especially in the southwest of Japan.

Climate Data

The JMA operates 157 national weather stations for the government of Japan. Of these, 62 stations have daily records for the past 100 years. Climate data for 16 of these stations were obtained from the JMA and used in this study. The dataset used includes observed annual and mean monthly air temperature, annual precipitation, and the number of days with precipitation at each of the study sites. The data used cover the 100 year period from Jan 1, 1906 to Dec 31, 2005. No missing data had to be filled in.

The study sites (Fig. 1) were selected based on geographic location and population density. The latitude, longitude, elevation, and names of the weather observatories are listed in Table 1a, and information on population at or near each study site, obtained from the Japan Ministry of Internal Affairs and Communications is given in Table 1b. The 16 study sites are believed to be representative of Japan as a country. The majority of the 16 study sites were located less than 50 km from the nearest ocean. Oceanic effects can therefore be incorporated. All but one site (weather station) were at elevations less than 50 m AMSL (above mean sea level). The effect of topographic elevation could therefore not be assessed.

Some climate observatories underwent site changes during the analysis period. There have also been changes in observational equipment (eg rain gauges) and practice.[17] While data inhomogeneity in the present study is a limitation for the accuracy of the quantitative results, it is believed that it does not affect the major findings.

Japan has several climate types depending on the location (latitude and longitude) and topography (altitude and proximity to the ocean). Five climate types are specifically identified in Table 1a based on precipitation and air temperature:

(1) Japan Sea climate: There is a lot of precipitation in winter caused by the monsoon from the Asian continent.

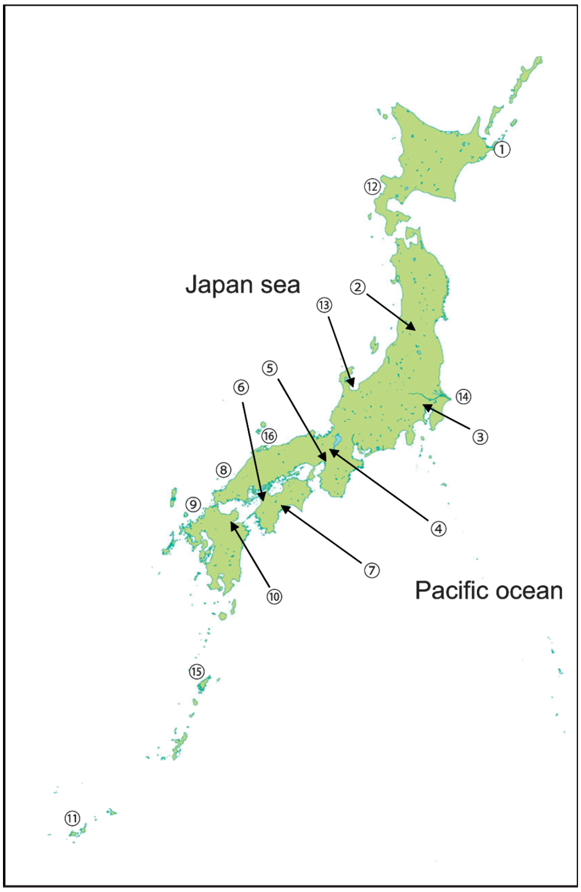

Figure 1. Locations of the study sites (weather stations) 1–16 on a map of Japan.

(2) Pacific climate: Rainfall is due to the monsoon from the Pacific Ocean and typhoons, and occurs from the rainy season to summer.
(3) Inland climate: The effect of monsoons on the precipitation in the area surrounded by mountains is of little significance, and seasonal climate variation is moderate.
(4) Subarctic climate: Annual precipitation is less than in the other regions because there is no rainy season. Some precipitation occurs in the form of snow.
(5) Subtropical climate: Air temperatures are warm and precipitation is plentiful during the entire year.

Methods

The study sites are divided into three categories according to population density:

(A) Large metropolitan urban areas: population during the last couple of decades has been over one million.
(B) City or urban areas of significant size: population during the last couple of decades has been over 100,000 and less than one million.
(C) Rural areas: Population during the period has been less than 100,000.

Four major metropolitan areas (category A), four cities of significant size (category B), and eight rural sites (category C) are included in the 16 selected weather stations. A metropolitan area is defined as a region made up of several large cities in sufficient proximity and their surrounding areas.

Japan's population in 2010 was estimated to be 127.3 million, and the average population density was 337 individuals per km^2. Since the weather records analyzed go back to 1906, one has to wonder what the populations were then. We were not able to find complete records from 100 years ago, except a few population figures from 1889. Populations were considerably smaller than they are now (Table 1b). Not counting suburban development, the population growth of the cities from 1889 to 2010 has been from fivefold for Kyoto to nearly thirtyfold for Fukuoka. Population in metropolitan urban areas (megalopolises) has not increased monotonically. One cause of population fluctuation was WWII (clearly visible in Figure 6 for the Tokyo area). Population changes in rural areas are considered immaterial for this study.

The study sites were also divided into a northern and a southern region. A latitude of 35 N was the dividing line.

Data were obtained from the JMA for the national weather stations at the 16 selected study sites. Mean annual air temperatures and total annual precipitation over the period of record (1906–2005) were calculated, and so were standard deviations and variation coefficients.

Linear regression equations were fitted to the annual data and to winter (January) and summer (August) records to determine 100 year trends in mean annual air temperature and total annual precipitation. The goodness of fit was determined by the coefficient of determination (r^2). Optimum fit is at $r^2 = 1.0$. In addition, the root mean square error (RMSE) was calculated.

Linear trends of air temperatures over shorter, recent periods of 50 years (1956–2005) and 25 years (1981–2005) were also calculated for the 16 study sites and compared to the linear trend for the full 1906–2005 (100 year) period to determine if warming had accelerated or slowed in recent years.

Results of the statistical parameter values were tabulated and interpreted for each study site separately, and for the average of the entire data set. To assess the effects related to latitude, averages of statistical parameter values were calculated for eight sites in the northern and eight in the southern half of Japan (dividing latitude is 35°N). To assess UHI effects, averages of statistical parameter values for study sites in categories (A), (B), and (C) were calculated separately. Because of the strong seasonality of Japanese climate, air temperature trends were also determined for the months of January (winter) and August (summer).

The number of days with precipitation and the quotient of annual precipitation (mm) to actual days of precipitation (average daily precipitation intensities) in a year were calculated and their changes were correlated with annual air

Table 1a. Study sites (weather stations).

SITE	LATITUDE (°)	LONGITUDE (°)	ELEVATION AMSL (m)	POPULATION CATEGORY	CLIMATE	GEOGRAPHIC LOCATION
1	43.33	145.58	25.2	C	Subarctic	Nemuro[a]
2	38.25	140.34	152.5	B	Japan sea	Yamagata[b]
3	35.69	139.69	6.1	A	Pacific	Tokyo[b]
4	35.01	135.77	41.4	A	Inland	Kyoto[b]
5	34.69	135.50	23.0	A	Inland	Osaka[b]
6	33.84	132.77	32.2	B	Inland	Matsuyama[c]
7	33.56	133.53	0.5	B	Pacific	Kochi[c]
8	34.90	132.08	19.0	C	Japan sea	Hamada[b]
9	33.59	130.40	2.5	A	Pacific	Fukuoka[d]
10	33.24	131.61	4.6	B	Inland	Oita[d]
11	24.34	124.16	5.7	C	Subtropics	Ishigaki[e]
12	48.80	140.22	33.4	C	Japan sea	Sutsu[a]
13	36.80	137.05	11.6	C	Japan sea	Hushiki[b]
14	35.73	148.85	20.1	C	Pacific	Thoushi[b]
15	28.37	129.45	2.8	C	Pacific	Naze[e]
16	35.53	133.23	2.0	C	Japan sea	Sakai[b]

Category A: megalopolis, metropolitan urban area (2010 population is over 1 million); Category B: city, urban area (2010 population is between 100,000 and 1 million); Category C: rural area (2010 population is less than 100,000).
Notes: [a]Hokkaido. [b]Honshu. [c]Shikoku. [d]Kyushu. [e]Ryuku Islands.

temperatures and their changes. Results of this analysis were compared with findings by the IPCC for global warming during the identical period (1906–2005). Trends for precipitation parameters were expressed as coefficients of determination (r^2) and RMSE values.

Results

Annual averages and standard deviations.

Annual air temperatures. Longterm average annual air temperature (Tables 2 and 3) ranges from 5.8°C at Nemuro, in the northern island of Hokkaido, to 23.7°C at the small southern

Table 1b. Estimates of population and area of study sites (weather stations). Data are from the Ministry of Internal Affairs and Communications, Japan.

SITE	2010 POPULATION (MILLION)	2010 AREA (km²)	2010 POPULATION DENSITY/(km²)	1889 POPULATION (MILLION)
1	0.029	512.72	57	
2	0.254	381.34	667	
3	8.95	621.83	14390	1.390
4	1.47	827.90	1780	0.280
5	2.67	222.47	11990	0.476
6	0.517	429.05	1205	0.033
7	0.343	309.22	1109	0.032
8	0.062	689.60	89	
9	1.46	341.32	4277	0.053
10	0.47	501.28	945	
11	0.047	229.00	204	
12	0.0034	95.37	36	
13	0.012	150.6	78	
14	0.070	83.91	836	
15	0.043	127.6	337	
16	0.035	28.79	1224	

island of Ishigaki, with an average of 14.8°C for all 16 study sites. The standard deviation (°C) of annual average air temperature decreases from 0.90°C in metropolitan areas to 0.57°C in rural areas (Table 2), and is about the same (0.67–0.69°C) in the cooler north and the warmer south of Japan.

The variation coefficient of annual average air temperatures has an average value of 0.051 over 16 sites. Variation coefficients are the highest for the colder northern sites 1 and 12, and the lowest for the warmer southern sites 11 and 15 (Table 2) as could be anticipated because of the lower annual average values. The variation coefficient of longterm average annual air temperature is higher in large metropolitan areas (0.058 on average) than in smaller urban and rural areas (0.048 on average) (Table 2).

Annual precipitation. Total annual precipitation at the 16 sites (Table 4) is on average 1740 mm, but varies from 1040 mm at Nemuro, in the colder northeastern Hokkaido, to nearly 3000 mm at the warmer southern island of Naze. Precipitation increases going from north to south in Japan, but orographic effects and proximity to the ocean have strong local influence. Sites with inland climate or located near the Japan Sea (sites 2, 4, 5, 6, 8, and 10) have average annual precipitation near 1500 mm (range 1200–1680 mm), and Pacific sites (3, 7, and 9) have an average of 1920 mm (range 1530–2600 mm).

The lowest standard deviation of annual precipitation, ~180 mm, is found at the northern sites 1, 2, and 12 (Fig. 1), and the highest, ~500 mm, at the southern sites 7, 11, and 15 (Table 4). The variability of annual precipitation as measured by the average variation coefficient, 0.175, for all 16 sites is moderate. The coefficient of variability for annual precipitation is only slightly lower in the north (0.16) than in the south (0.19) (Table 4). Variation coefficients of annual precipitation seem uncorrelated with population (A), (B), or (C).

Warming trends in the past 100 years.

Trends of annual average air temperatures. Figure 2 is a plot of local annual surface air temperatures recorded from 1906 to 2005 at four sites, from the far north to the far south. The linear regression lines, also shown in Figure 2, indicate significant and somewhat surprisingly linear warming trends. At Nemuro, a rural site in northeastern Hokkaido, and in Tokyo, the trends are 0.0099 and 0.0307°C/year, respectively, or 0.99 and 3.07°C

Table 2. 1906–2005 annual air temperature.

SITE	AVERAGE (°C)	STANDARD DEVIATION (°C)	VARIATION COEFFICIENT (–)	TREND (°C/YEAR)	COEFFICIENT OF DETERMINATION (r^2) (–)	RMSE OF LINEAR FIT (°C)
1	5.8	0.656	0.113	0.0099	0.189	0.591
2	11.1	0.648	0.058	0.0143	0.407	0.499
3	15.0	0.988	0.066	0.0307	0.803	0.439
4	14.9	0.893	0.060	0.0266	0.740	0.456
5	15.8	0.811	0.051	0.0233	0.686	0.455
6	15.5	0.715	0.046	0.0196	0.625	0.438
7	16.1	0.694	0.043	0.0181	0.570	0.455
8	14.9	0.569	0.038	0.0124	0.395	0.442
9	15.8	0.895	0.057	0.0273	0.773	0.428
10	15.5	0.707	0.046	0.0187	0.585	0.456
11	23.7	0.490	0.021	0.0120	0.499	0.347
12	8.3	0.545	0.066	0.0073	0.150	0.503
13	13.4	0.588	0.044	0.0121	0.352	0.473
14	15.0	0.649	0.043	0.0096	0.181	0.588
15	21.2	0.463	0.022	0.0094	0.344	0.375
16	14.6	0.578	0.040	0.0117	0.340	0.470
Average	14.8	0.681	0.051	0.0164	0.477	0.463
Average (A)	15.4	0.897	0.058	0.0270	0.751	0.445
Average (B)	14.6	0.680	0.048	0.0177	0.547	0.462
Average (C)	14.6	0.567	0.048	0.0106	0.306	0.474
North[1]	12.9	0.694	0.061	0.0152	0.395	0.501
South[2]	17.3	0.668	0.040	0.0176	0.560	0.425
IPCC*				0.0074		

Notes: [1]Above 35°N latitude, [2]Below 35°N latitude, * from Meehl et al. (2007).

Table 3a. Annual air temperature warming trends (α_{years}) for 100 years (1906–2005), recent 50 years (1956–2005), and recent 25 year (1981–2005).

ALL SITES	α_{100} (1906–2005) (°C/YEAR)	α_{50} (1956–2005) (°C/YEAR)	α_{25} (1981–2005) (°C/YEAR)	α_{50}/α_{100}	α_{25}/α_{100}
Lowest	0.0073	0.0087	0.0245	1.03	1.89
Highest	0.0307	0.0331	0.0708	1.57	4.92
Average	0.0164	0.0209	0.0474	1.30	3.14
Average (A)	0.0270	0.0311	0.0560	1.16	2.09
Average (B)	0.0177	0.0243	0.0593	1.37	3.38
Average (C)	0.0106	0.0141	0.0371	1.33	3.54
North[a]	0.0152	0.0216	0.0526	1.26	3.47
South[b]	0.0176	0.0202	0.0423	1.34	2.81
IPCC*	0.0074	0.013	~0.03	1.76	~5.0

Notes: [a]Above 35°N latitude. [b]Below 35°N latitude. *Meehl et al (2007).

air temperature increases over the 100 year period, 1906–2005. Both are substantial increases, but they differ by a factor of three. The warming trend of 0.0307°C/year in metropolitan Tokyo is the highest of all 16 study sites. The 100 year trend of 0.0099°C/year at the northern rural site (1) almost matches the trends of 0.0096 and 0.0094°C/year at the southern rural sites (14) and (15), respectively. The lowest trend (0.0073°C/year) was obtained for the rural site (12), in Hokkaido.

Surface air temperatures in Japan have risen at all 16 study sites (Table 2). The average trend from 1906 to 2005 for all 16 sites was 0.0164°C/year, slightly lower (0.0152°C/year) for the colder northern sites (average annual air temperature is 12.9°C), and slightly higher (0.0176°C/year) for the warmer (average annual temperature is 17.3°C) southern sites. Latitude appears to have a much weaker influence on the results than urbanization.

On average, the warming trends in mean annual air temperatures were 0.0270, 0.0177, and 0.0106°C/year for site categories A (metropolitan areas), B (cities), and C (rural areas), respectively (Tables 2 and 3a). Very large metropolitan areas (A) have experienced warming trends over the last 100 years that are, on average, 2.55 times larger than those in rural areas (C). Cities (B) with populations between 100,000 and 1,000,000 experienced temperature rises that were, on average, 1.67 times higher than in rural areas.

The linear fit of the trend lines for annual average air temperatures at all 16 sites has an average $r^2 = 0.48$, and an average RMSE of 0.46°C (range from 0.37 to 0.59°C). The coefficient of determination in metropolitan areas is $r^2 = 0.75$, drops to $r^2 = 0.55$ in smaller urban areas, and $r^2 = 0.31$ in rural areas. By comparison, the RMSE is fairly constant (≈0.46°C) for all three population densities (Table 2).

Seasonal air temperature trends. Climate trends are usually not uniform throughout a year, but can differ significantly by season.[18] Therefore mean monthly air temperatures in Japan were investigated separately for winter (January) and summer (August). Selecting January and July as representative for winter and summer, respectively, is customary in hydroclimate research (see eg Ref. 19, Table 1 and Fig. 2). August instead of July was chosen here, because August is often warmer in Japan than July due to the rainy season (usually from beginning of June to the middle of July). Trends in mean monthly air temperatures were investigated only for January and August, and results are given in Table 3b for urban areas. It appears that air temperatures in the period from 1906 to 2005 have risen more in winter than in summer. For the 100 year period, the average air temperature rise in eight urban areas was on average 1.28 times greater in winter (January) than in summer (August) (Table 3b).

Table 3b. Winter (January) and summer (August) air temperature warming trends in urban areas.

ALL SITES	JANUARY			AUGUST		
	α_{100} (1906–2005) (°C/YEAR)	α_{50} (1956–2005) (°C/YEAR)	α_{25} (1981–2005) (°C/YEAR)	α_{100} (1906–2005) (°C/YEAR)	α_{50} (1956–2005) (°C/YEAR)	α_{25} (1981–2005) (°C/YEAR)
Lowest	0.0132	0.0173	0.0517	0.0056	0.0129	−0.0089
Highest	0.0413	0.0444	0.0764	0.0240	0.0221	0.0459
Average (A)	0.0289	0.0382	0.0558	0.0208	0.0196	0.0255
Average (B)	0.0161	0.0276	0.0636	0.0139	0.0158	0.0269

Table 4. 1906–2005 annual precipitation amount.

SITE	AVERAGE (mm)	STANDARD DEVIATION (mm)	VARIATION COEFFICIENT (–)	TREND (mm/YEAR)	CHANGE (% IN 100 YEARS)	COEFFICIENT OF DETERMINATION (r^2) (–)	RMSE OF LINEAR FIT (mm)
1	1040	181	0.174	–0.114	–1	$<10^{-3}$	181
2	1200	173	0.144	–1.393	–12	0.054	169
3	1540	269	0.175	–2.148	–14	0.053	262
4	1550	276	0.178	–0.380	–2	0.002	276
5	1320	228	0.173	0.474	4	0.002	228
6	1340	255	0.190	–0.702	–5	0.006	255
7	2600	512	0.197	–0.017	0	$<10^{-3}$	512
8	1680	290	0.173	0.779	5	0.006	289
9	1630	332	0.204	–0.177	–1	$<10^{-3}$	332
10	1660	341	0.205	0.474	3	0.002	341
11	2130	440	0.207	–2.125	–10	0.019	436
12	1239	189	0.153	–0.006	0	0.018	187
13	2263	302	0.133	0.000	0	0.003	302
14	1672	283	0.169	–1.474	–9	0.023	280
15	2996	559	0.187	–3.138	–10	0.026	551
16	1968	273	0.139	–0.205	–1	$<10^{-3}$	273
Average	1740	292	0.175	–0.600	–3	0.013	305
Average (A)	1510	216	0.182	–0.558	–3	0.014	275
Average (B)	1700	320	0.184	–0.572	–3	0.016	319
Average (C)	1874	315	0.167	–0.635	–3	0.012	312
North[a]	1828	214	0.158	–0.646	–3.5	0.019	241
South[b]	1920	370	0.192	–0.554	–2.9	0.008	368

Notes: [a]Above 35°N latitude. [b]Below 35°N latitude.

Warming trends in recent 50 and 25 year periods.

Trends of annual average air temperatures. The linear warming trends of annual air temperatures at each study site over the recent 50 years (1956–2005) and 25 years (1981–2005) are given in Table 3a. The values suggest that air temperature rise in Japan has accelerated substantially. Average factors of increase for the most recent 50 and 25 year periods relative to the 100 year period (1906–2005) are 1.3 (range 1.03~1.57) and 3.1 (range 1.81~4.92), respectively. Values for individual sites are given in Table 3a.

Partitioned into categories (A)–(C) for population, warming trends have accelerated, on average, by a factor of 1.16 (range 1.03~1.37) for large urban metro areas (A), by 1.37 (range 1.12~1.54) for cities (B), and by 1.33 (range 1.18~1.57) for rural areas (C) (Table 3a) in the 1956–2005 time window relative to 1906–2005. In other words, warming over the recent 50 years accelerated the least in the large metropolitan areas (A), and more in the urban (B), and rural areas (C). Intermediate urban areas (B) had the highest warming trends, which would point to a growing UHI effect, whereas large metropolitan areas already had an established one.

In the last 25 years warming has accelerated even more (Table 3a). From the 100 year period (1906–2005) to the 25 year period (1981–2005) warming trends have, on average, increased by a factor of 2.09 (range 1.89~2.41) for metropolitan areas (A), by 3.38 (range 2.71~3.79) for urban areas (B), and by 3.54 (range 2.04~4.92) for rural areas (C). In other words, warming over the recent 25 years accelerated the least in the established metropolitan areas (A), and substantially more in the urban areas (B) and rural areas (C), compared to the 100 year period (1906–2005).

Trends of seasonal air temperatures. Seasonal differences in climate warming have also increased in Japan. It appears that air temperatures in the periods 1956–2005 and 1981–2005 have continued to rise more in winter than in summer (Table 3b). The differences in air temperatures between summer and winter have become smaller. For the 50 and 25 year periods the average air temperature rise in eight urban areas was on average 1.34 and 2.27 times, respectively, and greater in winter (January) than in summer (August) (Table 3b).

Changes in precipitation.

Total annual precipitation amounts. Figure 3 gives examples of the total annual precipitation records at four study sites spread

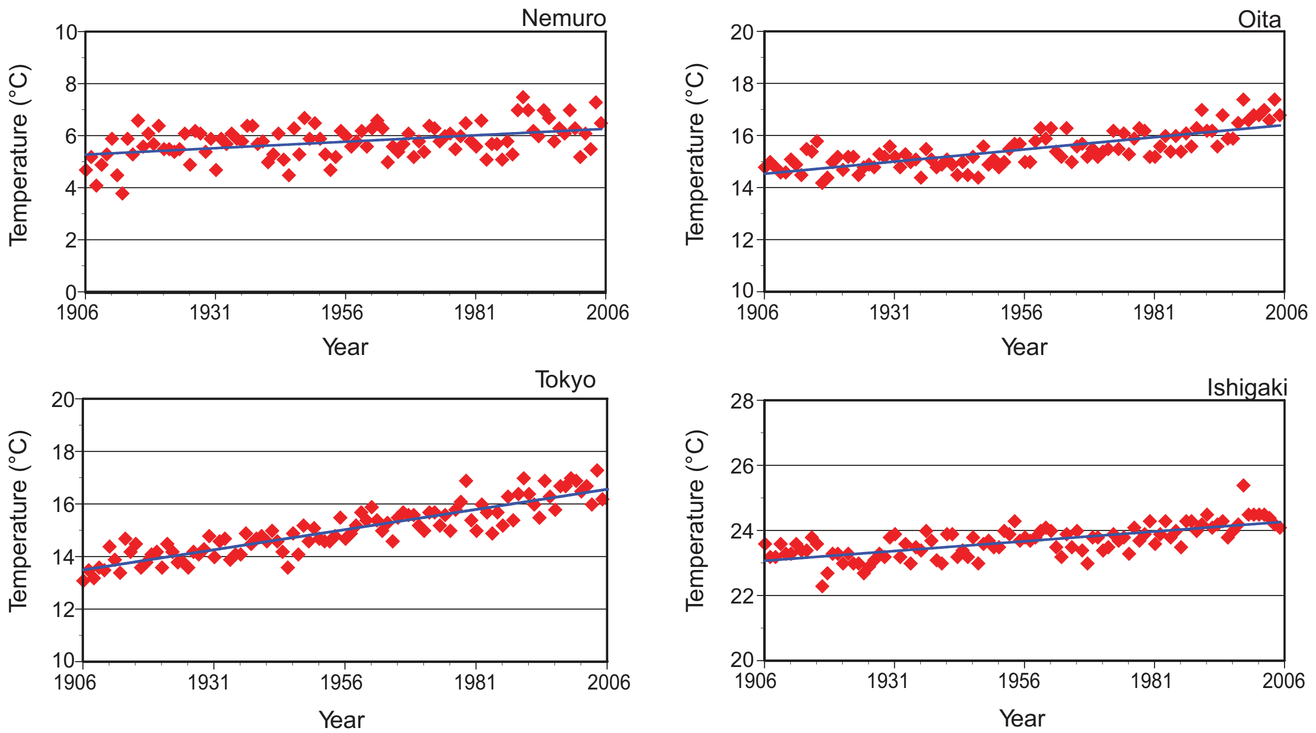

Figure 2. Record of mean annual air temperature (°C) at site 1 (Nemuro, rural), site 3 (Tokyo, megalopolis), site 10 (Oita, urban), and site 11 (Ishigaki, rural) from 1906 to 2005 (100 years). A linear 100 year warming trend is shown by a line.

from north (Nemuro, Hokkaido) to south (Ishigaki, Ryuku Islands) over the period 1906–2005 (100 years). One can see in these examples that the annual precipitation has not changed much in the last 100 years. The fitted lines indicate a small decrease at most sites. Only at 3 of the 16 study sites has annual precipitation increased (Table 4). Trends in annual precipitation at all 16 study sites show a range from −3.1 mm/year (decrease) to +0.8 mm/year (increase) with an average of −0.6 mm/year. This is a small number compared to the 1740 mm annual precipitation. The most extreme changes in annual precipitation at the 16 study sites over the 100 year period from 1906 to 2005 are a decrease by 14% in Tokyo (site 3), and an increase by 5% in Hamada (site 8). The average percentage change for all 16 stations has been −3% in 100 years. The calculated trends in precipitation (Table 4) are statistically insignificant; the coefficients of determination are all very low ($r^2 \leq 0.054$). Overall, annual precipitation amounts have not changed significantly in Japan over the period from 1906 to 2005.

There seems to be no correlation between the trends in annual precipitation amounts, population, or latitude at the 16 individual study sites.

Annual days with precipitation. Records of annual days with precipitation from 1906 to 2005 show fewer annual rainfall days at the end of the 100 year period (Fig. 4). The number of precipitation days has decreased at each of the 16 study sites (Table 5). The average decrease for all 16 records is 12 days of precipitation or −8%; decreases have a range from 4 to 34 days of precipitation, or −3 to −21%. The decrease in days with precipitation appears to be higher at sites in the south than in the north (15 vs. 9 days or −10% vs. −6%, respectively), and slightly smaller in the large urban metro areas than in rural areas (10 vs. 15 days, or −8 vs. −9%, respectively).

Daily precipitation intensities. On days with precipitation, intensities (mm/day) have increased at 13 study sites and decreased at 3 study sites over the past 100 years (Table 6). Figure 5 shows increasing precipitation intensity in Nemuro (Hokkaido) and decreasing intensity in Tokyo. The highest increases have occurred at three rural sites in the south (Kochi, Hamada, and Ishigaki), and the highest decreases have occurred at three sites in the north (Yamagata, Tokyo, and Sutsu). The average increase in daily precipitation intensity over the 1906–2005 (100 year) period is, however, only 0.6 mm/day or 4% (range from −0.46 to +2.35 mm/day or −6 to +14%). Increases in average daily precipitation intensities have been similar in urban and rural areas. Annual air temperature and precipitation are considered in this paper. Extreme events such as localized torrential downpours have increased as temperatures rise. An investigation of individual storm events (short time scales) is, therefore, necessary. Observed global temperature and precipitation extremes, eg warm days, cold days, and maximum 1 day precipitation amount, were reported by Alexander et al.[20]

Interpretation of Results

Annual air temperature rises in rural vs. urban areas. The UHI effect is a well-known phenomenon.[12] UHI

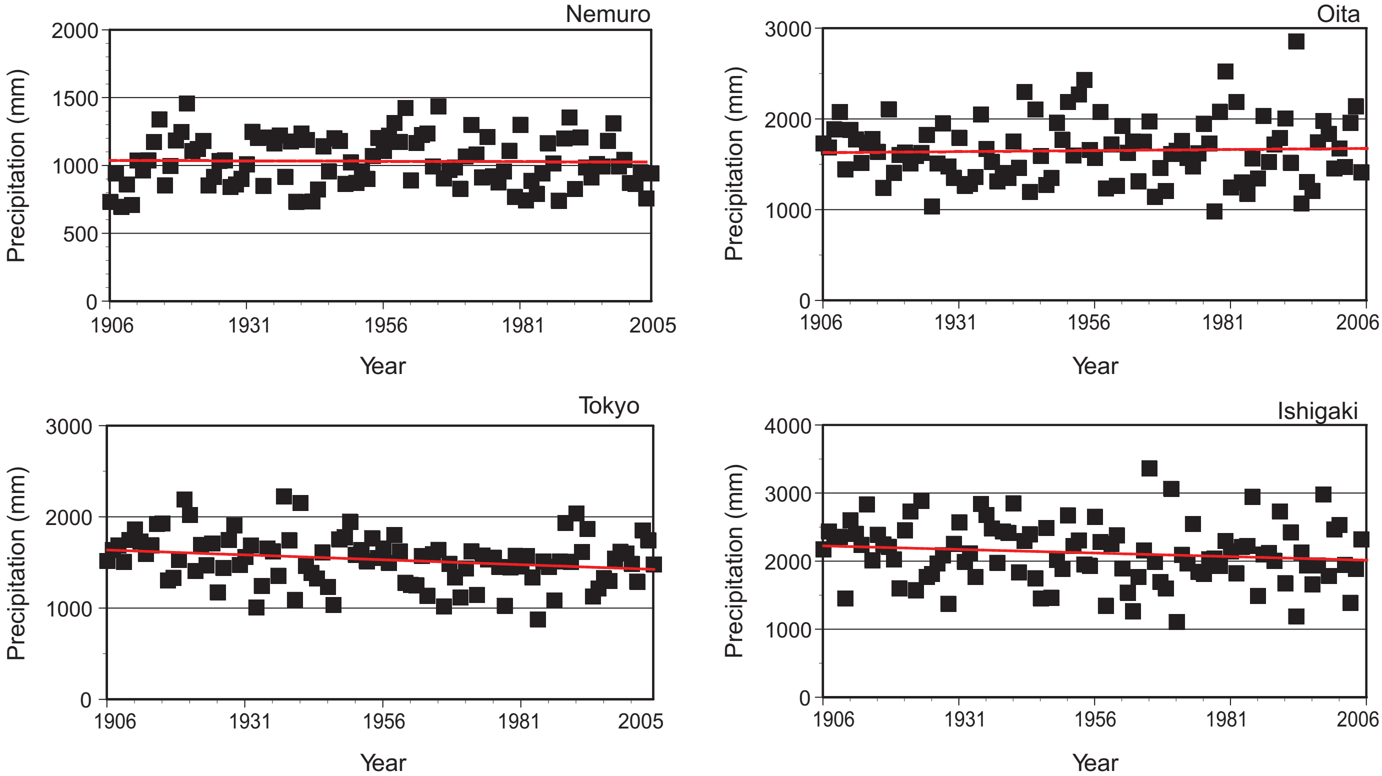

Figure 3. Record of annual precipitation (mm) at site 1 (Nemuro, rural), site 3 (Tokyo, megalopolis), site 10 (Oita, urban), and site 11 (Ishigaki, rural) from 1906 to 2005 (100 years). A linear 100 year trend is shown by a line.

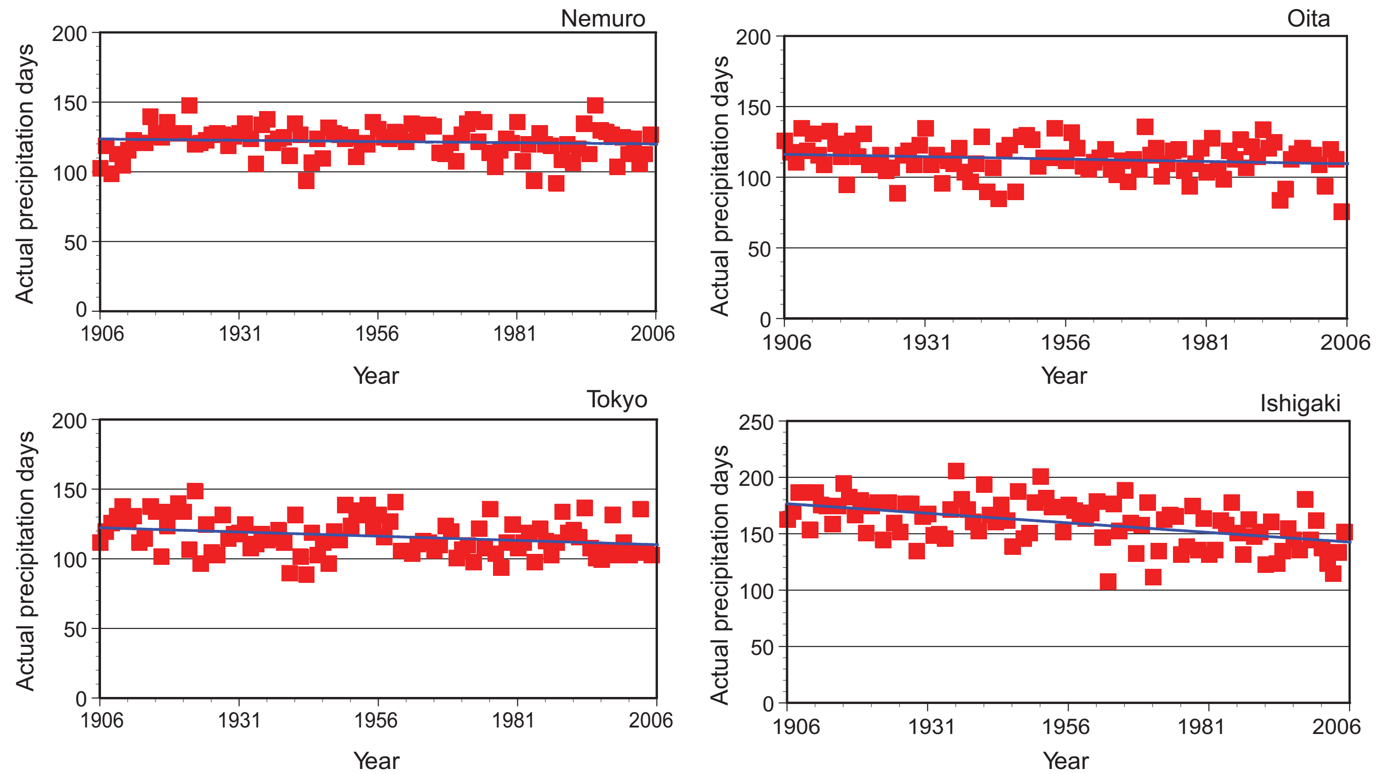

Figure 4. Record of annual precipitation days at site 1 (Nemuro, rural), site 3 (Tokyo, megalopolis), site 10 (Oita, urban), and site 11 (Ishigaki, rural) from 1906 to 2005 (100 years). A linear 100 year trend is shown by a line.

Table 5. 1906–2005 annual precipitation days.

ALL SITES	AVERAGE NUMBER (DAYS)	VARIATION COEFFICIENT (–)	TREND (DAYS/YEAR)	CHANGE (% IN 100 YEARS)	COEFFICIENT OF DETERMINATION (r^2) (–)	RMSE OF LINEAR FIT (DAYS)
Lowest	113	0.051	−0.343	−21	0.021	10.0
Highest	195	0.190	−0.035	−3	0.645	17.4
Average	146	0.125	−0.123	−8	0.372	12.1
Average (A)	122	0.152	−0.095	−8	0.467	11.6
Average (B)	132	0.127	−0.106	−8	0.487	11.7
Average (C)	165	0.110	−0.146	−9	0.268	12.6
North	153	0.117	−0.094	−6	0.291	11.4
South	139	0.132	−0.152	−10	0.454	12.8

effects on air temperatures have been investigated for many metropolitan areas. UHI processes have been reviewed eg by Arnfield,[21] and simulated, eg by Johnson et al.[22] Oke[23,24] addressed the energetics and the size effect of urban areas. Heat emissions from UHIs are eventually distributed by atmospheric circulation, but are not considered to indirectly contribute to global climate change in addition to chemical emissions and greenhouse effects.[9,10] The goal of our study was not to add another study of UHIs, but to study local climate change (including UHI effects) in all of Japan.

The observed atmospheric temperature record at each of our study sites integrates global warming and local heat island (UHI) effects. The heat island effect of urban areas on local trends in mean annual air temperatures in Japan can be clearly seen in Tables 2 and 3a. The four highest air temperature warming trends of 0.0307, 0.0273, 0.0266, and 0.0233°C/year were found in the large metro areas of Tokyo, Osaka, Kyoto, and Fukuoka (category A), respectively. The smaller urban areas and cities of Yamagata, Matsuyama, Kochi, and Oita (category B), had trends of 0.0141, 0.0196, 0.0181, and 0.0187°C/year, respectively. The weakest trends of 0.0073, 0.0094, 0.0096, and 0.0099°C/year were found in sparsely populated rural areas at sites 12, 15, 14, and 1, respectively (category C).

The strength of the UHI effect is compounded by several different processes, which are difficult to quantify individually. We retained the sizes of urban populations, urban areas, and urban population densities as three possible indicators (Table 1b) of UHI effects. The metropolitan areas (A) of Tokyo, Osaka, and Fukuoka are identified by populations greater than 1.46 million, and are reported to have areas of 622, 222, and 341 km^2, giving them population densities of 14400, 12000, and 4300/km^2. Kyoto does not fully fit because it is identified by an area of 828 km^2, giving it a population density of 1740/km^2. Yet Kyoto's warming trends are no outliers.

Rural sites in Table 1b are all identified by populations of less than 47,000 or 1/30 of the metropolitan urban sites. The "rural" weather stations are associated with a wide range of population densities from 40 to 1220/km^2 because the population areas may be identified by political boundaries or geographic limitations on islands or between mountains. The rural sites 14 and 16 (Thoushi and Sakai) have relatively high population densities, ie 840 and 1220/km^2, respectively, because their areas are small, ie 29 and 84 km^2, respectively (see Table 1b). Although their population densities are approaching those of urban areas, they are lacking the UHI effect because of the small total population.

Table 6. 1906–2005 daily average precipitation intensity.

ALL SITES	AVERAGE (mm/DAY)	VARIATION COEFFICIENT (–)	TREND (mm/DAY/YEAR)	CHANGE (% IN 100 YEARS)	COEFFICIENT OF DETERMINATION (r^2) (–)	RMSE OF LINEAR FIT (mm/DAY/YEAR)
Lowest	7.2	0.112	−0.0046	−6	$<10^{-3}$	0.87
Highest	20.4	0.221	0.0235	14	0.410	3.38
Average	12.1	0.170	0.0058	4	0.188	1.73
Average (A)	12.4	0.181	0.0025	2	0.259	1.73
Average (B)	13.4	0.180	0.0089	7	0.200	2.14
Average (C)	11.3	0.159	0.0060	5	0.148	1.53
North	10.5	0.152	0.0015	1	0.151	1.32
South	13.7	0.187	0.0102	8	0.226	2.14

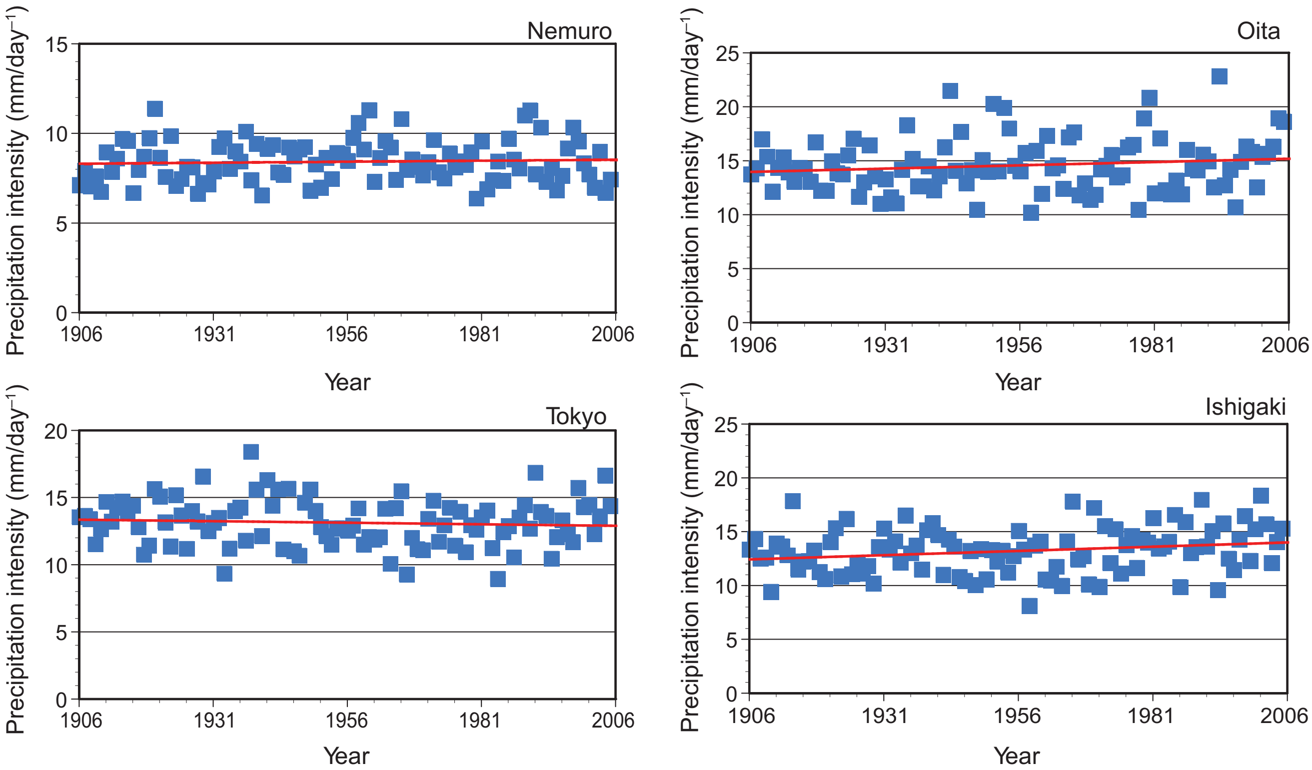

Figure 5. Record of average daily precipitation intensity (mm/day) at site 1 (Nemuro, rural), site 3 (Tokyo, megalopolis), site 10 (Oita, urban), and site 11 (Ishigaki, rural) from 1906 to 2005 (100 years). A linear 100 year trend (mm/day per year) is shown by a line.

These two examples show that at least two parameters are helpful in identifying UHI sites. Total population as well as population density has to exceed critical values before local UHI effects are produced. The requirement for identification of an UHI in Japan would seem to be: (1) total population ≥ 1.5 million, and (2) population density ≥ 2000/km^2. No significant UHI effects seem to be associated with populations ≤ 50,000 and population densities ≤ 2000. Advective and diffusive effects associated with wind are not included here.

Heat island effects would be expected to be absent at rural sites. The proximity to the oceans and seasonably reversible wind directions will limit any downwind effects from urban areas. Local impacts of urbanization can be assessed more specifically if the urban site is close to the rural site (within 25–50 km) and in the same climate regimes.[25] Considering urban and rural sites in vicinity would undoubtedly make for a more direct comparison. UHI effects can be identified by the differences between results for meteorological stations in all rural and all urban areas.

Linear warming trends in urban areas might be expected to be proportional to the rate of progressive urbanization over time. Population growth in two cities is tracked in Figure 6. Clearly, the population growth in Tokyo was non-linear, making the linearity of the air temperature rise more remarkable; this also suggests that infrastructure (asphalt, concrete, and steel surfaces) produces the UHI rather than population, but this simplistic view does not include the energy consumption of people in cities.[24,26]

Geographic patterns of warming trends are correlated with industrial and socioeconomic development.[27,28,30] In addition, the analysis of observed warming trends is rendered difficult by atmospheric circulation and its changes. We have not attempted to address these complex relationships. Instead, urban population numbers and densities have been used as indicators of urbanization, although population may not be as representative of the urban thermal environment as building characteristics or urban energy consumption.[23,24,29] Also, to be representative of an urban area, weather observatories must be located within the central area of a city[17] as they are in Tokyo, Osaka, and Kyoto, not at an airport outside it.

Acceleration of annual air temperature rises with time. Local air temperatures respond to many physical drivers, notably the rate of accumulation of greenhouse gases in the global atmosphere and the rate of local land use changes, especially urbanization. Following the progression of these two processes in time, one can imagine that local warming can accelerate or decelerate. Local air temperature increase does not have to be as linear as shown in Figure 3. It can be non-linear as shown in Figure 7.

An example of strongly accelerated warming in Japan is found in the city of Oita (site 10, and Fig. 3). Warming trends have been 0.0187, 0.0288, and 0.0708°C/year in the 100, 50, and 25 year periods, respectively. 0.0708°C/year

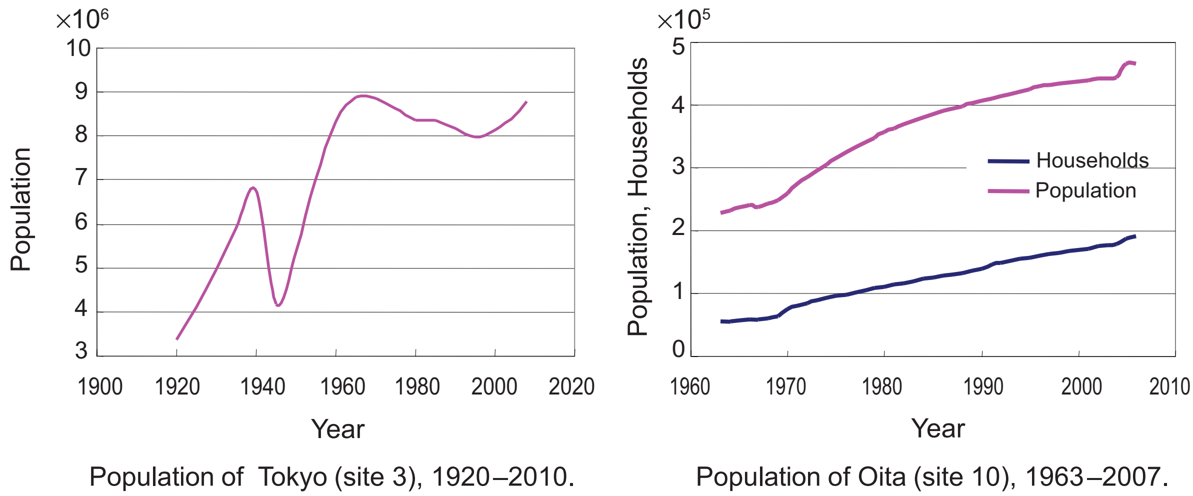

Figure 6. Population of Tokyo (site 3), 1920–2010, and Oita (site 10), 1960–2010.

is the highest trend found at all the 16 sites or times of this study. Oita has seen exceptional urban growth as shown in Figure 6, and urban population has nearly doubled in 50 years. Such growth will accelerate the urban UHI effect and air temperature rise.[14,15]

In the most recent 25 years, the weakest linear warming trends are 0.0245 and 0.0248°C/year in the southern rural islands of Ishigaki (site 11) and Naze (site 15), or 2.0 and 2.6 times the 100 year trends, respectively. It is noteworthy that even the weakest warming trends have more than doubled in the recent 25 year (1981–2005) period.

Annual air temperature rises in Northern vs. Southern latitudes. A comparison of accelerations of warming at northern and southern sites (Table 3a) shows that the difference is less than 20%. The higher warming trends were at the southern sites in the 1906–2005 period, whereas the warming trends became higher at the northern sites in the more recent 1981–2005 period.

Globally, the surface air temperature increase has been greater at higher northern latitudes; average air temperatures in the Arctic have increased at almost twice the global average rate in the past 100 years.[8] Over the range of latitudes

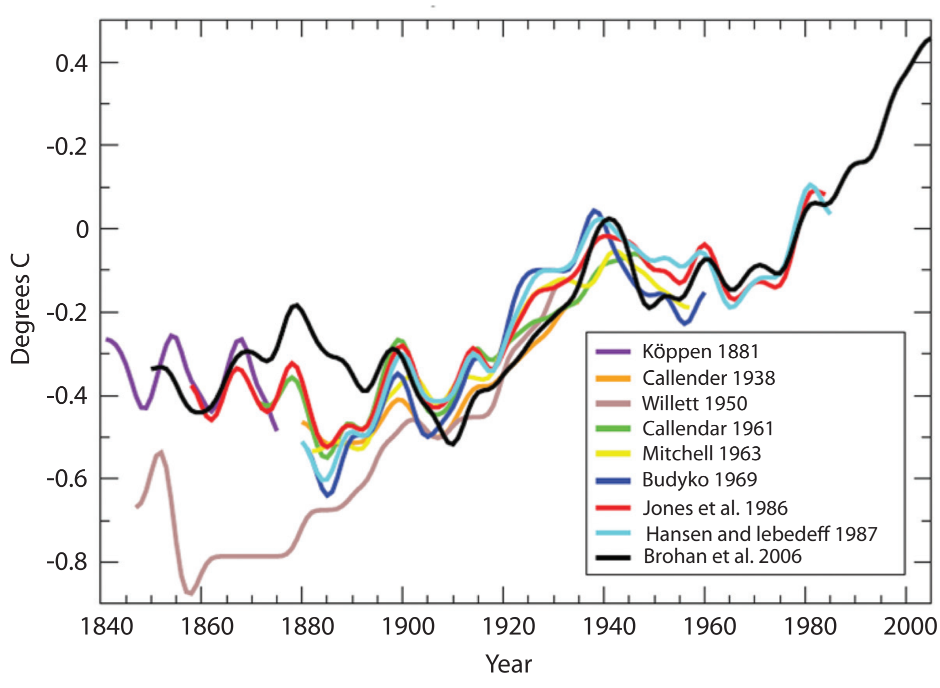

Figure 7. IPCC 2007, working group 1, historical overview of climate change. Temperature reconstruction in the last 150 years (global reconstructions).

encountered in Japan, latitude does not seem to have a strong effect on the linear warming trend as indicated by the averages for the northern and southern study sites.

Mean annual air temperatures in Japan have risen at all 16 study sites (Table 2). The average annual air temperature rise from 1906 to 2005 for all 16 sites was 0.0164°C/year, slightly lower (0.0152°C/year) for the colder northern sites (average annual air temperature is 12.9°C), and slightly higher (0.0176°C/year) for the warmer (average annual temperature is 17.3°C) southern sites. In the more recent 25 year period from 1981 to 2005 the warming trends were reversed to (0.0526°C/year) for the northern sites, and (0.0423°C/year) for the southern sites. Overall, latitude appears to have a much weaker influence on the results than has urbanization. Air temperature changes in Japan depend only weakly on latitudes.

Annual precipitation changes vs. air temperature changes. Compared to air temperature, precipitation is of a more "chaotic" nature—with finer and greater spatial variability—which also limits predictability of precipitation compared to the higher predictability of air temperature, as is clear from GCM outputs.[7]

In Japan the amount of annual precipitation remained essentially unchanged from 1906 to 2005 (Table 4), while the number of days with precipitation decreased (Table 5), and the average rainfall intensity on days of precipitation increased somewhat at 13 of 16 study sites (Table 6). A change in precipitation days at 51 stations in Japan since 1901, including the decrease in precipitation days over the last century has also been documented by Fujibe.

One may ask whether the decrease in annual rainfall days in Japan and the associated increase in daily rainfall intensity are related to (1) large-scale global climate change, and/or (2) local UHI effects. Figure 8a is a plot of three precipitation characteristics against annual air temperature at the 16 study sites. This semi-log plot does not reveal much new information, merely that in warmer climates the total annual precipitation and the precipitation intensity are higher, while the number of precipitation days is fairly unaffected by local air temperatures in Japan. Precipitation intensity increases with annual precipitation amount in Japan while the number of precipitation days remains fairly constant.

According to Figure 8b greater changes in daily rainfall intensity (mm/day) seem to occur where annual precipitation (mm/year) is higher. The coefficient of determination is $r^2 = 0.804$. While total annual precipitation at each study site has not changed significantly over the recent 100 years, patterns of precipitation have changed, such that the apparent rainfall intensity has increased—at least somewhat.

No correlation ($r^2 = -0.105$) was found between the trends in daily rainfall intensity and mean annual air temperature change (°C/year), over the period of record 1906–2005 (Fig. 9). This is not surprising since it is well-known that precipitation and temperature are not linearly related, and therefore no additional information would be expected from the correlation analysis between the trends of precipitation and temperature. It is noteworthy that in Figure 9 the data for the categories (A), (B), and (C) are separated from each other. If a separate line is fitted to the three data sets for (A), (B), and (C), the slopes are very similar, but overall, no relationship between trends in air temperatures and trends in precipitation can be detected.

Since local increases in mean annual air temperature do not have a correlation with changes in local rainfall intensity

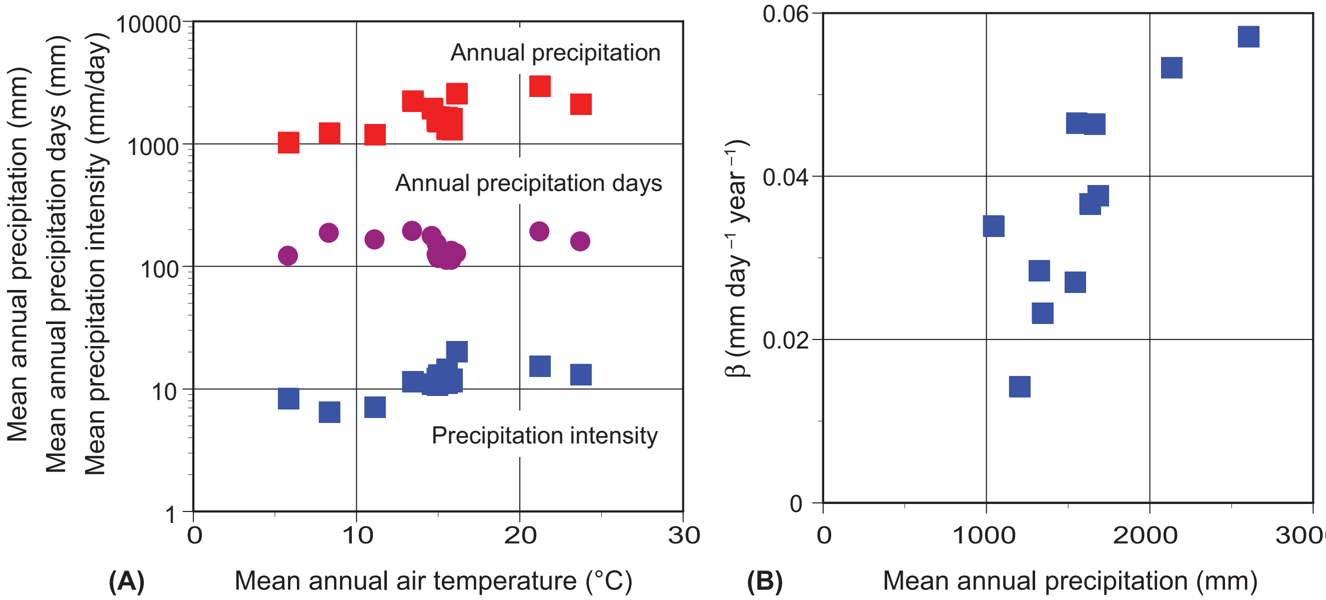

Figure 8. (**A**) Annual precipitation (mm), annual days with precipitation, and average precipitation intensity (mm/day) vs. mean annual air temperature (°C). (**B**) Trend in average precipitation intensity (β) (mm/day/year) vs. mean annual precipitation (mm).

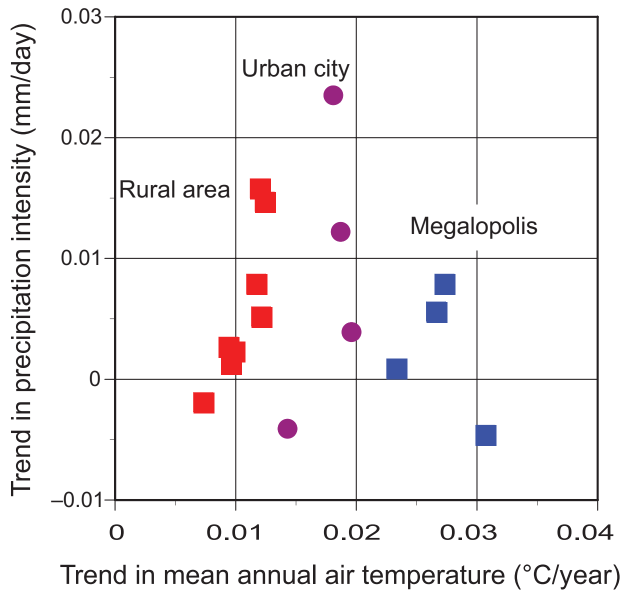

Figure 9. Linear trend in average precipitation intensity (β) (mm/day/year) vs. linear warming trend (α) (°C/year). Separate symbols are used for large metropolitan areas (**A**), cities (**B**), and rural areas (**C**).

(Fig. 9), precipitation intensity changes in Japan over the period 1906–2005 are probably caused by climate changes at larger than local scales. That Japan is surrounded by the sea may be one reason why UHIs do not have a significant effect on the changes in patterns of local precipitation. Monsoons have a strong effect on precipitation in Japan. Major urban metro areas cover only a small total area relative to the size of the country.

Comparison of global (IPCC) and Japanese synoptic climate trends.

Air temperatures. The global average air temperature on the ground surface has risen in the period 1906–2005 (Fig. 7). The linear trend was reported by the IPCC to be 0.0074 and 0.0130°C/year for the 100 year (1906–2005) and 50 year (1956–2005) periods, respectively. The 25 year (1981–2005) trend was estimated to be in the order of ~0.03°C/year.

Warming trends at rural sites would be expected to be essentially due to global warming, and heat island effects would be expected to be absent at rural sites.[19] Indeed, the lowest warming trends of 0.0073–0.0099°C/year at four rural sites and the average trend of 0.0106°C/year at all eight rural sites are consistent with the IPCC-reported global average warming trend of 0.0074°C/year for the 1906–2005 period.[8] Even the highest rural warming trends of 0.0117–0.0124°C/year at four rural study sites of this study are not out of line, although they seem to include some other local effects. A population (energy consumption) effect at the rural sites, or advective atmospheric circulation may account for the difference between the IPCC's 0.0074°C/year and the 0.0106°C/year for the eight rural study sites in Japan. The distance from large urban metro areas, the proximity to the oceans, and seasonally reversible wind directions would exclude all downwind effects from any large urban areas.

The global surface air temperature has risen more remarkably since 1956 than before. The 0.0130°C/year global temperature rise since 1956[8] is consistent with the trends found in this study for rural areas (category C) in Japan. The observed trends for the eight rural study sites were, on average, 0.0141°C/year (Table 3a) and had a range from 0.0087 to 0.0179°C/year in the recent 50 year period.

The 100 year trend at the eight rural sites (C) was, on average, 0.0106/0.0074 = 1.43 times higher than the global trend; the 50 year trend at the eight rural sites was, on average, 0.0141/0.0130 = 1.08 times the global trend; and the 25 year trend was 0.0371/(~0.03) = 1.24 times the global trend. Overall, the ratio of rural air temperature change in Japan to global air temperature rise identified by the IPCC, seems to remain in fairly consistent proportion at about 1.25, regardless of the time period considered, and despite significant acceleration of warming. If it is considered that air temperature rise in the northern hemisphere is larger on land than on sea, the 1.25 value is a meaningful result.

Precipitation. Historical local precipitation trends reported on a global scale are either positive or negative.[7] It was reported, for example, that precipitation increased significantly in the eastern parts of North and South America, northern Europe, and northern central Asia, but declined in the Mediterranean, southern Africa, and parts of southern Asia over the recent 100 years.[8] By comparison, the annual precipitation at each of the 16 study sites in Japan has not changed significantly in the last 100 years (Table 4).

Summary and Conclusions

1. Local hydro-climatic changes from 1906 to 2005 at 16 sites (weather observatories) in Japan have been investigated. Trends are summarized in Tables 3a and 7.
2. Local annual air temperatures have increased by an average 1.64°C (for all 16 sites) in 100 years. The largest increase from 1906 to 2005 was recorded in Greater Tokyo (3.07°C in 100 years), and the lowest in rural Sutsu, Hokkaido (0.73°C).
3. Local precipitation changes have been moderate (positive or negative) from 1906 to 2005, The largest decrease (–) of 315 mm was recorded in the southern island of Naze and the largest increase (+) of 78 mm at Hamada on the southern portion of the mainland (Honshu). The average precipitation change for all sites was a small decrease (–) of 60 mm.
4. The eight urban sites showed significantly larger increases in mean annual air temperature than the eight rural sites. The increases were largest in four metropolitan urban areas (more than 1 million population), compared to four smaller urban areas (100,000–1 million population).
5. Over the 1906–2005 period, mean annual air temperatures in large metropolitan urban areas rose, on average, 2.5 times more than in rural areas, and in smaller urban areas, 1.5 times more. The difference is interpreted as

Table 7. Summary of 1906–2005 annual precipitation and its trends in Japan.

	ANNUAL AVERAGE PRECIPITATION (mm)	TREND: ANNUAL AVERAGE (mm/YEAR)	PRECIPITATION DAYS (d)	TREND: PRECIPITATION DAYS (d/YEAR)	MEAN PRECIPITATION INTENSITY (mm/d)	TREND: PRECIPITATION INTENSITY (mm/d/YEAR)
16 study sites	1740	−0.60	146	−0.123	12.2	0.0058
Metro areas (A)	1510	−0.56	122	−0.095	12.4	0.0025
City areas (B)	1700	−0.57	132	−0.106	13.4	0.0089
Rural areas (C)	1874	−0.64	165	−0.146	11.3	0.0060
North of 35°N	1828	−0.65	153	−0.094	10.5	0.0015
South of 35°N	1920	−0.55	139	−0.152	13.7	0.0102

an indicator that the level of urban development (heat island) effects causes local air temperature increases over and above global warming.

6. The average air temperature rise of 1.06°C over 100 years in rural areas of Japan is consistent with the global air temperature rise of 0.74°C over 100 years determined by the IPCC.[8]
7. The mean annual air temperature rise at the 16 study sites in Japan has accelerated significantly in the most recent 50 and 25 year periods. The mean annual air temperature rise from 1981 to 2005 has been fastest in growing urban areas (0.059°C/year), and slowest in rural areas (0.0371°C/year) (Table 3a).
8. The relative increase in warming rates (°C/year) from the 1906–2005 (100 year) to the 1981–2005 (25 year) period has been higher in smaller urban areas than in established large metropolitan and rural areas (Table 3a).
9. Trends in annual precipitation have been very weak, compared to trends in annual air temperatures (Table 7). Air temperature change appears to be no driver of precipitation change.
10. Urban and rural sites experienced similar changes in the annual precipitation in Japan. The average of annual precipitation at all study sites in the 1906–2005 period was 1740 mm, including 1510 mm/year in large urban metro areas, and 1870 mm/year in rural areas.
11. Days with precipitation in a year decreased by an average 12 days for all sites from 1906 to 2005. The decrease was 10 days in urban areas and 14 days in rural areas. Precipitation occurred on 146 days annually (average for all study sites from 1906 to 2005).
12. Average intensity of precipitation on days of occurrence has risen, on average, by 0.6 mm/day from 1906 to 2005 for the study sites, respectively. Increases in precipitation intensities were similar in urban and rural areas. The average daily rainfall intensity on rainy days was 12.1 mm/day for all study sites in the 1906–2005 period.
13. Magnitudes and trends of hydro-climatic changes in northern and southern Japan (35°N is taken as the dividing line) are fairly similar (Tables 2, 3a, and 7). In the 1981–2005 period, rates of mean annual air temperature increases have become higher in the north (0.053°C/year) than in the south (0.042°C/year). In the 1906–2005 period, rates of mean annual precipitation intensity increases have been higher at sites in the south than in the north (on average 1.0 vs. 0.1 mm/day).
14. UHI effects have been strong on air temperatures and weak on precipitation.
15. Local air temperature increases in rural areas are taken as an indication of significant global warming in the absence of an UHI effect. The average rate of air temperature increase at eight rural study sites was 1.06, 1.41, and 3.71°C/100 years in the 100, 50, and 25 year periods, all ending in 2005. The corresponding IPCC-values for global warming are 0.74, 1.30, and ~3.0°C.

Author Contributions

Conceived and designed the experiments: MH. Analyzed the data: MH. Wrote the first draft of the manuscript: MH. Contributed to the writing of the manuscript: MH, HS. Agree with manuscript results and conclusions: MH, HS. Jointly developed the structure and arguments for the paper: MH, HS. Made critical revisions and approved final version: MH, HS. All authors reviewed and approved of the final manuscript.

DISCLOSURES AND ETHICS

REFERENCES

1. Kavvas M, ed. SPECIAL ISSUE: modeling of hydroclimate and climate change. *J Hydrol Eng.* 2011;16:969–1099.
2. Hossain F, Degu A, Yigzaw W, Burian S, Niyogi D, Shepherd J, Pielke R. Climate feedback–based provisions for dam design, operations, and water management in the 21st century. *J Hydrol Eng.* 2012;17(8):837–850.

3. Kang B, Ramírez J. Response of streamflow to weather variability under climate change in the Colorado rockies. *J Hydrol Eng.* 2007;12(1):63–72.
4. Aral, et al. 2011.
5. Berggren K, Olofsson M, Viklander M, Svensson G, Gustafsson A. Hydraulic impacts on urban drainage systems due to changes in rainfall caused by climatic change. *J Hydrol Eng.* 2012;17(1):92–98.
6. Forsee W, Ahmad S. Evaluating urban storm-water infrastructure design in response to projected climate change. *J Hydrol Eng.* 2011;16(11):865–873.
7. IPCC (Intergovernmental Panel on Climate Change). Climate change 2007, the physical science basics. In: Solomon S et al, ed. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press; 2007;93–940.
8. Meehl GA, et al. Global climate projections. In: Solomon S et al, ed. *Climate Change 2007. The Physical Science Basics. Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge Univ. Press; 2007:747–845.
9. Parker DE. Large-scale warming is not urban. *Nature.* 2004;432:290.
10. Parker DE. A demonstration that large-scale warming is not urban. *J Climate.* 2006;19:2882–2895.
11. Landsberg H. *The Urban Climate*. London: Academic Press; 1981.
12. Voogt JA. Urban heat island. In: Munn T, ed. *Encyclopedia of Global Environmental Change.* Vol 3. Chichester: Wiley; 2002:660–666.
13. Fujibe F. Temperature rising trends at Japanese cities during the last hundred years and their relationship with population, population increasing rates and daily temperature ranges. *Meteorol Geophys.* 1995;46:35–55.
14. Fujibe F. Detection of urban warming in recent temperature trends in Japan. *Int J Climatol*. 2009;29(12):1811–1822.
15. Fujibe F. Urban warming in Japanese cities and its relation to climate change monitoring. *Int J Climatol*. 2011;31:162–173.
16. Das L, Annan JD, Hargreaves JC, Emori S. Centennial scale warming over Japan: are the rural stations really rural? *Atmos Sci Lett*. 2011;12(4):362–367.
17. Oke TR. *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites*. Geneva, Switzerland: World Meteorological Organization; 2006.
18. Manabe S, Ploshay JJ, Lau N-C. Seasonal variation of surface temperature change during the last several decades. *J Climate*. 2011;24(15).
19. Trenberth KE. Changes in precipitation with climate change. *Climate Res*. 2011; 47:123–138.
20. Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL. Global observed changes in daily climate extremes of temperature and precipitation. *J Geophys Res*. 2006;111:1984–2012.
21. Arnfield JA. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int J Climatol*. 2003; 23:1–26.
22. Johnson GT, Oke TR, Lyons TJ, Steyn DG, Watson ID, Voogt JA. Simulation of surface urban heat islands under "ideal" conditions at night. Part 1: theory and tests against field data. *Boundary Layer Meteorol.* 1991;56:275–294.
23. Oke TR. City size and the urban heat island. *Atmos Environ*. 1973;7:769–779.
24. Oke TR. The energetic basis of the urban heat island. *Q J R Meteorol Soc.* 1982;108:1–24.
25. Mishra V, Lettenmaier DP. Climatic trends in major U.S. urban areas, 1950–2009. *Geophys Res Lett.* 2011;38:L16401.
26. Oke TR, Johnson GT, Steyn DG, Watson ID. 1991. Simulation of surface urban heat islands under "ideal" conditions at night. Part 2: diagnosis of causation. *Boundary Layer Meteorol*. 1991;56(4):339–358.
27. McKitrick R, Michaels PJ. A test of corrections for extraneous signals in gridded surface temperature data. *Climate Res*. 2004;26:159–173.
28. De Laat TJ, Maurellis AN. Evidence for the influence of anthropogenic surface processes on lower tropospheric and surface temperature trends. *Int J Climatol.* 2006;26:897–913.
29. Karl TR, Diaz HF, Kukla G. Urbanization: its detection and effect on the United States climate record. *J Climate*. 1988;1:1099–1123.
30. McKitrick R, Michaels PJ. Are temperature trends affected by economic activity? Reply to Benestad (2004). *Climate Res.* 2004;27:175–176.
31. Aral M, Guan J, Chang B. Dynamic system model to predict global sea-level rise and temperature change. *J Hydrol Eng.* 2012;17(2):237–242.