CrossMark

Urban and peri-urban precipitation and air temperature trends in mega cities of the world using multiple trend analysis methods

Aws A. Ajaaj[1] · Ashok K. Mishra[1] · Abdul A. Khan[1]

Abstract Urbanization plays an important role in altering local to regional climate. In this study, the trends in precipitation and the air temperature were investigated for urban and peri-urban areas of 18 mega cities selected from six continents (representing a wide range of climatic patterns). Multiple statistical tests were used to examine long-term trends in annual and seasonal precipitation and air temperature for the selected cities. The urban and peri-urban areas were classified based on the percentage of land imperviousness. Through this study, it was evident that removal of the lag-k serial correlation caused a reduction of approximately 20 to 30% in significant trend observability for temperature and precipitation data. This observation suggests that appropriate trend analysis methodology for climate studies is necessary. Additionally, about 70% of the urban areas showed higher positive air temperature trends, compared with peri-urban areas. There were not clear trend signatures (i.e., mix of increase or decrease) when comparing urban vs peri-urban precipitation in each selected city. Overall, cities located in dry areas, for example, in Africa, southern parts of North America, and Eastern Asia, showed a decrease in annual and seasonal precipitation, while wetter conditions were favorable for cities located in wet regions such as, southeastern South America, eastern North America, and northern Europe. A positive relationship was observed between decadal trends of annual/seasonal air temperature and precipitation for all urban and peri-urban areas, with a higher rate being observed for urban areas.

1 Introduction

More than 50% of the global population lives in cities, and it is projected to be 70% by 2050 (UNFPA 2007). The expansion of global urban area was about 60,000 km[2] during 1970–2000 (Seto et al. 2011) and it is projected to increase by 1.7 million km[2] in the less-developed countries during 2000 to 2050 (Angel et al. 2011). Development of urban areas significantly alters the natural land cover. Consequently, it has been suggested that human activities in cities lead to a distinct urban climate (e.g., urban heat island) in comparison to the less built-up areas. These changes are primarily attributed to three drivers including land cover change, greenhouse gas, and aerosols (Niyogi et al. 2009; Rosenzweig et al. 2011; Liu et al. 2014). The climate change can bring additional stresses to the urban environment leading to heat waves, extreme urban flood, and health problems for vulnerable urban populations (Rosenzweig et al. 2011).

Several studies indicated the possible influence of global warming on intensification of precipitation near urban centers (Diem and Mote 2005; Kug and Ahn 2013; Sun et al. 2014; Shahid et al. 2015; Han et al. 2015) https://www.researchgate.net/profile/Shamsuddin_Shahid. A positive correlation between precipitation and urbanization has been confirmed using different climate models (Changnon and Westcott 2002; Argüeso et al. 2016). Such response in urban rainfall patterns were mainly attributed to Urban Heat Island (UHI;

✉ Ashok K. Mishra
  ashokm@g.clemson.edu

  Aws A. Ajaaj
  aajaaj@g.clemson.edu

  Abdul A. Khan
  abdkhan@g.clemson.edu

[1] Glenn Department of Civil Engineering, Clemson University, 131G Lowry Hall, Clemson, SC 29634-0911, USA

Springer

Dixon and Mote 2003; Stallins et al. 2010; Bentley et al. 2010). However, there are few studies that did not agree with this hypothesis. For example, Tayanc and Toros (1997), Shepherd (2006) and Kusaka et al. (2014) found that air temperature in mega cities has no effect on urban rainfall, while Kaufmann et al. (2007) showed a decreasing precipitation trends over urban zones. A consensus whether the urbanization results in an increase in precipitation are yet to be confirmed (Laurian 2013). It is often a challenge to quantify the possible impact of UHI on urban rainfall, which is further compounded by lack of accurate observed data in the vicinity of urban areas.

Climatological trends in air temperature and precipitation have been extensively analyzed for different regions around the world (Keggenhoff et al. 2014; Pingale et al. 2014; Sharma et al. 2016). For example, Argüeso et al. (2016) investigated the possible urban effect on precipitation over western Maritime by examining two scenarios (before and after construction of urban areas). Several studies analyzed short-term trends in sub-daily air temperature and precipitation over multi-urban areas based on the direction of predominant storms (Shepherd et al. 2002; Kharol et al. 2013; Velpuri and Senay 2013). Alexander et al. (2006) investigated long-term (1901 to 2003) global daily air temperature and precipitation over the Northern Hemisphere mid-latitudes (and part of Australia) and observed a significant warming and wetting trends during the second half of the twentieth century (1951–2003).

Precipitation in urban area is highly influenced by many factors such as, hydroscopic nuclei, turbulence via surface roughness, and convergent wind flow which may lead to rain producing clouds (Burian and Shepherd 2005). The land use change (urbanization/imperviousness) can possibly influence the urban climate due to the changes in surface albedo, surface roughness, and thermal and hydrological features (Hu and Jia 2010). Therefore, evaluation of climatological trends in urban areas is important in order to plan, manage, and take actions regarding water related issues, such as water supply, avoiding over or under designing of water resource systems, and assessing the urban floods and droughts. Moreover, air temperature and precipitation trends in both urban and peri-urban areas should be examined to determine possible changes in local climatology. In this study, we used a long-term (>100 year period) gridded mean monthly air temperature and precipitation data to investigate: (a) annual and seasonal precipitation (air temperature) trends in 18 mega cities using multiple trend analysis methods. We have selected top three mega cities from each continent and each city was further classified into urban and peri-urban areas according to their percentage of land cover imperviousness; and (b) the decadal change in air temperature and precipitation as well as their possible relationship.

2 Study area

Three densely populated urban areas (>5 million people in population) from each of the six continents; namely, Asia (AS), North America (NA), Africa (AF), South America (SA), Europe (EU), and Australia (AU) were selected based on the population data provided by Environmental Systems Research Institute (ESRI). The geographic and climate information for the selected cities are provided in Table 1. These cities witness a wide range of climatic patterns, such as, tropical monsoon, humid continental, Mediterranean, high-land climate, humid sub-tropical, humid continental, oceanic climate, and semi-arid type.

The urban/peri-urban area is classified based on the percentage of the land imperviousness, (Lu and Weng 2006). Based on this criterion, areas with imperviousness greater than or equal to 20% are identified as urban areas (Ganeshan et al. 2013). For each urban area, the corresponding peri-urban area was delineated using a band width of 80.5 km (50 miles) from urban boundaries. The delineation between urban and peri-urban areas was accomplished manually using the Geographic Information System (GIS) maps. The band width of the peri-urban area was selected to include at least one precipitation and air temperature grid point within the selected polygon. Selected urban and their corresponding peri-urban areas are shown in Fig. 1. The percentages of imperviousness (land use) for the selected cities are shown in Fig. 2, where the percentages refer to the land imperviousness.

3 Data

Long-term terrestrial air temperature (TAT) monthly data available for the period 1900–2008 was used in this study. TAT data is compiled from actual station data gathered from several updated sources (e.g., Global Historical Climatology Network GHCN2) with support from the Institute of Global Environmental Strategies (IGES).

The Global Precipitation Climatological Center (GPCC) (full data reanalysis version 7) precipitation data (Schneider et al. 2014) are used to compare the precipitation trends in urban (peri-urban) areas. One of the main reasons for selecting GPCC data was the availability of long-term data sets for 110-year period (1901–2010). The GPCC data is derived from rain gauge information (over 85,000 stations worldwide) acquired from multiple sources and updated continuously to generate reanalysis product. GPCC compared well with observed data, for example, Funk et al. (2015) reported that interpolated data from GPCC reanalysis version 6

Table 1 Geographic information and climate type for the selected cities

Content	No.	City	Country	Area (mi^2)	Latitude	Longitude	Climate type
Asia	1	Tokyo	Japan	791	35.5	139.75	Humid subtropical climate
	2	Delhi	India	127	28.75	77.25	Monsoon
	3	Beijing	China	1002	40	116.25	Monsoon
North America	4	New York	USA	1209	41.25	−73.5	Humid continental
	5	Los Angeles	USA	996	34.25	−118.25	Mediterranean
	6	Mexico city	Mexico	171	19.5	−99	Tropical
Africa	7	Lagos	Nigeria	516	7	3.25	Tropical
	8	Johannesburg	South Africa	598	−26.25	27.5	High-land climate
	9	Cairo	Egypt	493	30	31	Mediterranean
South America	10	Sao Paulo	Brazil	3305	−23.5	−46.5	Humid sub-tropical
	11	Buenos Aires	Argentina	377	−34.75	−58.5	Humid sub-tropical
	12	Santiago	Chile	1151	−33.25	−70.25	Mediterranean
Europe	13	Moscow	Russia	3278	56	37.5	Humid continental
	14	Berlin	Germany	6053	52.5	13	Oceanic climate
	15	Madrid	Spain	1674	40	−3.75	Mediterranean
Australia	16	Sydney	Australia	503	−34	150.25	Mediterranean
	17	Alice Spring	Australia	1063	−23.5	133.75	Semi-arid
	18	Perth	Australia	408	−32	116.5	Mediterranean

precipitation product performed well when compared with station data in Africa even though the lack of actual station data.

Both TAT and GPCC data were reviewed for missing data. Grid points with one or more year of missing data were removed from the analysis. The missing data for shorter duration was estimated by taking the mean of the four surrounding grid points. The newly developed 1 km resolution Global Land Cover-SHARE (GLC-SHARE) shapefile created by Food and Agriculture Organization (FAO; Latham et al. 2014) was used to distinguish grids located within urban and peri-urban boundaries.

4 Methodology

This section describes four different methods used to for trend analysis for air temperature and precipitation over selected cities.

4.1 Linear least square fit (LR)

The linear least square fit is given by Eq. (2) where t is the sample number ($t = 1, 2, n$; n being the length of the sample), $z(t)$ is the variable being considered (such as air temperature or precipitation), and $\bar{t}$ and $\bar{Z}$ indicate the average values (Haan 2002).

$$b = \frac{\sum_{t=1}^{n}\left(t-\bar{t}\right)\left(Z(t)-\bar{Z}\right)}{\sum_{t=1}^{n}\left(t-\bar{t}\right)^{2}} \tag{1}$$

$$a = \bar{Z}-b\bar{t} \tag{2}$$

## 4.2 Mann–Kendall test (MK1)

The Mann–Kendall (MK) nonparametric test was first proposed by Mann (1945) and then Kendall (1975). The Mann–Kendall test statistic S is given by Eq. (3) and variance of S is given by Eq. (5). The standardized normal test statistics Z is computed using Eq. (6):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sign}\left(x_j-x_k\right) \tag{3}$$

$$\text{sign}(x) = \begin{cases} 1 & \text{for} \quad x \quad > 1 \\ 0 & \text{for} \quad x \quad = 1 \\ -1 & \text{for} \quad x \quad < 1 \end{cases} \tag{4}$$

$$V(S) = \frac{n(n-1)(2n+5)}{18} \tag{5}$$

Fig. 1 Location of selected mega cities and their urban and peri-urban boundaries. The *blue polygon* represents the urban area selected based on the surface imperviousness. The *green polygons* represent the peri-urban areas
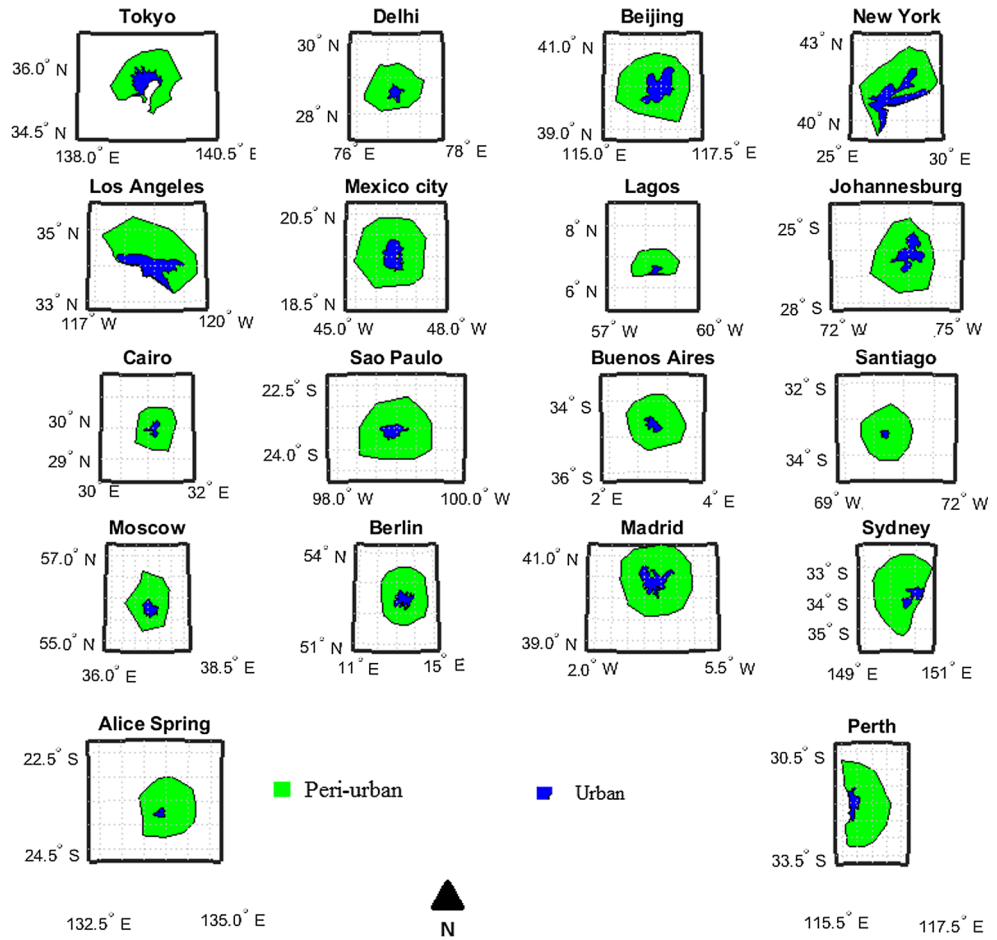
$$
Z = \begin{cases} \dfrac{S-1}{\sqrt{V(S)}} & \text{if} \quad S > 1 \\ 0 & \text{if} \quad S = 0 \\ \dfrac{S+1}{V(S)} & \text{if} \quad S < 0 \end{cases} \tag{6}
$$

A positive (negative) value of Z indicates upward (downward) trend in the time series being tested (Luo et al. 2008; Drápela and Drápelová 2011). The advantage of MK1 is that it is distribution-free test and insensitive to the outliers. However, the MK1 test requires the data to be serially uncorrelated or in other words the time series data should be independent (Yue et al. 2002; Kumar et al. 2009). The MK test is widely used for trend analysis in hydro-climatic variables (Mishra et al. 2011; Mishra and Singh 2010).

4.3 Mann–Kendall test with trend-free pre-whitening (MK2)

The trend-free pre-whiting process (TFPW) was proposed by (Yue et al. 2002) as a way to remove the serial correlation from the data before applying MK1 test. Detrending the time series is a necessary step to remove the effect of a significant linear trend on the serial correlation. It is demonstrated in Eq. (7),

where X_t' is the de-trended data, X_t is the original data, slope (b) is calculated using the Theil-Sen Approach (TSA), and t is the time.

$$
X_t' = X_t - bt \tag{7}
$$

Then lag-1 serial correlation can be removed from detrended time series by using Eq. (8), where Y_t' is the trend-free and pre-whitened time series, and r_1 is the lag-1 serial correlation for the de-trended time series. The residuals are added to the time series data to get the blended time series as in Eq. (9), which is less influenced by serial correlation. Finally, the MK1 test is applied on the final data set Y_t as described in Section 4.2.
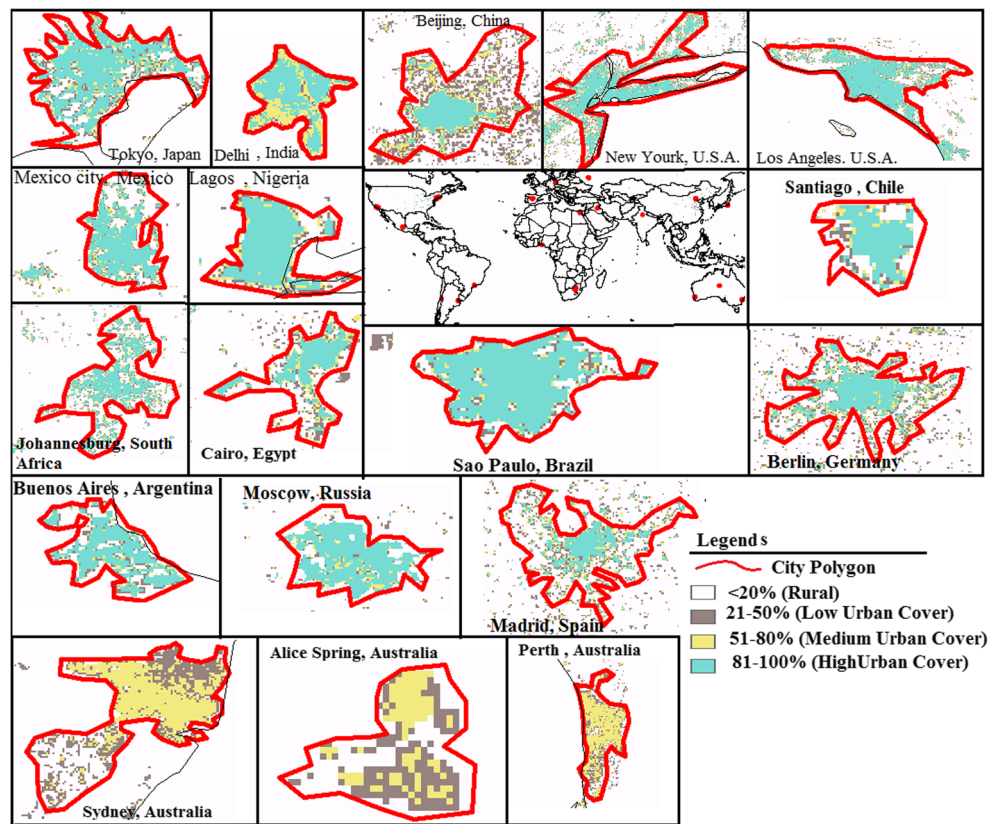
$$
Y_t' = X_t' - r_1 X_{t-1}' \tag{8}
$$

$$
Y_t = Y_t' + bt \tag{9}
$$

4.4 Mann–Kendall test with variance correction (MK3)

To overcome the limitation of the presence of serial autocorrelation in time series, a correction procedure was

**Fig. 2** Percentage of imperviousness for the selected urban areas

proposed by (Hamed and Rao 1998). First, the corrected variance S is calculated by Eq. (10), where $V(S)$ is the variance of the MK1 and CF is the correction factor due to existence of serial correlation in the data. This correction factor was suggested by Hamed and Rao

(1998) and Yue and Wang (2004) and given by Eq. (10), where r_r^R is lag-ranked serial correlation, while n is the total number of observations.

$$V^*(S) = \mathrm{CF}V(S) \tag{10}$$

Fig. 3 Variations of mean monthly precipitation for the selected cities calculated from GPCC data for the period 1901–2010
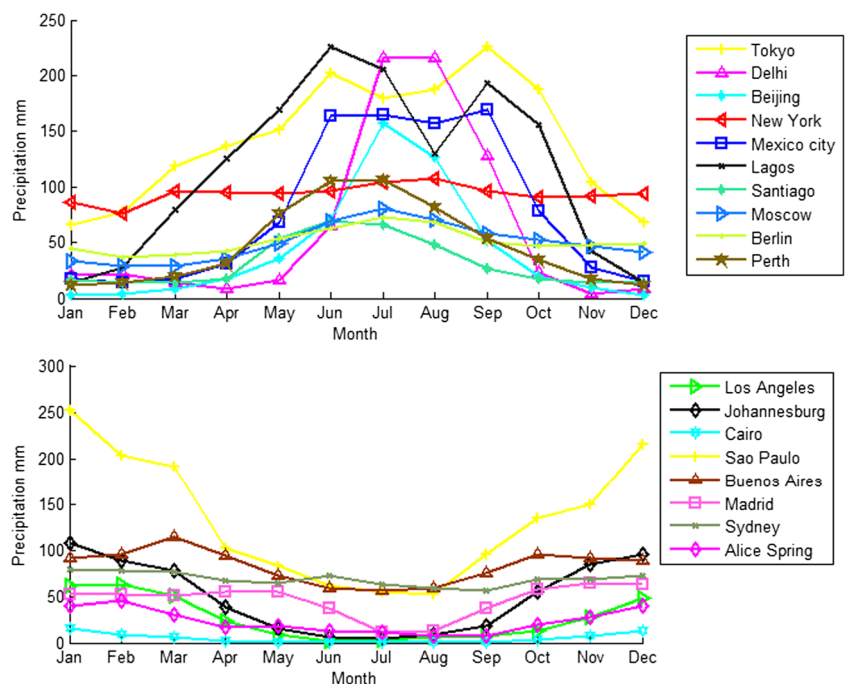
Table 2 Percentage of urban/peri-urban areas registered significant trend (at 5% significance level) using MK1, MK2, and MK3 test

Method	Urban			Peri-urban			Urban			Peri-urban		
	ANNT[a]	WETT	DRYT	ANNT	WETT	DRYT	ANNP[a]	WETP	DRYP	ANNP	WETP	DRYP
MK1	88.9	66.7	88.9	83.3	66.7	77.8	33.3	38.9	22.2	38.9	33.3	16.7
MK2	83.3	66.7	88.9	77.8	66.7	77.8	33.3	38.9	22.2	38.9	33.3	16.7
MK3	55.6	50	50	55.6	44.4	38.9	16.7	22.2	11.1	16.7	16.7	0

[a] The terms ANNT and ANNP shown in Table 2 and later tables are the annual air temperature and precipitation, WETT and WETP represent wet season air temperature and precipitation, and DRYT and DRYP are dry season air temperature and precipitation

$$CF = 1 + \frac{2}{n(n-1)(n-2)} \sum_{k-1}^{n-1} (n-k)(n-k-1)(n-k-2)r_k^R \quad (11)$$

The advantage of MK3 test over MK2 test is that it includes all possible serial correlations (lag-k) in the time series, while MK2 only considers the lag-1 serial correlation (Yue and Wang 2004).

5 Results

The selected cities are located in a wide range of climatic zones; therefore, they witness different rainfall, air temperature, and wet (dry) seasons. For example, Johannesburg winter months are counted from May to September, while in Delhi from November to January. For this reason, the year was

divided into two distinct groups as wet and dry spells (or seasons). For each city, wet spell includes the months in which the total rainfall exceeds the average annual rainfall. The dry spell includes the months with total rainfall less than the average annual rainfall. The average monthly precipitation pattern for each city is presented in Fig. 3, which clearly shows the variation of wet and dry seasons for different cities analyzed in this study. The mean of annual, dry and wet season precipitation was calculated from the GPCC monthly data for the period 1901 to 2010.

5.1 Comparison between Mann–Kendall tests

The trend analysis was carried out using different Mann–Kendall tests (i.e., MK1, MK2, and MK3). In order to overcome the limitations due the presence of serial correlation in

Table 3 Trend analysis of air temperature using MK1/MK2/MK3 tests for urban and corresponding peri-urban areas. Significant trends tested at 95% confidence level (i.e., $|Z| \geq 1.96$) are shown as values in italics

City	Urban			Peri-urban		
	ANNT	WETT	DRYT	ANNT	WETT	DRYT
Tokyo	*7.77/7.71/2.29*	*5.65/5.55/2.33*	*7.47/7.53/2.13*	*6.16/6.1/2.23*	*4.63/4.58/2.33*	*5.7/5.67/2.02*
Delhi	−0.59/−0.48/−0.67	−1.3/−1.09/−1.35	0.39/0.3/0.48	−0.33/−0.01/−0.4	−0.92/−0.68/−1	0.67/0.58/0.91
Beijing	*4.31/5.97/1.77*	*2.2/3.2/1.24*	*5.45/5.98/2.02*	*3.88/5.41/1.67*	1.82/2.76/1.05	*5.11/5.42/2.01*
New York	*4.32/4.16/2.22*	*3.48/3.57/2.14*	*3.48/3.24/2.12*	*2.6/2.33/1.95*	1.58/1.63/1.79	*2.38/2.05/1.97*
Los Angeles	*6.29/6.7/2.02*	*6.6/6.77/2.06*	*4.25/4.31/1.84*	*5.63/6.01/2.04*	*5.86/5.87/2.11*	*3.08/3.35/1.72*
Mexico City	*7.04/8.09/2.04*	*5.89/6.4/1.92*	*7.39/7.95/2.11*	*6.68/7.66/2.13*	*6.06/6.4/2.06*	*6.37/7.2/2.12*
Lagos	−0.11/0.46/−0.06	0.33/0.96/0.19	−0.54/0.05/−0.25	−0.1/0.26/−0.06	0.17/0.41/0.12	−0.5/0.03/−0.29
Johannesburg	*5.63/6.05/2.2*	*4.64/4.93/2.11*	*5.36/5.37/2.13*	*4.87/4.95/2.13*	*3.23/3.24/1.87*	*5.08/5.11/2.07*
Cairo	*2.59/3.27/1.56*	*3.08/3.57/1.68*	1.73/2.02/1.4	*2.06/2.62/1.22*	*2.93/3.67/1.53*	0.52/0.75/0.4
Sao Paulo	*9.17/9.1/2.28*	*8.91/8.8/2.26*	*7.86/7.76/2.24*	*8.66/8.53/2.24*	*8.38/8.28/2.22*	*7.14/6.99/2.2*
Buenos Aires	*9.19/9.25/2.25*	*7.12/7.05/2.17*	*7.61/7.95/2.15*	*8.06/7.96/2.23*	*6.16/6.05/2.2*	*6.35/6.85/2.08*
Santiago	*4.2/4.71/1.77*	*5.99/6.61/1.97*	1.49/1.89/1.34	*5.06/5.39/2.05*	*6.49/6.88/2.15*	*2.47/2.81/1.81*
Moscow	*5.66/5.78/2.19*	*5.09/5.32/2.22*	*4.23/4.22/1.99*	*4.49/4.57/2.19*	*4.19/4.33/2.22*	*3.08/3.09/1.91*
Berlin	*3.14/3.27/1.86*	*3.36/3.58/2.08*	1.62/1.59/1.34	*2.84/3.02/1.82*	*3.25/3.41/2.11*	1.49/1.41/1.3
Madrid	*5.75/5.58/2.27*	*3.48/3.65/1.96*	*5.28/4.99/2.04*	*5.67/5.9/2.12*	*4.16/4.41/1.91*	*4.74/4.7/2*
Sydney	*2.02/1.74/1.87*	0.51/0.53/0.81	*3.19/3.05/2.13*	−0.34/−0.27/−0.59	−1.39/−1.24/−1.72	0.96/0.52/1.45
Alice Spring	*3.86/4.38/1.98*	*4.29/4.62/2.07*	*2.54/2.43/1.88*	*4.09/4.62/2.05*	*4.49/4.65/2.12*	*2.73/2.54/1.95*
Perth	*3.01/2.86/1.67*	*2.62/2.54/1.64*	*2.71/2.56/1.66*	*2.05/1.96/1.52*	*2.07/2.08/1.7*	1.44/1.35/1.15

Fig. 4 Box plot of mean slopes based on decadal change in air temperature during the period 1901–2008. [Steps used: (a) for a selected city, the time series is divided into decades, (b) the slopes associated for each decade are calculated, (c) the mean of decadal slope is calculated for each city, and (d) the box plot is constructed based on the mean of decadal slope calculated for the 18 selected cities]
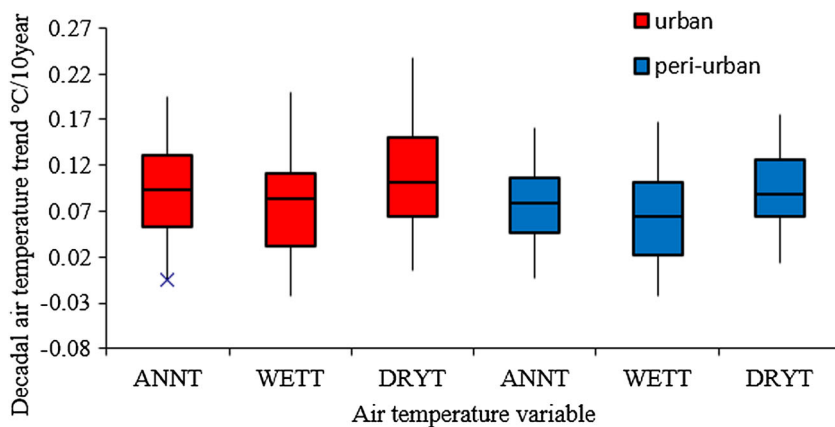
annual and seasonal mean air temperature and precipitation, MK2 and MK3 methods were applied in trend analysis. MK2 eliminates the lag-1 auto correlation by using free pre-whitening (FPW), while MK3 removes the lag-k serial correlation by variance correction (VC) method. The percentage of significant trends for air temperature and precipitation based on MK1, MK2, and MK3 test are provided in Table 2. When using MK1 and MK2 tests, similar number of cities have significant trend in precipitation which indicates the removal of lag-1 auto-correlation that may not have much influence on the trend analysis. This pattern is also similar for air temperature during wet and dry seasons. However, MK1 test comparatively has higher number of stations for air temperature at

annual scale. As reported in Table 2, the number of urban areas showing significant trend decreased when auto correlation correction was applied. The lower percentage of significant trends for both air temperature and precipitation was observed in case of MK3 test in comparison to MK1 and MK2 tests. Overall, the result obtained from MK3 test is more conservative in comparison to other two tests, therefore it is important to evaluate multiple MK test in trend analysis of hydro-climatic variables.
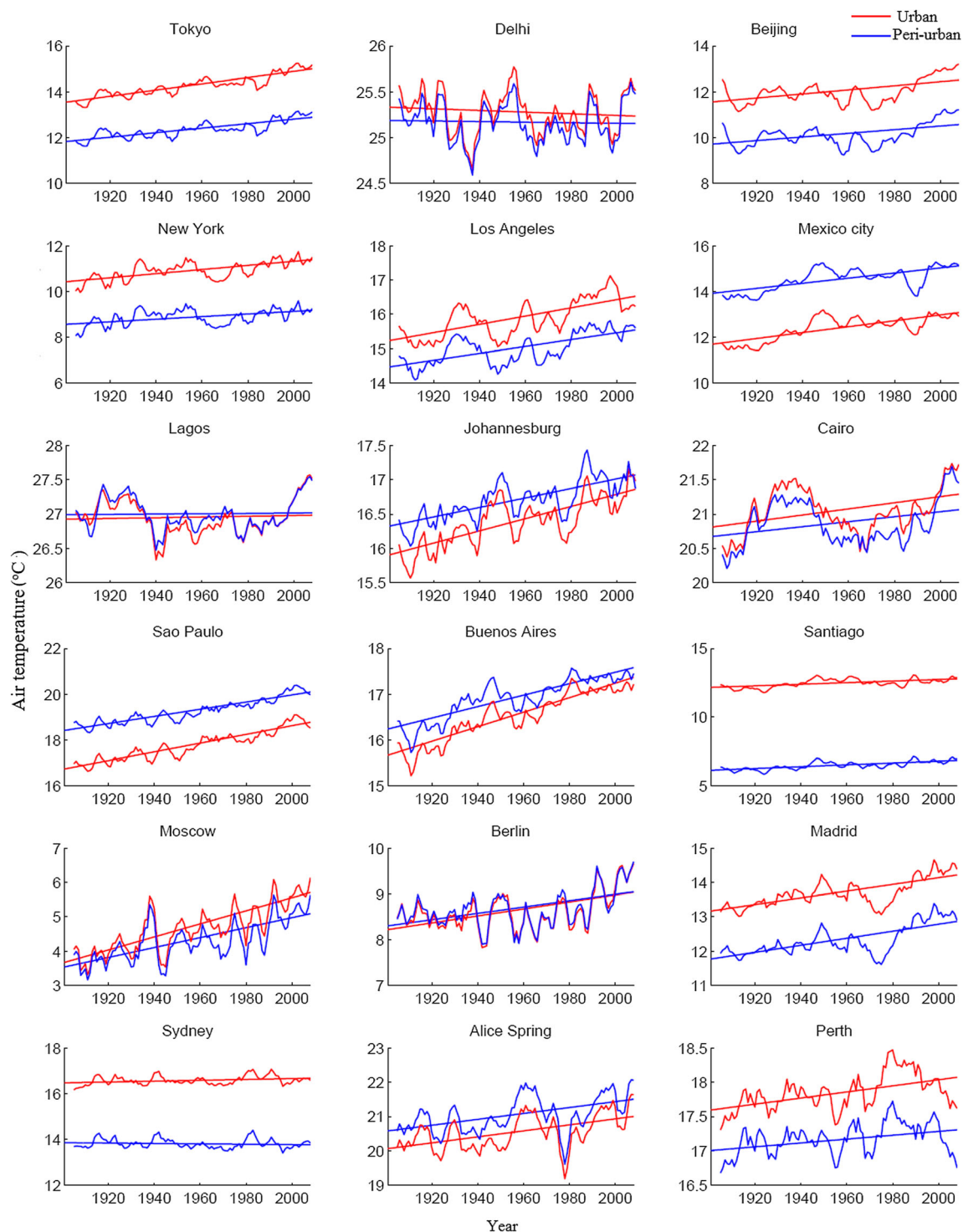
5.2 Trends in air temperature

The annual, wet, and dry season mean air temperature were analyzed using MK1, MK2, and MK3 tests for the period 1901–2008 to determine whether each city is experiencing cooling or warming trends (Table 3). The MK1, MK2, and MK3 test results were investigated for possible influence of presence of serial-1 and serial-k correlations on significant trend results for air temperature in urban and peri-urban areas. Many of the previous studies only focused on classical MK1 test for trend analysis in hydro-climatic time series, which ignores the presence of correlation in time series (Karabulut et al. 2008; Karmeshu 2012). However, we observed that MK3 results provide a conservative estimate after removing all forms of serial correlations.

Overall, there is an increasing trend for urban and peri-urban annual and seasonal air temperature. Based on the MK3 results (Table 3), it was observed that 70% of the urban areas experienced warmer trend (i.e., $Z > 0$) in annual and seasonal air temperature in comparison to the peri-urban areas. Significant warming trends are found in about 56% of urban areas (likewise for peri-urban areas) based on annual air temperature. None of the urban and peri-urban areas register a significant cooling trend based on annual and seasonal air temperature. However, the urban air temperature in wet and dry seasons illustrates higher significant trends (i.e., $Z > 1.96$) than peri-urban areas. About 50% of urban areas show significant warming trends, whereas for peri-urban areas, these values are lower than those in the urban areas with about 44

Table 4 Decadal slope obtained from linear regression for air temperature during the period 1901–2008

City	Urban (°C/10 years)			Peri-urban (°C/10 years)		
	ANNT	WETT	DRYT	ANNT	WETT	DRYT
Tokyo	0.14	0.11	0.16	0.10	0.08	0.11
Delhi	−0.01	−0.03	0.00	0.00	−0.03	0.01
Beijing	0.09	0.03	0.12	0.08	0.02	0.11
New York	0.09	0.08	0.11	0.06	0.04	0.08
Los Angeles	0.12	0.09	0.14	0.10	0.07	0.12
Mexico city	0.13	0.11	0.15	0.11	0.09	0.12
Lagos	0.01	0.00	0.01	0.00	0.00	0.01
Johannesburg	0.09	0.08	0.10	0.07	0.05	0.09
Cairo	0.04	0.03	0.05	0.04	0.01	0.06
Sao Paulo	0.19	0.19	0.19	0.16	0.16	0.15
Buenos Aires	0.16	0.15	0.17	0.13	0.12	0.14
Santiago	0.06	0.02	0.08	0.07	0.04	0.08
Moscow	0.19	0.13	0.23	0.15	0.11	0.17
Berlin	0.08	0.08	0.08	0.07	0.07	0.07
Madrid	0.10	0.10	0.10	0.10	0.10	0.11
Sydney	0.02	0.00	0.04	−0.01	−0.02	0.01
Alice Spring	0.09	0.11	0.07	0.09	0.10	0.08
Perth	0.04	0.04	0.05	0.03	0.02	0.04

Fig. 5 Linear trends based on 5-year moving average of annual air temperature for urban and peri-urban areas

and 39% during wet and dry seasons, respectively. Significant warming trends in annual air temperature are observed in Tokyo and selected cities in North America, Johannesburg, Sao Paulo and Buenos Aires, and Moscow and Madrid. Urban areas located in Australia do not show any significant trend for annual air temperature; these urban areas show the lowest imperviousness among all selected urban areas (Fig. 2).

We applied linear regression method to estimate the magnitude of change in air temperature with respect to time. The change in annual and seasonal air temperature over a 10-year period for urban and peri-urban areas is shown in Fig. 4. The rectangular box plot shows three horizontal lines that represent the median (intermediate line), 25th percentile (lower line), and 75th percentile values (upper line), while the two

Table 5 Trend analysis of precipitation using MK1/MK2/MK3 tests for urban and corresponding peri-urban areas. Significant trends are considered at 95% confidence level (i.e. $|Z| \geq 1.96$) are shown as values in italics
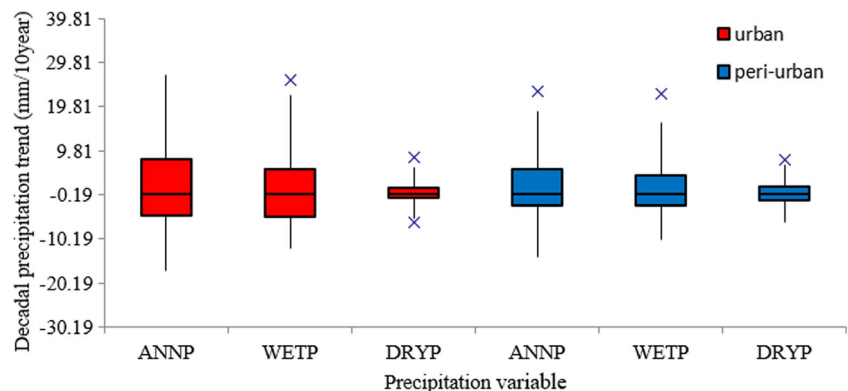
City	Urban			Peri-urban		
	ANNP	WETP	DRYP	ANNP	WETP	DRYP
Tokyo	−1.81/−1.91/−1.45	−1.49/−1.61/−1.34	−1.41/−1.36/−1.74	*−1.97/−2.07/−1.69*	−1.72/−1.87/−1.59	−1.44/−1.38/−1.71
Delhi	1.18/1/1.53	0.79/0.6/1.14	0.88/0.99/0.93	1.12/1/1.52	0.78/0.54/1.16	0.95/0.97/0.99
Beijing	−0.76/−0.57/−0.9	−1.22/−1.23/−1.15	*1.98/1.97/1.77*	−0.23/−0.09/−0.34	−0.92/−0.73/−0.95	*2.17/2.35/1.8*
New York	0.89/1.08/1.12	0.87/1.17/1.13	0.44/0.42/0.91	*2.14/2.32/1.76*	1.69/1.88/1.66	1.47/1.63/1.79
Los Angeles	−0.92/−0.98/−1.38	−0.83/−0.88/−1.33	−1.09/−0.91/−1.2	−1.33/−1.37/−1.51	−1.12/−1.21/−1.44	−1.62/−1.48/−1.49
Mexico city	*3.3/3.25/1.83*	*3.96/4.15/1.89*	0.2/−0.15/0.28	1.39/1.28/0.88	*2.43/2.37/1.35*	−0.68/−0.97/−0.75
Lagos	−1.61/−1.29/−1.61	−0.9/−0.73/−1.23	*−2.65/−2.55/−1.54*	0.08/0.31/0.13	1.04/1.26/1.23	*−3.15/−3.16/−1.67*
Johannesburg	−1.14/−1.01/−1.8	−1.1/−1.08/−1.55	−0.36/−0.22/−0.38	−0.51/−0.41/−0.98	−0.6/−0.49/−1.32	−0.11/0.1/−0.12
Cairo	*−3.74/−3.34/−2.09*	*−2.38/−2.25/−2.03*	*−2.11/−1.1/−2.04*	*−4.34/−4.35/−2.13*	*−3.29/−3.31/−2.14*	−1.63/−0.79/−1.61
Sao Paulo	*2.45/2.49/1.74*	*2.91/2.71/1.98*	0.46/0.44/0.7	*1.98/1.99/1.63*	*2.46/2.33/1.83*	0.4/0.48/0.62
Buenos Aires	*4.64/4.51/2.08*	*4.81/4.74/1.96*	0.87/0.87/0.93	*4.13/3.97/2.08*	*4.44/4.36/2.04*	0.46/0.38/0.51
Santiago	−0.94/−0.87/−1.24	−1.09/−1/−1.5	0.6/0.46/0.84	−0.37/−0.37/−0.52	−0.98/−0.83/−1.19	1.87/1.67/1.87
Moscow	*4.31/4.37/1.94*	2.52/2.23/1.9	*4.2/4.24/1.82*	*4.15/4.06/1.86*	2.41/2.04/1.85	*4.13/4.19/1.78*
Berlin	1.16/1.05/*2.01*	0.08/−0.06/0.17	1.27/1.3/1.59	0.95/0.89/1.98	−0.23/−0.37/−0.39	1.3/1.4/1.77
Madrid	−0.58/−0.59/−0.86	0.04/0.08/0.07	−1.86/*−1.97/−2.01*	−0.36/−0.32/−0.52	0.2/0.13/0.36	−1.48/−1.43/−1.8
Sydney	1.14/1/1.14	*2.3/2.05/1.5*	−1.1/−1.05/−1.6	1.2/1.12/1.07	1.71/1.6/1.43	−0.47/−0.51/−0.69
Alice Spring	0.75/0.75/0.95	0.36/0.47/0.6	0.15/0.01/0.25	−0.17/−0.07/−0.28	−0.33/−0.16/−0.55	−0.4/−0.54/−0.97
Perth	*−2.36/−2.54/−1.9*	*−3.33/−3.37/−2.03*	0.85/0.72/1.55	*−1.96/−2.22/−1.86*	*−2.99/−3.13/−1.97*	1.4/1.13/1.9

top and bottom vertical lines represent the maximum and minimum changes over the 10-year period for the urban and peri-urban areas. The results show that the median rise in urban annual and seasonal air temperature is higher than that in the peri-urban areas, which is consistent with the results revealed by MK3 test. The magnitudes of decadal slopes for urban and peri-urban areas are presented in Table 4. Linear trend results indicate that about an average of 20% of urban areas experienced higher mean decadal increase in annual and seasonal air temperature in comparison to peri-urban areas. During the period 1901–2008, the average increase in air temperature for all 18 urban areas observed to be 1, 0.8, and 1.1 °C for annual, wet season, and dry season, respectively. Similarly upward trends are also observed in peri-urban areas albeit with

lower rates of warming. The average increase in 18 peri-urban areas observed to be remarkably less with 0.8, 0.6, and 0.9 °C for annual, wet, and dry air temperature respectively for the time period 1901–2008. For the same time period, Sao Paulo (Delhi) recorded the highest (lowest) change among all urban and peri-urban areas for annual data with 2 (−0.1) °C.

Figure 5 shows the linear regression and the 5-year moving average trend for the annual air temperature. It can be observed that warming signature based on urban areas is located in the Mediterranean climate except Cairo, and Monsoon climate is comparatively higher than the corresponding suburban areas. Furthermore, the annual air temperature for peri-urban areas of Sao Paulo and Buenos Aires (both located in humid sub-tropical climate), and Johannesburg (located in

Fig. 6 Box plot of mean slopes based on decadal change in precipitation. [Steps used: similar to Fig. 4]

Table 6 Decadal slope for precipitation based on linear regression line during the period 1901–2010

City	Urban (mm/10 years)			Peri-urban (mm/10 years)		
	ANNP	WETP	DRYP	ANNP	WETP	DRYP
Tokyo	−14.35	−11.02	−3.33	−14.30	−10.26	−4.05
Delhi	7.41	5.21	2.21	6.24	4.27	1.97
Beijing	−4.14	−6.34	2.20	−0.70	−2.78	2.08
New York	4.72	2.56	2.16	9.23	4.41	4.82
Los Angeles	−3.02	−2.09	−0.92	−5.40	−4.06	−1.34
Mexico city	10.96	11.55	−0.59	5.24	7.19	−1.95
Lagos	−17.48	−11.00	−6.48	−4.32	1.93	−6.24
Johannesburg	−5.72	−5.02	−0.71	−2.66	−2.34	−0.32
Cairo	−1.75	−1.11	−0.63	−2.41	−1.82	−0.59
Sao Paulo	17.81	14.77	3.04	14.52	11.61	2.91
Buenos Aires	27.87	25.77	2.10	23.27	22.72	0.55
Santiago	−4.99	−5.20	0.21	−1.23	−3.29	2.06
Moscow	14.69	6.43	8.26	13.22	5.57	7.65
Berlin	3.41	0.51	2.89	2.44	−0.02	2.46
Madrid	−1.59	0.48	−2.07	−0.69	0.82	−1.51
Sydney	9.16	13.52	−4.36	5.85	7.17	−1.32
Alice Spring	5.59	3.75	1.84	1.71	1.36	0.35
Perth	−11.29	−12.44	1.15	−5.94	−7.33	1.39

high-land climate) show higher values than corresponding urban pairs. However, the rates of warming for these urban areas are relatively higher than those for the peri-urban sites (Table 4). It can be suggested that regardless of the urban heat effect over urban areas, there is a general persistent growth of warming with time over almost all urban and peri-urban areas. For the period (1901–2008), significant warming trends were observed in mean annual and seasonal air temperature over the majority of urban and peri-urban pairs. The level of significance was found to be higher over urban areas in comparison to corresponding peri-urban areas, which indicates the clear influence of urbanization on air temperature.

5.3 Trends in precipitation

Trend analysis was performed for annual and seasonal (i.e., wet and dry) precipitation during the period 1901–2010 using MK1, MK2, and MK3 tests (Table 5). Overall, annual and seasonal precipitation for urban and peri-urban areas shows mix (increasing and decreasing) trends unlike air temperature data. For annual precipitation, it was found that half of urban and peri-urban areas witness increasing trend while the other half a decreasing trend based on MK3 test. Trends in precipitation data were determined at a statistical significant level of 5% (similar to air temperature analysis). A significant increase in mean annual precipitation was found in two urban and peri-urban areas while one location shows a significant decreasing

trend. Significant increasing precipitation trends for annual rainfall are mainly observed in the cities of Buenos Aires and Berlin, while a significant decreasing trend was found for Cairo. Trend results of seasonal precipitation for both urban/peri-urban areas exhibit similar pattern as in annual precipitation (Table 5). For the wet season, only two cities (Sao Paulo and Buenos Aires) appeared to have significant increasing trends, while peri-urban areas located in Buenos Aires witness a significant increasing trend. Both Perth and Cairo found to have a significant decreasing precipitation trend during wet season. For dry season, none of the urban/peri-urban areas have a positive significant trend. However, the urban areas of Cairo and Madrid show significant decreasing trend in dry season. It is worth to mention that the number of cities witnessing significant increasing (decreasing) trend is higher in MK1 and MK2 test in comparison to MK3 test (Table 5).

The boxplot for the decadal change in precipitation was estimated using linear regression for annual and seasonal precipitation during the time period 1901–2010 (Fig. 6). The interquartile range (IQR) for decadal trends in annual and wet season precipitation for selected urban areas are comparatively higher than the peri-urban areas. This effect becomes less obvious in case of dry season. The median of decadal precipitation trends in urban areas during 1901–2010 is slightly higher than the peri-urban areas by the amount of 3.6, 1.6, and 0.5 mm/10 years for the annual, wet and dry season, respectively. An increase in mean annual and seasonal precipitation was also observed in urban averages over the surrounding peri-urban areas. The relative increase in average precipitation in urban areas with respect to peri-urban areas observed to be 41, 29.3, and 11.87 mm for annual, wet, and dry seasons, respectively (Table 6).

The maximum linear decadal increase for urban (and the corresponding peri-urban area) was observed for Buenos Aires with 27.87 (23.27) mm/10 years during annual precipitation, and 25.77 (22.72) mm/10 years for wet season precipitation. The lowest decadal trend in annual precipitation of urban (peri-urban) area was observed in Cairo with a value of −1.75 (−2.41) mm/10 years. The 5-year moving averages for the mean annual precipitation time series are given in Fig. 7. A general trend in annual precipitation for the urban/ peri-urban areas cannot be ascertained as both increasing and decreasing trends were observed in multiple cities. Interestingly, the significant increasing trends for both annual precipitation and air temperature were observed in urban areas of Sao Paulo and Buenos Aires (both located in humid subtropical climate), and Johannesburg (located in high-land climate). This obvious variation of urban precipitation signal in these locations (Fig. 5) is an option for future research direction and it deserves special attention.

The spatial distribution of trends based on MK3 statistics for annual and seasonal precipitation data for urban and surrounding peri-urban areas was analyzed and presented in

Fig. 7 The linear trends based on 5-year moving average for annual precipitation for the period 1901–2008 for urban and peri-urban areas
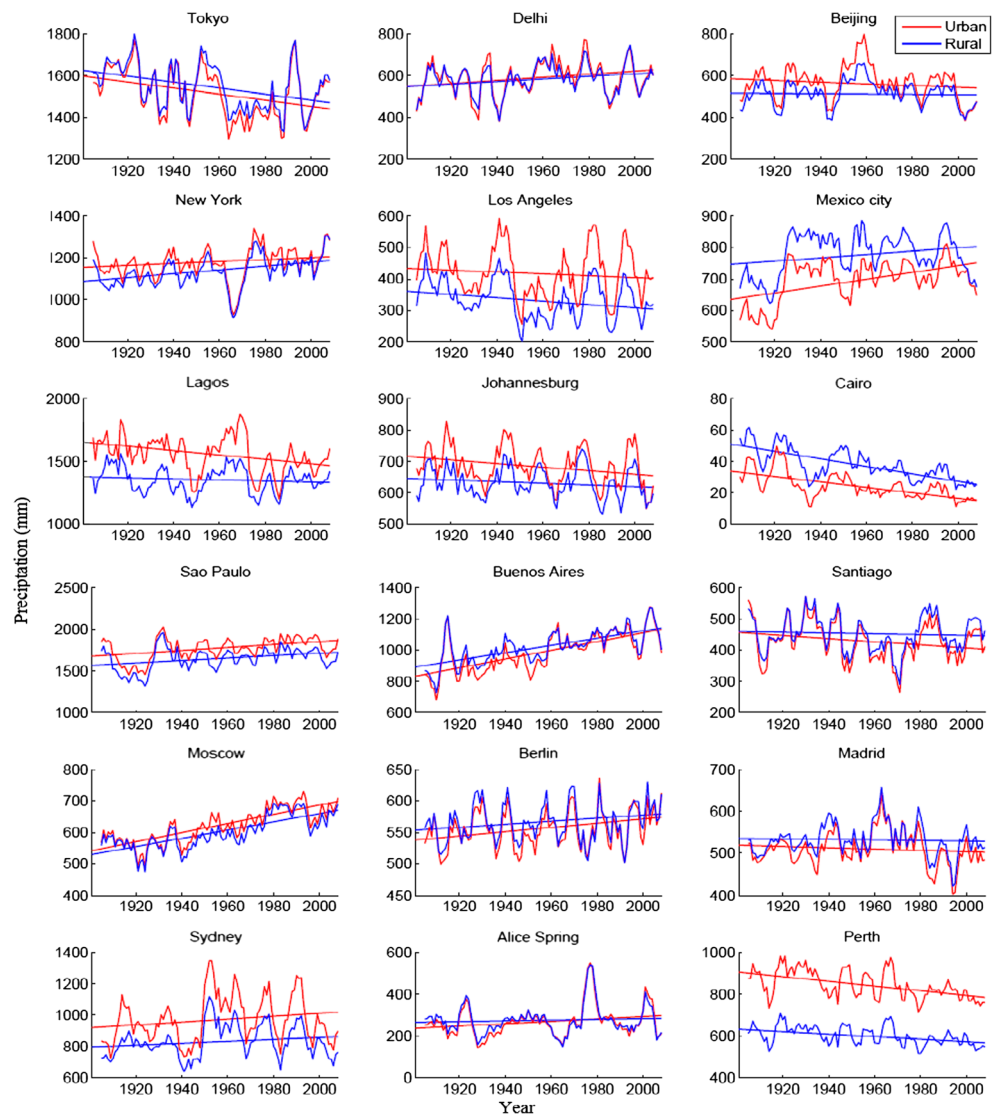

Figs. 8, 9, and 10. It was interesting to observe difference between annual precipitation trends for some urban and peri urban areas, for example in Beijing and Lagos, where the negative trends are observed for urban whereas positive trends were observed in the vicinity of the urban polygons (Fig. 8). During the wet spell and for most locations, the negative trends in precipitation are more predominant in most urban areas (Fig. 9). Negative trends were less prevalent during the dry spells particularly in the cities of Beijing, Tokyo, and Perth. During the dry spell, positive trends are more dominated over negative trends (Fig. 10).

5.4 Possible linkage between precipitation, temperature, and imperviousness

The scattered plots between decadal linear slopes of annual (seasonal) precipitation and air temperature for selected cities are shown in Fig. 11. A positive relationship between precipitation and air temperature was observed for all selected urban and peri-urban areas. The increments in precipitation and air temperature, however, seem to be relatively higher in urban than in peri-urban areas. This finding does not necessarily mean that higher air temperature trend results in higher precipitation over all urban areas because other drivers can influence the global precipitation such as topography and large climate oscillations.

The scatter plot between the decadal trends of annual and seasonal precipitation (air temperature) in urban areas and percentage of imperviousness of urban areas is presented in Fig. 12. As illustrated in the top panel, with the increase of surface imperviousness, the majority of urban centers experienced more warming conditions, while only Delhi and Lagos cities registered cooling trend. The bottom panel of Fig. 12 indicates that, along with the increasing imperviousness, an equal number of the cities showed two different trends, where 50 % registered an increase in annual and seasonal
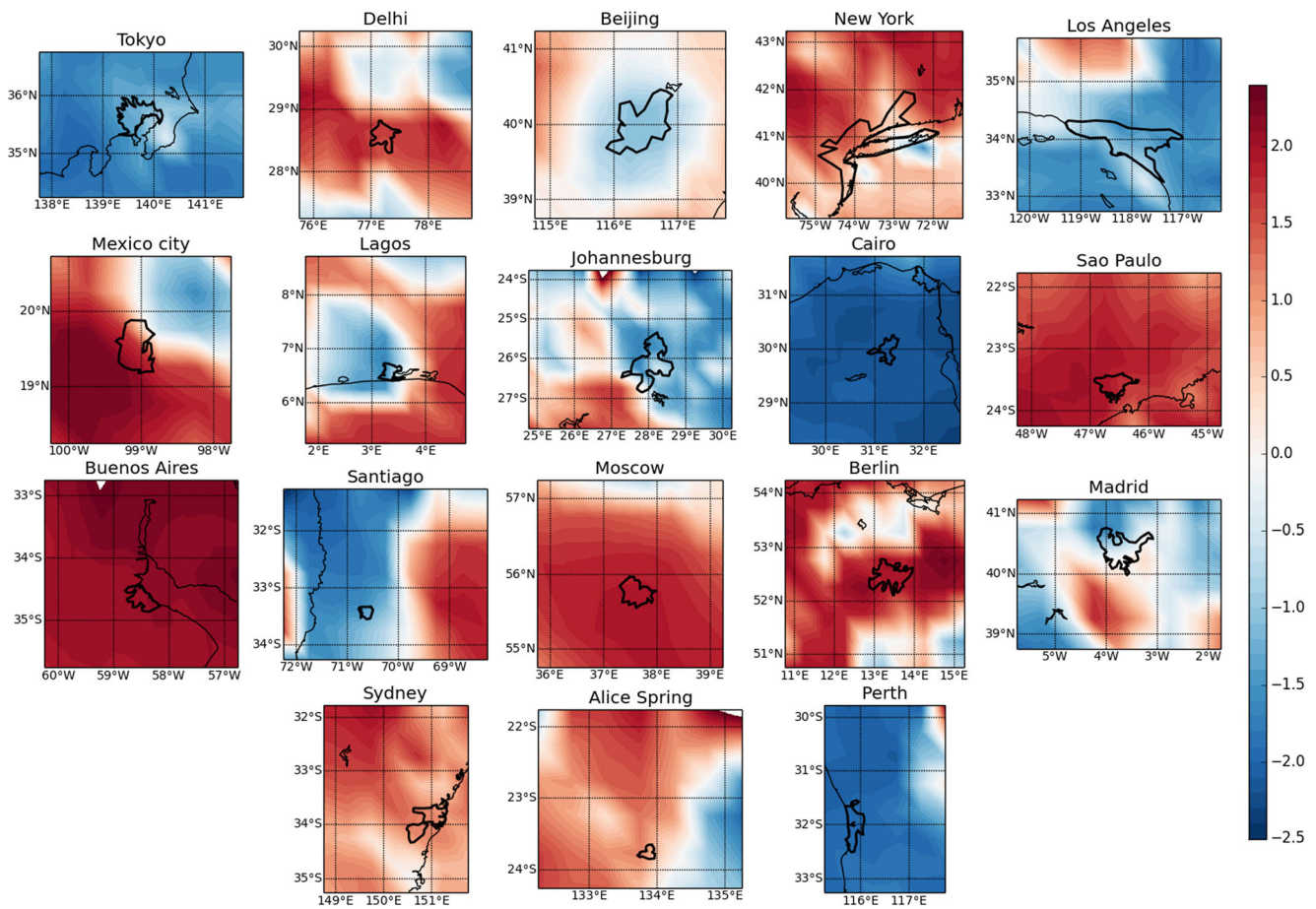
Fig. 8 Spatial distribution of *Z* statistics based on MK3 test for annual precipitation (1901–2010) in urban and peri-urban areas

precipitations and the other 50% showed decreasing trends. This suggests that, with land use change in urban areas, no clear signal was observed in annual and seasonal precipitation trends over the period 1901–2010.

Along with the increasing warming over urban areas, there might be a combined influence of climate and human factors on the annual and seasonal precipitation for the selected urban areas especially the ones that showed significant trends.

6 Discussion

The trend analysis is likely to be influenced by the length of the time series (Yue et al. 2002), and to overcome this limitation, we used longer data length (>100 years) in our analysis. We found that majority of urban areas considered in the study showed warming trends at annual and seasonal time scale (urban areas is more than peri-urban areas), which makes them highly vulnerable to the effect of the climate change. This conclusion is also confirmed by several studies (i.e., Han et al. 2015; Hu et al. 2016; Kephe et al. 2016). It was observed that cities located in dry regions such as Africa, southern parts of North America (Los Angeles), Eastern Asia (Tokyo and

Beijing) witness a decrease in annual and seasonal precipitation, whereas increasing precipitation pattern was observed for cities located in wet regions such as, Southeastern South America (Buenos Aires and Sao Paulo), Eastern North America (New York), and Northern Europe (Berlin and Moscow). These results generally agree with previous findings based on observed data (Sun et al. 2014) and climate model outputs (O'Gorman and Schneider 2009; Di Luca et al. 2015). In our analysis, we identified that difference in land use plays an important role in temperature (precipitation) trends associated with urban (peri-urban) areas. This study can supplement previous studies where additional variables that influence the precipitation and temperature patterns are as follows: (a) climate oscillations, such as El Niño–Southern Oscillation (ENSO) by circulating energy between the tropics which leads to change in wind, temperature, and precipitation (Trenberth and Caron 2000), (b) cloud mixing in urban areas which substantially increases near cities because uplifted moisture condenses once it reaches saturation level (Kusaka et al. 2014), and (c) Urban Heat Island (UHI), for example, Fumiaki (2009) reported that Tokyo metropolitan has more prominent summer heat island which is caused by increasing urban land area and population. According to Inoue and
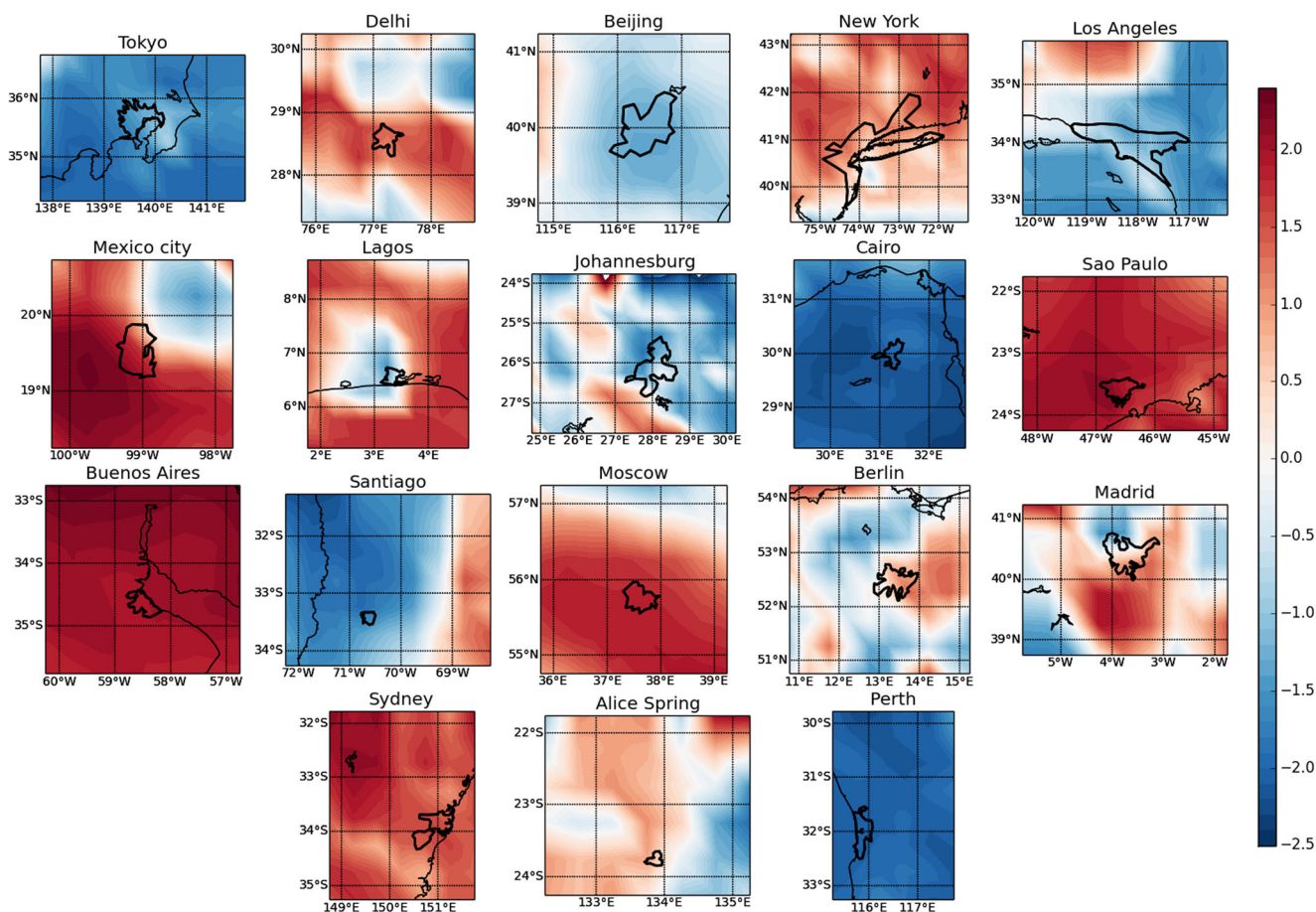
Fig. 9 Spatial distribution of *Z* statistics based on MK3 test for wet season precipitation (1901–2010) in urban and peri-urban areas

Kimura (2007), this UHI enhances short-term intense precipitation over the city during summer while the long-term precipitation signal decreased during the wet spell. Overall, the unclear precipitation signal over urban areas creates a room for more investigations.

7 Conclusions

The long-term trends in mean annual, wet spell, and dry spell air temperature and precipitation was analyzed for 18 pairs of urban and peri-urban areas selected from six contents. The Global Precipitation Climatological Center (GPCC) monthly data for the period 1901–2010 was used along with the corresponding air temperature data derived from Terrestrial Air Temperature (TAT) during the period 1901–2008. Three non-parametric Mann–Kendall and linear regression tests were adopted to identify the presence of serial correlation and to estimate the change value in the data. The following conclusions are drawn from the study:

(a). The presence of serial correlation in precipitation (air temperature) time series likely to impact trend analysis,

therefore application multiple trend analysis (i.e., MK1, MK2, and MK3) may be more useful in hydroclimate trend studies to arrive at a conservative result. In our study, the majority of the annual and seasonal air temperature and precipitation time series have significant lagged serial correlation; therefore, the variance correction (VC) approach seems to be more appropriate.

(b). There are relatively higher trends associated with annual and seasonal air temperature and precipitation in urban areas in comparison to peri-urban areas especially with significant trends.

(c). There is a positive correlation between decadal changes of annual (seasonal) air temperature and precipitation for all urban and peri-urban areas, with urban areas witnessing slightly higher correlation than peri-urban areas. This indicates that there might be a combined influence of climate and human factors on the annual and seasonal precipitation for the selected urban areas.

(d). It was observed that urbanization (i.e., % of imperviousness surface) brings more warming to the majority of geographic locations considered in the analysis; however, there is a mix (increasing and decreasing) pattern observed for precipitation. Additional efforts are
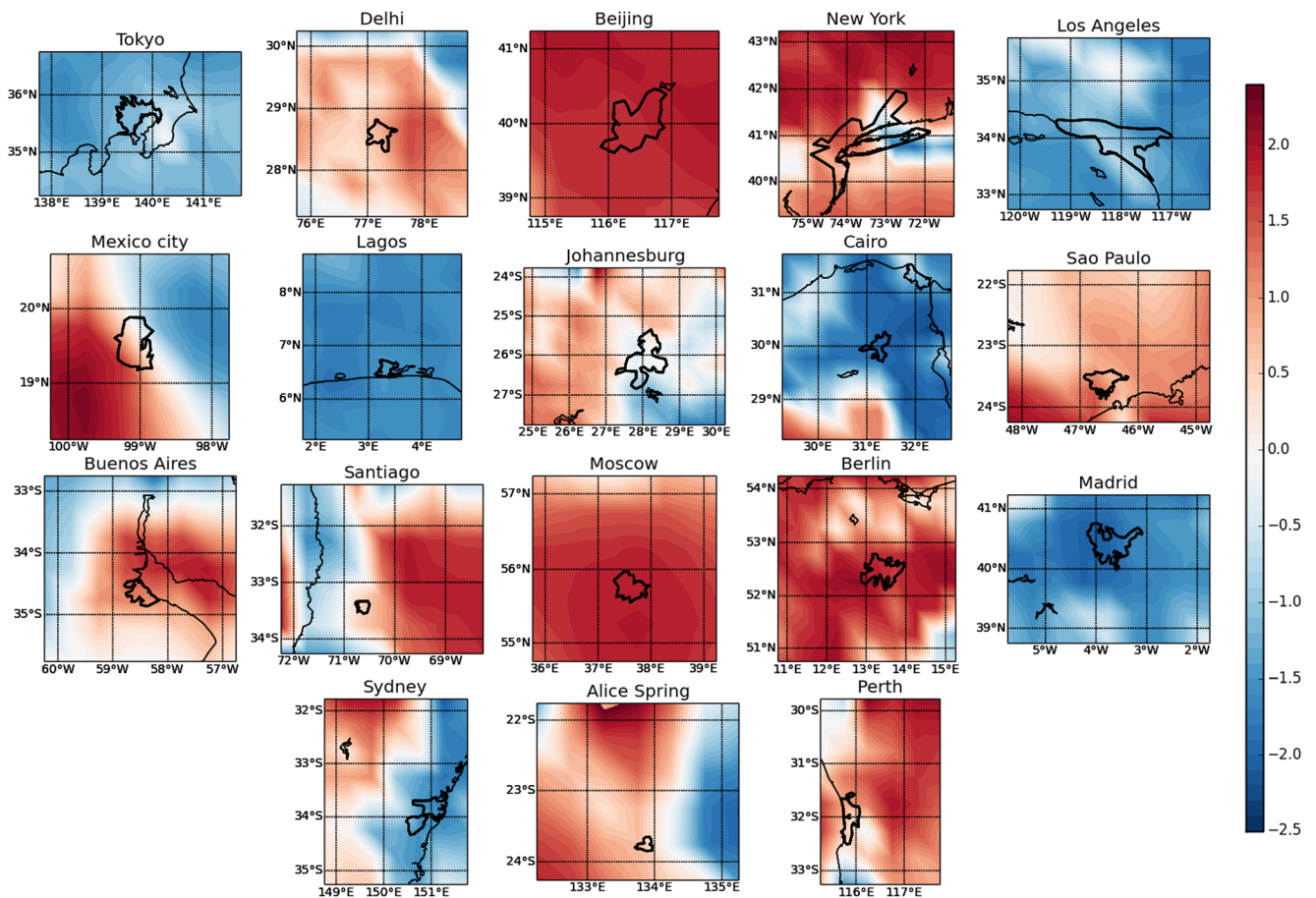
Fig. 10 Spatial distribution of Z statistics based on MK3 test for dry season precipitation (1901–2010) in urban and peri-urban area
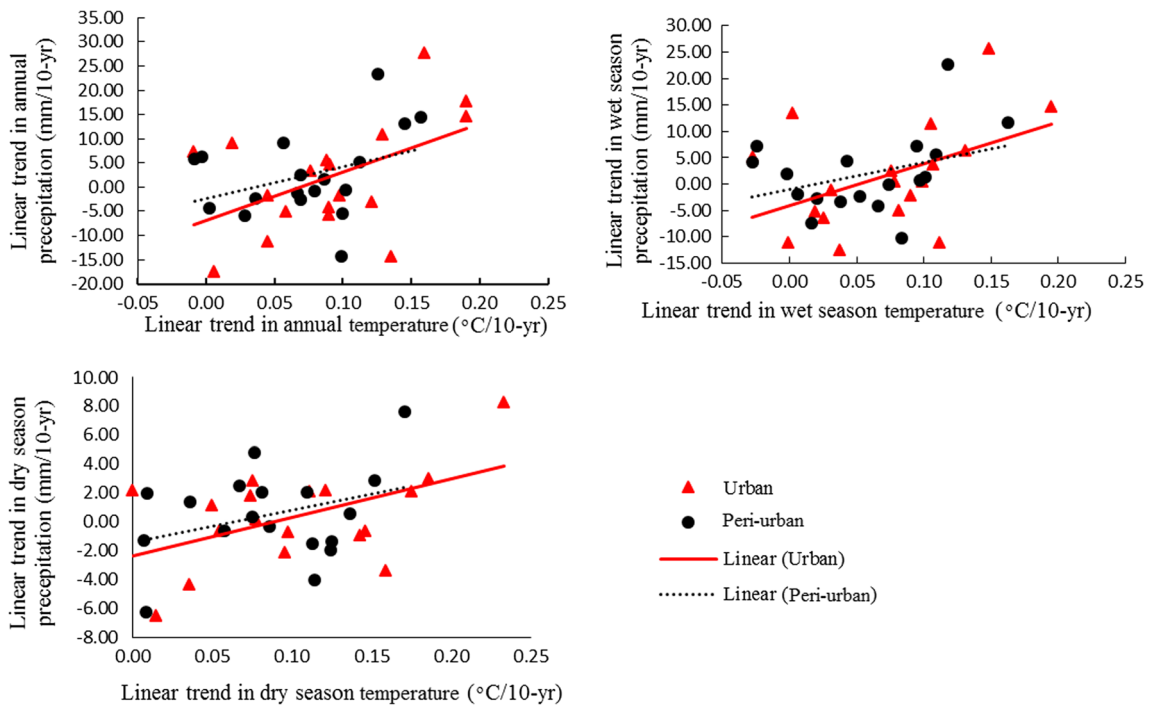
Fig. 11 Scatter plot between mean decadal slopes based on annual air temperature and precipitation for urban and peri-urban areas
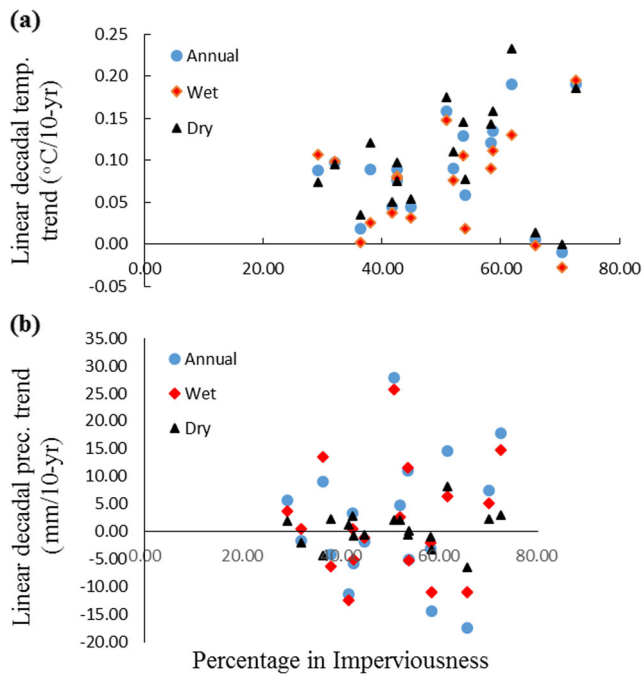
Fig. 12 Scatter plot between: (a) mean decadal slope of annual, wet and dry season's air temperature and the percentage of imperviousness for urban areas, (b) mean decadal slope of annual, wet and dry season's precipitation and the percentage of imperviousness for urban areas

required to investigate the influence of urbanization on hydrologic variables as well as climate extremes.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Alexander L, Zhang X, Peterson T, Caesar J, Gleason B, Klein Tank A et al (2006) Global observed changes in daily climate extremes of air temperature and precipitation. Journal of Geophysical Research: Atmospheres 1984–2012:111

Angel S, Parent J, Civco DL, Blei A, Potere D (2011) The dimensions of global urban expansion: estimates and projections for all countries, 2000–2050. Prog Plan 75:53–107

Argüeso D, Di Luca A, Evans JP (2016) Clim Dyn 47:1143. doi:10.1007/s00382-015-2893-6

Bentley ML, Ashley WS, Stallins JA (2010) Climatological radar delineation of urban convection for Atlanta, Georgia. Int J Climatol 30(11):1589–1594

Burian SJ, Shepherd JM (2005) Effect of urbanization on the diurnal rainfall pattern in Houston. Hydrol.Process. 19:1089–1103

Changnon, S. A., and Westcott, N. E. (2002) Heavy Rainstorms in Chicago: Increasing Frequency, Altered Impacts, and Future Implications1

Di Luca A, de Elía R, Laprise R (2015) Challenges in the quest for added value of regional climate dynamical downscaling. Current Climate Change Reports 1(1):10–21

Diem JE, Mote TL (2005) Interepochal changes in summer precipitation in the southeastern United States: evidence of possible urban effects near Atlanta, Georgia. J Appl Meteorol 44(5):717–730

Dixon PG, Mote TL (2003) Patterns and causes of Atlanta's urban heat island-initiated precipitation. J Appl Meteorol 42(9):1273–1284

Drápela K, Drápelová I (2011) Application of Mann-Kendall test and the Sen's slope estimates for trend detection in deposition data from Bílý Kříž (Beskydy Mts., the Czech Republic) 1997-2010. Beskydy 4: 133–146

Fumiaki F (2009) Detection of urban warming in recent temperature trends in Japan. Int J Climatol 29:1811–1822

Funk C et al (2015) The Centennial Trends Greater Horn of Africa precipitation dataset. Sci Data 2:150050. doi:10.1038/sdata.2015.50

Ganeshan M, Murtugudde R, Imhoff ML (2013) A multi-city analysis of the UHI-influence on warm season rainfall. Urban Climate 6:1–23

Haan, C. T., (2002) Statistical methods in hydrology

Hamed KH, Rao AR (1998) A modified Mann-Kendall trend test for autocorrelated data. J Hydrol 204:182–196

Han L, Xu Y, Pan G, Deng X, Hu C, Xu H, Shi H (2015) Changing properties of precipitation extremes in the urban areas, Yangtze River Delta, China, during 1957–2013. Nat Hazards 79(1):437–454

Hu Y, Jia G (2010) Influence of land use change on urban heat island derived from multi-sensor data. Int J Climatol 30(9):1382–1395. doi:10.1002/joc.1984

Hu C, Xu Y, Han L, Yang L, Xu G (2016) Long-term trends in daily precipitation over the Yangtze River Delta region during 1960–2012, Eastern China. Theor Appl Climatol 125(1):131–147

Inoue T, Kimura F (2007) Numerical experiments on fair-weather clouds forming over the urban area in northern Tokyo. SOLA 3:125–128

Karabulut M, Gürbüz M, Korkmaz H (2008) Precipitation and temperature trend analyses in Samsun. Journal International Environmental Application & Science 3(5):399–408

Karmeshu, N. (2012) Trend detection in annual temperature and precipitation using the Mann Kendall test—a case study to assess climate change on select states in the northeastern United States

Kaufmann RK, Seto KC, Schneider A, Liu Z, Zhou L, Wang W (2007) Climate response to rapid urban growth: evidence of a human-induced precipitation deficit. JClim 20:2299–2306

Keggenhoff I, Elizbarashvili M, Amiri-Farahani A, King L (2014) Trends in daily temperature and precipitation extremes over Georgia, 1971–2010. Weather and Climate Extremes 4:75–85

Kendall M (1975) Rank correlation methods. Griffin & Co, London

Kephe PN, Petja BM, Kabanda TA (2016) Theoretical Applied Climatology 126:233. doi:10.1007/s00704-015-1569-9

Kharol SK, Kaskaoutis D, Sharma AR, Singh RP (2013) Long-term (1951–2007) rainfall trends around six Indian cities: current state, meteorological, and urban dynamics. Adv Meteorol 2013

Kug JS, Ahn MS (2013) Impact of urbanization on recent temperature and precipitation trends in the Korean peninsula. Asia-Pac J Atmos Sci 49(2):151–159

Kumar S, Merwade V, Kam J, Thurner K (2009) Streamflow trends in Indiana: effects of long term persistence, precipitation and subsurface drains. J Hydrol 374(1):171–183

Kusaka H, Nawata K, Suzuki-Parker A, Takane Y, Furuhashi N (2014) Mechanism of precipitation increase with urbanization in Tokyo as revealed by ensemble climate simulations. J Appl Meteorol Climatol 53(4):824–839

Latham, J., Cumani, R., Rosati, I., Bloise, M. (2014) Global Land Cover SHARE (GLC-SHARE) database Beta-Release Version 1.0

Laurian L (2013) Climate change and cities: first assessment report of the urban climate change research network. J Plan Educ Res 33:242–244

Liu S, Chen M, Zhuang Q (2014) Aerosol effects on global land surface energy fluxes during 2003–2010. Geophys Res Lett 41. doi:10.1002/ 2014GL061640

Lu D, Weng Q (2006) Use of impervious surface in urban land-use classification. Remote Sens Environ 102(1):146–160

Luo Y, Liu S, Fu S, Liu J, Wang G, Zhou G (2008) Trends of precipitation in Beijing River basin, Guangdong province. China Hydrol Process 22:2377–2386

Mann HB (1945) Non-parametric tests against trend. Econo-metrica: Journal of the Econometric Society:245–259

Mishra AK, Singh VP (2010) Changes in extreme precipitation in Texas. J Geophys Res 115:D14106. doi:10.1029/2009JD013398

Mishra AK, Singh VP, Özger M (2011) Seasonal streamflow extremes in Texas river basins: uncertainty, trends, and teleconnections. J Geophys Res 116:D08108. doi:10.1029/2010JD014597

Niyogi D, Alapaty K, Raman S, Chen F (2009) Development and evaluation of a coupled photosynthesis-based gas exchange evapotranspiration model (GEM) for mesoscale weather forecasting applications. J Appl Meteorol Climatol 48(2):349–368

O'Gorman PA, Schneider T (2009) The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. Proc Natl Acad Sci 106(35):14773–14777

Pingale SM, Khare D, Jat MK, Adamowski J (2014) Spatial and temporal trends of mean and extreme rainfall and temperature for the 33 urban centers of the arid and semi-arid state of Rajasthan, India. Atmos Res 138:73–90

Rosenzweig C, Solecki WD, Hammer SA, Mehrotra S (2011) Climate change and cities: first assessment report of the urban climate change research network. Cambridge University Press

Schneider U, Becker A, Finger P, Meyer-Christoffer A, Ziese M, Rudolf B (2014) GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. Theor Appl Climatol 115:15–40

Seto KC, Fragkias M, Güneralp B, Reilly MK (2011) A meta-analysis of global urban land expansion. PLoS One 6(8):e23777. doi:10.1371/ journal.pone.0023777

Shahid S, Wang X-J, Harun SB, Shamsudin SB, Ismail T, Minhans A (2015) Climate variability and changes in the major cities of Bangladesh: observations, possible impacts and adaptation. Reg Environ Chang. doi:10.1007/s10113-015-0757-6

Sharma CS, Panda SN, Pradhan RP, Singh A, Kawamura A (2016) Precipitation and temperature changes in eastern India by multiple trend detection methods. Atmos Res 180:211–225

Shepherd JM, Pierce H, Negri AJ (2002) Rainfall modification by major urban areas: observations from space borne rain radar on the TRMM satellite. J Appl Meteorol 41(7):689–701

Shepherd JM (2006) Evidence of urban-induced precipitation variability in arid climate regimes. J Arid Environ 67(4):607–628

Stallins, J. A., Bentley, M. L., and Ashley, W. S. (2010) Climatological radar delineation of urban convection for Atlanta, Georgia

Sun Q, Kong D, Miao C, Duan Q et al (2014) Variations in global temperature and precipitation for the period of 1948 to 2010. Environ Monit Assess 186(9):5663–5679

Tayanc M, Toros H (1997) Urbanization effects on regional climate change in the case of four large cities of Turkey. Clim Chang 35(4):501–524

Trenberth KE, Caron JM (2000) The Southern Oscillation revisited: sea level pressures, surface air temperatures, and precipitation. J Clim 13:4358–4365

UNFPA, State of the World Population (2007) Unleashing the potential of urban growth. UNFPA, New York 45

Velpuri N, Senay G (2013) Analysis of long-term trends (1950–2009) in precipitation, runoff and runoff coefficient in major urban watersheds in the United States. Environ Res Lett 8:024020

Yue S, Wang C (2004) The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. Water Resour Manag 18:201–218

Yue S, Pilon P, Phinney B, Cavadias G (2002) The influence of autocorrelation on the ability to detect trend in hydrological series. HydrolProcess 16:1807–1829