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Half-century urban drying in Shijiazhuang City*

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Keywords: relative humidity, trend of change, urbanization effect, urban drying, China

Abstract

Climatic and environmental change in urban areas attracts more and more attention with rapid urbanization worldwide. Change in key surface climatic variables in urban areas is a core component of urban climatic change. Here we report an analysis of relative humidity (RH) change in Shijiazhuang City, China, over the period 1963–2012, based on the RH data of a typical urban station and the surrounding rural stations. We found that the annual mean RH at the urban station underwent a more significant downward trend (−0.74%/10 yr) than those at the four rural stations (−0.16%/10 yr on average), and the most significant decrease occurred after 1990s; urbanization effect on the decrease of annual mean RH at the urban station reached −0.59%/10 yr, which was highly significant, with the urbanization contribution to the overall RH decrease being 78.7%, indicating that the trend of urban drying was caused dominantly by the urbanization; urbanization effects on seasonal mean RH decrease at the urban station were −0.60%/10 yr, −0.61%/10 yr, −0.67%/10 yr and −0.46%/10 yr respectively for spring, summer, autumn and winter, which were all significant statistically, with a 100% urbanization contribution for winter; rising temperature, dropping evaporation and decreasing precipitation days relative to rural areas were found to be the main factors affecting the urban RH decrease. The conclusions are of practical significance to further understand the characteristics and causes of RH change at a typical urban meteorological station in North China, and to detect the large-scale climatic and environmental change for assessing the impact of climate change on agricultural production and water cycle.

1. Introduction

Water vapor is the most important energy carrier in the atmosphere, and also the most important greenhouse gas. Its spatial and temporal distribution has a considerable impact on weather and climate through such factors as latent heat exchange, radiative cooling and heating, cloud formation and rainfall, thus affecting the formation and variation of climate at varied scales (Ma *et al* 2014, Vicente-Serrano *et al* 2014), and also the living environment of human being and ecosystem (Gosling *et al* 2008). Water vapor near surface occupies a large proportion in the whole atmosphere. The total amount of atmospheric water vapor is closely related to the surface humidity and can be reflected by the surface air humidity (Yang and Qiu 1996).

As an indicator of degree of water vapor saturation in the atmosphere, surface air Relative Humidity (RH) is defined as the percentage of actual vapor pressure and saturated vapor pressure of the surface atmosphere (Sheng *et al* 2003). RH can well reflect the comprehensive effects of temperature, precipitation and other factors and the impact of climate change on regional water cycle as a direct observation compared with dew point temperature, specific humidity and other indicators of humidity (Lu and Takle 2010). At the same time, RH is

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also an important factor affecting surface water and energy budget (Trenberth *et al* 2003), aerosol (Zhang *et al* 2011), haze formation (Ding and Liu 2014), animal and plant growth and human comfort (Alberdi *et al* 1998).

In recent years, many scholars have studied the variation characteristics of RH. The study of Surratt *et al* (2004) showed that the RH in the United States experienced a downward trend and was negatively correlated with the evaporation of water droplets. The decreased humidity is one of the causes of increased drought frequency. Akinbode *et al* (2008) found that the RH in Akure, Nigeria, decreased significantly from 1980 to 2001. Based on North American reanalysis data from 1979 to 2007, Lu and Takle (2010) found that RH showed a downward trend from the ground to 300 hPa, and RH was positively correlated with the annual precipitation.

According to the domestic research in China, Wang *et al* (2004) concluded that the annual mean RH in the Qinghai-Tibetan Plateau and Northwest China had an obvious upward trend from 1951 to 2000, while a significant downward trend could be seen in Northeast China. Analyzing the surface data of China in the past 50 years from 1961 to 2010, Song *et al* (2012) found that RH in most areas of eastern China showed a significant downward trend. Lu and Xiong (2013) found that the regional variation of RH in China is divided by 95 °E, with the RH in the west of 95 °E tending to increase, while that in the east of 95 °E to mostly decrease. In addition, Chinese researchers have also published a series of articles on studies of regional and local scales (e.g. Jin *et al* 2009, Li *et al* 2010, Ma *et al* 2014, Li *et al* 2016, Liu *et al* 2017), which generally showed that annual mean RH was mainly in a long-term decreasing trend.

It was found that RH was closely related to precipitation and temperature, and the variations of precipitation and temperature would inevitably lead to the response and adjustment of RH (Gaffen and Ross 1999, Vicente-Serrano *et al* 2014); wind speed also affected RH in certain extent (Jin *et al* 2009). At the same time, urbanization process had a significant impact on RH (e.g. Jaureguie 1973, Aekerman 1987, Wen and Yang 2006, Fortuniak *et al* 2006, Zheng and Liu 2008, Liu *et al* 2009, Yang *et al* 2017). Aekerman (1987) considered that the main reason that RH in Chicago was usually lower than that in rural areas was the Urban Heat Island (UHI) effect. The effect of Urban Dryness Island (UDI) was more prominent when the intensity of urban heat island was high. The difference of RH between urban and suburban areas was the largest when the intensity of Mexican urban heat island was the strongest at night in the cold season. The RH of urban center was 50%, while the urban fringe was 75%, with a difference of 25% (Jaureguie 1973). Fortuniak *et al* (2006) found that the RH in the towns of Rhodes, Poland, from 1997 to 2002, was lower than that in the villages, and the difference between urban and rural areas exceeded 40% on some extreme cases. Um *et al* (2007) found that the annual average RH of Seoul Station, as a representative observatory of Korean metropolitan areas, had declined significantly since 1905, while the decreased trend of the medium-sized urban and rural stations selected was lower than that of Seoul Station.

Researches on RH and UDI were also conducted for a few cities of mainland China. The analysis of Zheng and Liu (2008) showed that the annual mean RH in Beijing urban area was declining in the past 40 years (1961–2000), while that in suburbs was increased slightly. With the development of urbanization in Beijing, the temperature in urban area had increased while the relative humidity had decreased, which resulted in the phenomenon of UDI in urban area becoming increasingly prominent. Yang *et al* (2017) analyzed the variation characteristics of RH and the UDI effect in Beijing City by using hourly RH data from 36 automatic weather stations from 2007 to 2015, showed that RH in Beijing urban areas were significantly smaller than rural areas, the strongest UDI effect appeared in the central urban area encircled by the Fourth Ring-Road, and urbanization has a remarkable impact on near-surface air RH and UDI magnitude.

Shijiazhuang station is a typical urban observation site in the continental temperate zone of East Asia. Past studies showed that the UHI intensity has a significant increasing trend along with rapid urbanization (Bian *et al* 2012). It had a significant impact not only on the trend of the mean surface air temperature of the urban station, but also on the trend of extreme temperature events (Bian *et al* 2015). However, it is not clear that the nature and magnitude of the impact urbanization has on the long-term trend of humidity variation at Shijiazhuang Station. To examine the long-term change in RH due to the urbanization at the typical urban station would be conductive to a further understanding of the urban climatology and urban climate change, and also of the data bias of the national station applied frequently in studies of regional climate change.

Based on the RH data of the urban station and four rural stations in Shijiazhuang areas from 1963 to 2012, this paper made a first comparative analysis of the RH trend between urban and rural sites, and evaluated the urbanization effect of the RH series at Shijiazhuang station in quantitatively. This work showed that a significant deceasing trend of RH was occurred at the urban station over 1963–2012, which indicated that the urban area of the city experienced a drying or UDI strengthening process of the near-surface atmosphere around the observational site with the rapid urbanization.

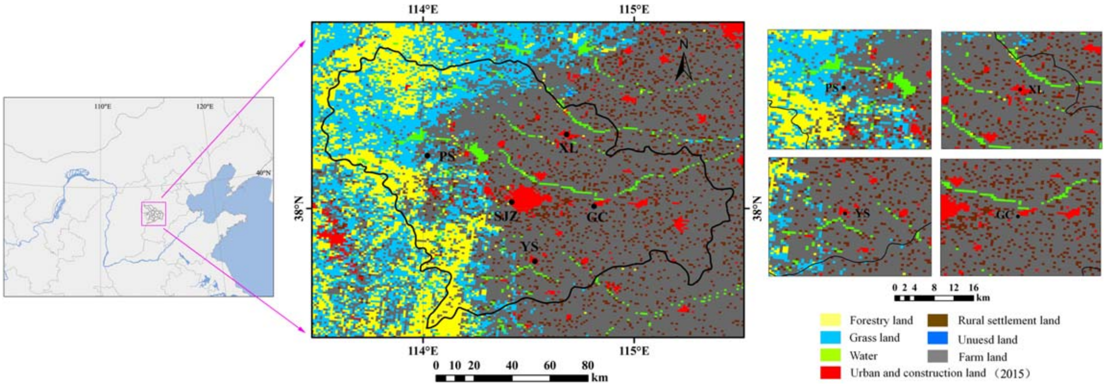

Figure 1. The stations distribution of this study and the land use and cover of satellite image map around the stations in 2015 (SJZ: Shijiazhuang; GC: Gaocheng; YS: Yuanshi; PS: Pingshan; XL: Xinle).

Table 1. Information of the five meteorological stations used in this study.

Station		Longitude (E) (°)	Latitude (N) (°)	Altitude (m a.s.l.)	Time of starting records	Time of relocation	Population (million)
Urban	Shijiazhuang	114.42	38.03	81.0	1955.01.01	2013.01.01	2.70
Rural	Gaocheng	114.81	38.01	53.5	1958.08.01	1969.07, 1999.01	0.10
	Yuanshi	114.53	37.75	66.4	1960.01.01	1982.02, 1998.01, 2007.01	0.08
	Pingshan	114.02	38.25	131.0	1959.01.01	1961.09, 1964.01, 2000.01	0.10
	Xinle	114.68°	38.35°	70.8	1959.03.01	1961.05, 1963.12, 1989.05, 2003.01	0.10

2. Data and methods

Shijiazhuang station, a national basic station before 2013, represented the typical urban surface atmospheric environment. Gaocheng, Yuanshi, Pingshan, Xinle stations are the national ordinary stations which represented the rural surface air condition. The distribution and basic information of the 5 stations were showed in figure 1 and table 1. The monthly average RH data of each station came from Hebei Information Sharing Platform (http://10.48.36.193/), which had been conducted strict quality control; and the start and end time was December 1962 to December 2012, respectively. The method of meteorological seasonal division was used, namely winter was December to February of the following year, spring was March to May, summer was June to August, autumn was September to November, respectively.

Shijiazhuang station, located in the mid-west of the city, was not moved until December 31, 2012. Before the early 1980s, the observation station was far from the urban built-up area, and the surrounding environment was open with few buildings; since then it had become a typical urban observation station, with the urbanization process around the observational site accelerating after the beginning of the 1990s. The rural stations are all located near the 4 small towns in the east, south, northwest and northeast of Shijiazhuang city, with a distance of more than 20 km from the urban areas. The permanent population in the built-up areas is about 0.1 million for each of the four towns (table 1), and the locations of the observational stations are generally located at the periphery zones of the built-up areas. In spite of the fact that the rural stations have been influenced by the urbanization in less extents as seen in figure 1, they are the most rural stations available in the study region. A few of buildings near the rural stations can be seen, but they are usually not tall, and the micro-environment around the observational grounds is somehow good. Real rural stations actually do not exist in any regions of the North China Plain. The 4 rural stations have an average altitude of 80.4 m above sea level and average latitude of 38.09 °N, which are close to the altitude and latitude of the urban station (81.0 m and 38.03 °N). The four rural stations also had the long observational records comparable to that of Shijiazhuang urban station. In the past research on the impact of urbanization at Shijiazhuang station (Bian *et al* 2012, 2015, 2017), these rural stations had been confirmed representative as reference sites.

Shijiazhuang station was not moved during the research period, but each of the 4 rural stations has been moved, and Xinle station has been moved 4 times so far (table 1). In order to understand the inhomogeneities of data series caused by relocation and instrumentation, the inhomogeneity test of the RH data series was carried out by referring to the method of Wang *et al* (2010). The results showed that, under the level of 95% confidence, there were suspected discontinuous points at Gaocheng and Xinle stations in 2002, but these were not caused by station relocation and instrument replacement by examining metadata. During 2005–2009, the manual observations had been replaced by automatic weather stations gradually. The inhomogeneity test showed that there were some significant differences between the observational results of RH between automatic and manual observations (Yu and Mou 2008, Yuan *et al* 2010), which had affected the homogeneity of the data series. The monthly RH data series had been adjusted accordingly in this study, with a corrected value of 3.5%, referring to the research results by Yu and Mou (2008) and Yuan *et al* (2010). The monthly mean RH since 2005 at the urban station was increased 3.5% and those at the rural stations since 2009 was increased 3.5%. The homogenization effectively eliminated the break points in the RH data series caused by the changes of observational sites and instruments.

The least square method was used to fit the linear trends (i.e., the tendency rate) of RH, with the sample size of 50. T-test method was used to test the statistical significance of the linear trends, and the significance levels of $a = 0.10$, $a = 0.05$ and $a = 0.01$ expressed that the trends were somehow significant, significant and highly significant respectively. Pearson correlation coefficient was used to analyze the correlations of RH with temperature, precipitation and wind speed series.

Urbanization generally refers to the process of population gathering in urban areas and the transformation of rural areas into built-up areas. The following terms was used for quantitatively evaluating the effect of urbanization on the change trends of annual and seasonal RH series, referring to Ren (2008), Zhou and Ren (2009) and Bian *et al* (2015, 2017):

Urbanization effect (ΔRH_{u-r}) refers to the effect of UHI and other local anthropogenic factors on the linear trends of RH recorded at an urban station. It is expressed as ΔRH_{u-r}:

$$\Delta RH_{u-r} = RH_u - RH_r \tag{1}$$

where RH_u (RH_r) is the linear trend of RH at urban (rural) station. If $\Delta RH_{u-r} > 0$, it means that the urbanization effect makes RH increase; If $\Delta RH_{u-r} = 0$, it means that the urbanization effect is 0; while if $\Delta RH_{u-r} < 0$, it means that the urbanization effect makes RH decrease. The linear trend of difference of RH between the urban station and the rural stations, which was also used in this paper, is another expression of the urbanization effect, and it is equal to ΔRH_{u-r}.

Urbanization contribution (C_u): this refers to the proportion of the urbanization effect (ΔRH_{u-r}) to the significant trend of RH at an urban station. It is expressed as C_u (%):

$$C_u = |\Delta RH_{u-r}/RH_u| \times 100\% \tag{2}$$

Because the urbanization effect (ΔRH_{u-r}) can be negative under certain circumstances, an absolute value was taken for C_u to enable $0 \leqslant C_u \leqslant 100\%$. If $C_u = 0$, the urbanization effect makes no contribution to the trend of RH at the urban station. If $C_u = 100\%$, the linear trend of RH at the urban station is caused entirely by the urbanization effect. In practical calculations, C_u may occasionally exceed 100%, indicating that unknown local anthropogenic factors might have an effect, but it was adjusted to 100%. In this study, the urbanization contribution would be not calculated if the urbanization effect was not statistically significant.

3. Results

3.1. Characteristics of the urban and rural RH

Figure 2 showed the changes of annual mean RH at the urban and rural stations of Shijiazhuang, decadal mean RH, and the linear trends of annual mean RH, during 1963–2012. In the 50 years, the annual mean RH at the urban station significantly decreased, and the downward trend was $-0.74\%/10$ yr which was significant at the $a < 0.10$ level. Before the 1990s, the annual mean RH of the urban stations remained unchanged; the remarkable decreasing trend occurred after the beginning of the 1990s, and the smallest annual mean RH (59.3%) appeared in the early 21st century.

In the 50 years, however, the annual mean RH of the rural stations only had a slight decreasing trend ($-0.16\%/10$ yr), which was not statistically significant; decadal mean RH decreased, with the largest mean RH in 1970s and the smallest one in period after 2000. The decrease in rural areas was consistent with the long-term drying trend due to the decrease of annual precipitation in North China (Ren *et al* 2012). Figure 2 also shows that, the mean RH of the urban station was smaller than that of the rural stations for annual or decadal mean values, indicating that urban area was generally drier than the rural areas and the UDI effect in the city was obvious. The urban-rural RH difference was getting bigger, and the decadal mean difference from 1960s was 2.2% for 1980s, 3.5% for 1990s, and 4.8% for the period after 2000, indicating a strengthening urbanization effect on the decadal mean RH at the urban station.

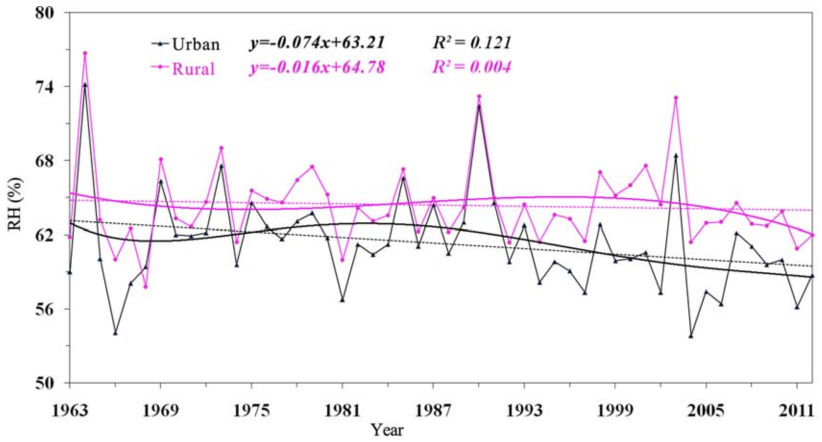

Figure 2. Changes in annual mean RH (marked curve line), polynomial fitting of RH (smooth line) and the linear trends (dotted line), at the urban (black) and rural stations (pink) of Shijiazhuang, during 1963–2012.

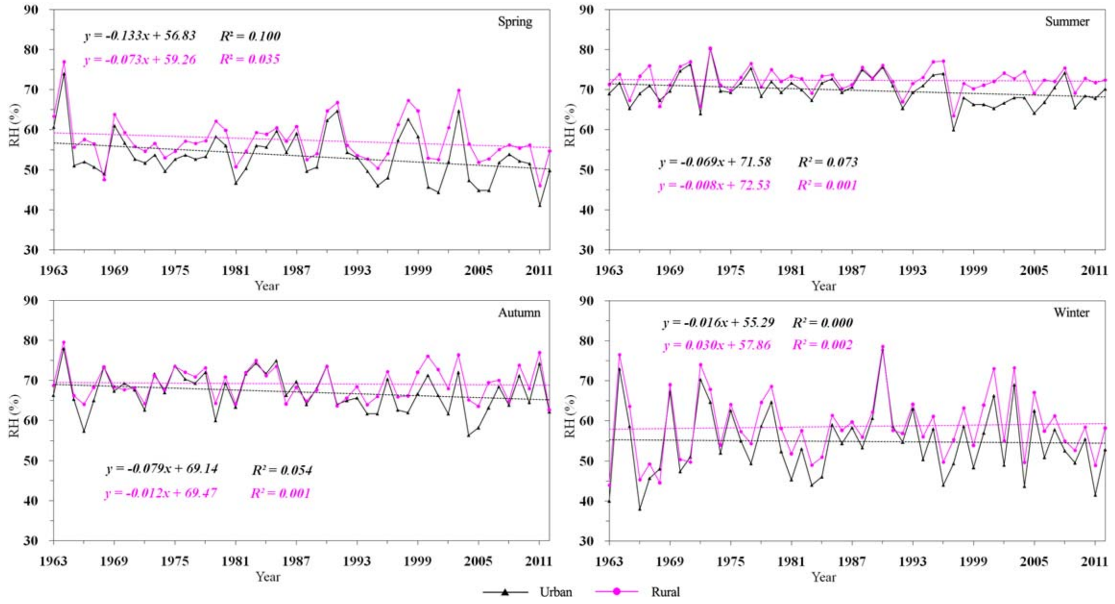

Figure 3. Change in seasonal mean RH (solid line) and the linear trends (dotted line) at the urban and rural stations of Shijiazhuang during 1963–2012.

Seasonal mean RH of the urban station showed decreasing trends at the rates of −1.33%/10 yr, −0.69%/10 yr, −0.79%/10 yr and −0.16%/10 yr for spring, summer, autumn and winter, respectively, with the strongest decrease in spring and the weakest in winter (figure 3). The decreasing trend of the urban station in spring was significant at the $a < 0.05$ level, and those in summer and autumn were marginally significant ($a < 0.10$), while that in winter showed no significant trend. The seasonal mean RH of the rural stations experienced a weaker change, with spring, summer and autumn decreasing at −0.73%/10 yr, −0.08%/10 yr and −0.12%/10 yr, respectively, and winter an increase at 0.30%/10 yr. However, all the seasonal mean trends were not significant. The differences of the urban-rural annual mean RH in spring, summer, autumn and winter were −4.0%,−2.5%, −2.0% and −3.8% respectively, indicating that there was a seasonal UDI effect at the urban station, and the UDI intensity was stronger in spring and winter.

Figure 4 shows linear trends of monthly mean RH at Shijiazhuang station and the four rural stations in the 50 years. The urban station RH in January, June, November and December increased at rates between 0.09%/10 yr and 0.43%/10 yr, but all the trends were not significant at the $a < 0.05$ level; those in February to May and July to October were negative trends ranging from −2.50%/10 yr to −0.36%/10 yr, with the trend in October significant ($a < 0.05$) and those in March, July and August highly significant ($a < 0.01$). The monthly mean RH had a less change through time, with only the increasing trend of June and decreasing trend of March significant ($a < 0.05$) and the decrease of July less significant ($a < 0.10$).

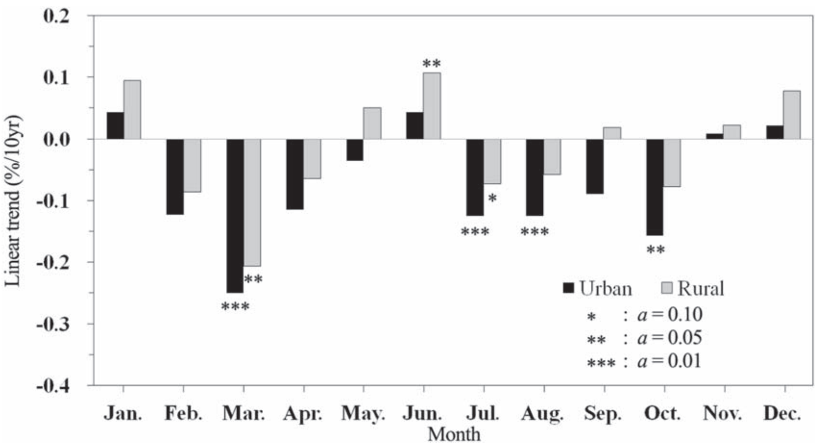

Figure 4. The linear trends of monthly mean RH at the urban and rural stations of Shijiazhuang during 1963–2012.

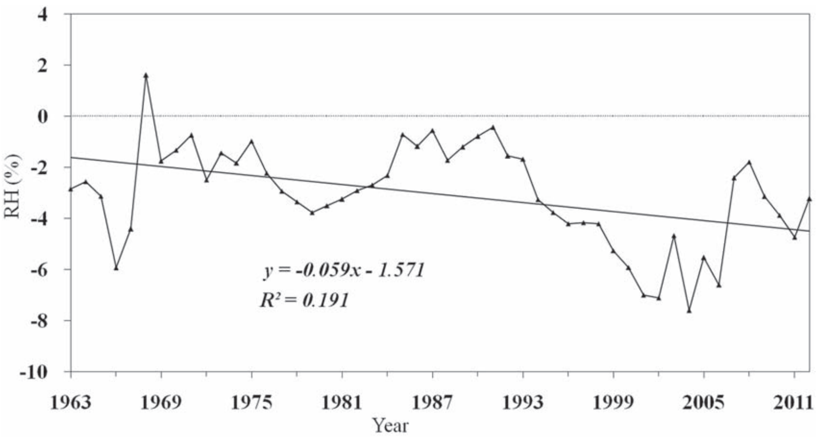

Figure 5. The difference of annual mean RH between Shijiazhuang station and the rural stations during 1963–2012 and its trend line.

3.2. Effect of urbanization

Figure 5 shows the difference series of annual mean RH between Shijiazhuang station and the rural stations during 1963–2012 and its trend line. The annual mean RH differences in the 50 years were negative except for one year (1968), and the urban-rural differences were generally higher than −3% before the mid-1990s, but after then generally lower than −4%. The difference began to rapidly decrease since 1991, and the lowest value of −7.6% appeared in 2004. As a whole, the annual mean RH difference of the urban-rural stations in the past 50 years showed a decreasing trend at a rate of −0.59%/10 yr. The urbanization effect on the annual mean RH decrease at Shijiazhuang station was thus large and also highly significant ($a < 0.01$). The urbanization contribution was 78.7%, indicating that the decreasing trend of annual mean RH at Shijiazhuang station, or the trend of becoming dry at the urban station, was mostly caused by the urbanization.

Figure 6 shows that the urbanization effects on the seasonal mean RH trends in spring, summer, autumn and winter at the urban station were all negative, which were −0.60%/10 yr, −0.61%/10 yr, −0.67%/10 yr and −0.46%/10 yr respectively. In winter, the effect was significant ($a < 0.05$), and other three seasons witnessed highly significant urbanization effects ($a < 0.01$). The urbanization contributions in four seasons were 45.1%, 88.7%, 84.3% and 100% respectively. Therefore, the decreasing trend of seasonal mean RH in winter at the urban station was almost entirely caused by urbanization.

In view of monthly mean RH trends (figure 7), except for the weak urbanization effects in February and November (−0.37%/10 yr and −0.13%/10 yr), which did not pass the significance test, the urbanization effects of other months (ranging from −1.07%/10 yr to −0.43%/10 yr) were all significant or highly significant. The trends of the urban-rural difference in months from April to October were all highly significant. Except for February and November, the monthly urbanization contributions ranged from 17.3% to 100%, with the largest contributions seen for January, May, June, September and December (100%), indicating that the reduction of monthly mean RH in the five months was almost entirely caused by urbanization.

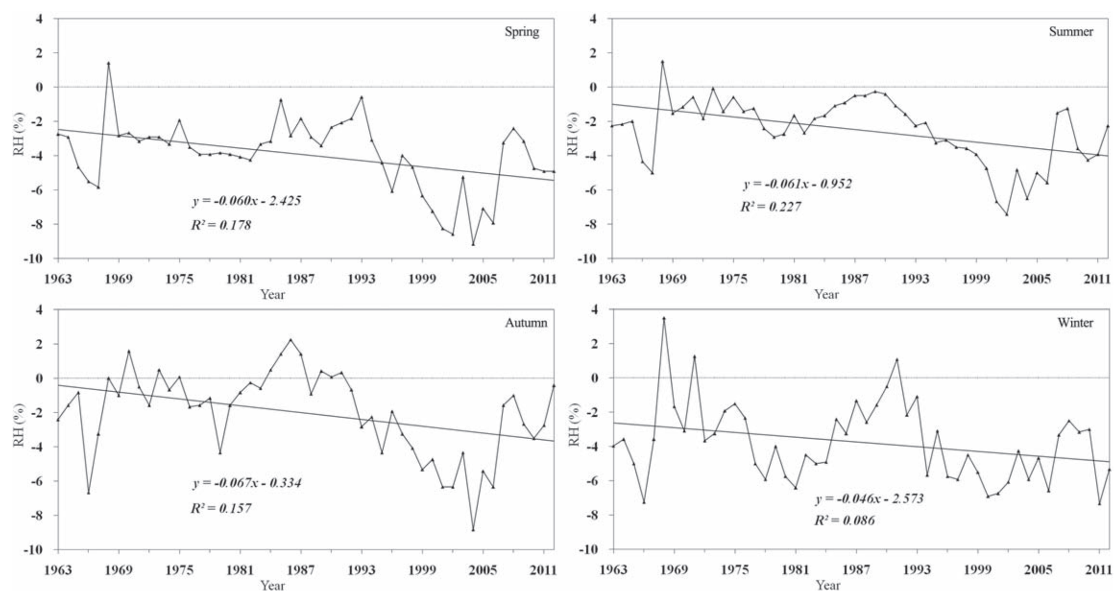

Figure 6. The difference series of seasonal mean RH between Shijiazhuang station and the rural stations during 1963–2012 and their linear trends.

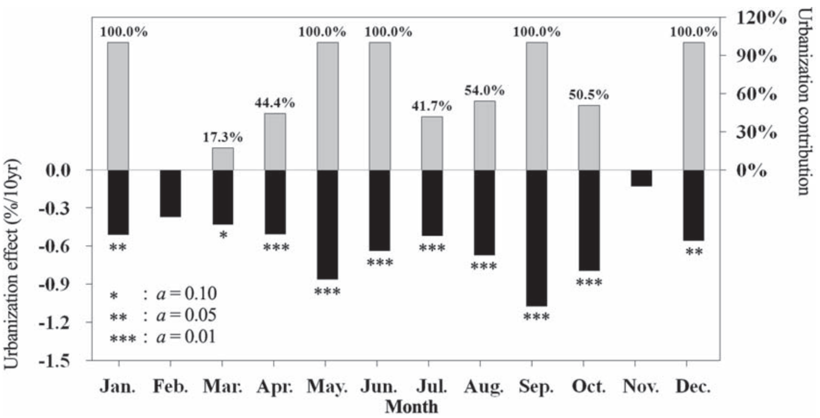

Figure 7. Urbanization effects and contributions in the monthly mean RH series at Shijiazhuang station during 1963–2012.

4. Discussion

Over the 50 years of 1963–2012, both the annual and seasonal mean RH of the urban station in Shijiazhuang showed decreasing trends, which were consistent with the national (Song *et al* 2012, Lu and Xiong 2013) and regional (Jin *et al* 2009, Li *et al* 2010, Ma *et al* 2014, Li *et al* 2016, Liu *et al* 2017) studies, which all reported a notable decrease in annual RH over the past decades.

Natural variability of climate may have contributed to the long-term change in annual and seasonal mean RH in mainland China. Qi and Cai (2017) showed, for example, that the weakening (strengthening) of the latitudinal sea-land thermal difference in winter resulted in the anomaly of southwest wind (northeast wind) in the low-altitude monsoon circulation system, and regulated the water vapor transport from the eastern part of the Bay of Bengal and the South China Sea (East China Sea) to the eastern part of mainland China. It can affect the change of RH in the above areas by restricting water vapor transport and precipitation. The increase of latitudinal sea-land thermal difference may lead to the decrease of relative humidity in North China and other areas, and the significant increase of relative humidity in South China, and vice versa.

The decreasing trend of the annual mean RH in the whole country during 1951–2000 was −0.03%/10 yr, and that in North China was −0.30%/10 yr (Wang *et al* 2004). The decreasing trend (−0.74%/10 yr) of the annual mean RH in the urban station at Shijiazhuang was stronger than that in the whole country and North China, however, and the urbanization might have played an important role, in addition to the natural variability of East Asian Monsoon system including the decadal shift of water vapor transport and precipitation resulting

Table 2. Relationship of RH with other climate variables at Shijiazhuang station over 1963–2012.

	Temperature	Precipitation days	Precipitation	Wind speed
R^2	−0.48	+0.57	+0.21	+0.12
Significance	Significant ($a < 0.01$)	Significant ($a < 0.01$)	Not significant	Not significant

from the latitudinal land-sea thermodynamics. The decreasing trend (−0.16%/10 yr) of the annual mean RH at the rural stations of Shijiazhuang was slightly larger than that of the whole country and slightly smaller than that of North China, which showed large urbanization effect of the urban station on one hand and that the rural stations selected in this paper were relatively representative on the other hand.

During 1961–2000, the decreasing rate of annual mean RH in Beijing urban area was −1.25%/10 yr (Zheng and Liu 2008). Compared with Beijing station, the downward trend of RH at Shijiazhuang station was obviously weaker, which may be related to such factors as different research periods analyzed, the city size and urbanization rate and the reference stations applied in the studies of the two cities. The annual mean RH in Beijing suburbs increased slightly, while that the slight decrease was seen at the four Shijiazhuang rural stations, though the annual mean RH changes of both Beijing and Shijiazhuang suburbs sites were not significant. Only in winter, was the decreasing trend of seasonal mean RH at Shijiazhuang station was weak and insignificant, and the other three seasons underwent more or less significant trends, in spite of the fact that the winter mean UHI intensity at Shijiazhuang station was the strongest in four seasons (Bian *et al* 2012). It is likely that the obvious increase of light fog and haze days in winter in recent years (Ding and Liu 2014) slowed down the decreasing trend of RH in winter.

The results of this paper showed that the urbanization had a significant effect on the annual mean RH decrease at Shijiazhuang station in the past 50 years, and the urbanization contribution reached 78.7%. Although Zheng and Liu (2008) did not directly give the urbanization effect on, and contribution to, the RH reduction in urban areas of Beijing, according to their results of RH reduction in urban and suburban areas of Beijing from 1961 to 2000 (urban area −1.25%/10 yr, and rural area 0.60%/10 yr) and the calculation method in this paper, the urbanization effect on the annual mean RH decrease at Beijing urban areas was −1.85%/10 yr and the urbanization contribution was 100%. The larger urban extent in Beijing City may have contributed to the difference, and the reference stations selected and the different analysis periods used for the two studies may have been also important in the estimated urbanization effect and contribution of the two urban stations.

As can be seen from figure 2, the annual mean RH of the urban and rural areas in 1964 was the highest, with the urban station of 74.2% and the rural station of 76.7%, and the annual mean temperature in this year was 12.0 °C, which was 0.8 °C 1ower than that (12.8 °C) in 1960s. The annual precipitation days in this year were 149 days, 39 days in excess of 1960s (110 days), and the precipitation amount in 1964 was also significantly higher (47%) and the wind speed was 0.3 m s^{-1} lower. The high value of RH in 1964 was thus closely related to low temperature, more precipitation days and larger precipitation amount, and the less wind speed. In 1966, there was a low value (54.1%) in RH of the urban station, the annual mean temperature anomaly of the year was +0.4 °C, and the precipitation days was 106 days or 4 days less than normal, the percent precipitation anomaly in the year was −26%. The low value of RH in 1981 and 2004–2006 was also related to higher temperature, and less precipitation days and precipitation amount. The relationship between RH and temperature, precipitation (precipitation days) and wind speed at Shijiazhuang station in the same 50 decades was examined by using multiple linear regression. The linear relationship was as follows,

$$y = -0.47x_1 + 0.58x_2 + 0.17x_3 + 0.14x_4 \quad (3)$$

where, y refers to RH; x_1 refers to temperature, x_2 refers to precipitation days, x_3 refers to precipitation, and x_4 refers to wind speed.

The annual mean RH at Shijiazhuang station was largely affected by the change of temperature and precipitation days, followed by precipitation amount, and the influence of wind speed was relatively small (table 2, and figure 8). The annual mean RH was significantly negatively correlated with annual mean temperature and significantly positively correlated with annual precipitation days. The annual precipitation amount and annual mean wind speed also had an influence on annual mean RH, and the RH was positively correlated with the two variables though the correlation was weak. Therefore, the main factors affecting annual mean RH in the semi-arid region were surface air temperature and precipitation frequency. The regional temperature increase and precipitation day decrease over the last 50 years were one of the major reasons for the significant RH decline (figures 8(a), (b)), in addition to the urbanization effect. This conclusion was consistent with previous analyses (Gaffen and Ross 1999, Vicente *et al* 2014, Jin *et al* 2009).

Research by Yu and Mou (2008) showed that, there was a certain observational 'deviation' between the automatic weather stations and the manual stations in most areas, and the dry bias existed in the automatic

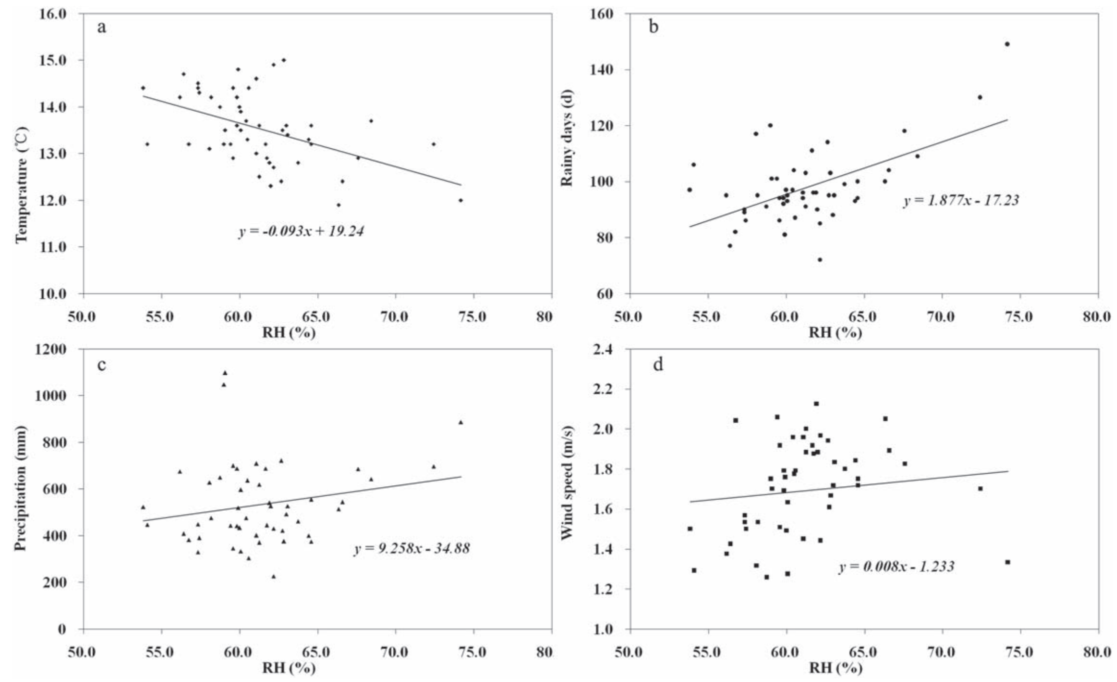

Figure 8. Relationship of annual mean RH with annual mean surface air temperature (a), annual precipitation days (b), annual precipitation amount (b), and annual mean wind speed (d) at Shijiazhuang station during 1963–2012.

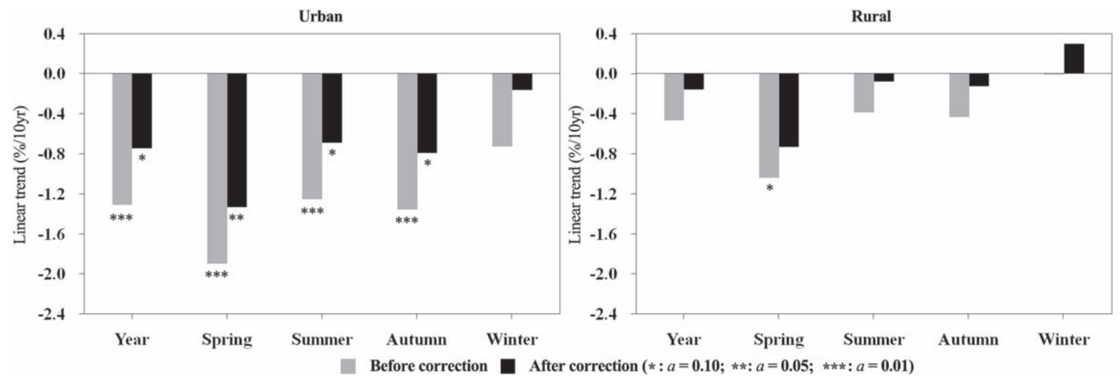

Figure 9. Comparison of the linear trends between the urban and rural stations in Shijiazhuang before and after data homogenization.

weather stations records of RH. The data series of monthly mean RH was adjusted in this paper in order to eliminate the inhomogeneities induced by the application of the automatic weather stations. The decreasing trend of the annual mean RH at Shijiazhuang station after adjustment (−0.74%/10 yr) was significantly weaker than that before adjustment (−1.31%/10 yr) (figure 9, left). The significance test of $a < 0.01$ was passed before the adjustment, but the trend only passed the significance test of $a < 0.10$ after the adjustment. The correction of the inhomogeneities made the urban station data series more homogeneous, and also made the annual mean RH trend closer to that of North China (−0.30%/10 yr). The same is true for the seasonal mean RH series in the four seasons. After adjustment, the decreasing trend of the rural stations in spring, summer and autumn was also weaker (figure 9, right), and the downward trend (−0.01%/10 yr) in winter even reversed to an increase (0.30%/10 yr), though all the seasonal mean trends were weak and insignificant. Therefore, the homogeneity of the data had been improved after the adjustment, and it was more reliable to use the adjusted data for analyzing the long-term trends of RH.

The rural stations selected in this study were more representative than those near the urban stations as reference observational sites. However, because these stations were near small towns, their RH observation records may still be affected by urbanization in certain extent. Therefore, the urbanization effect on the trends of surface air RH series at Shijiazhuang station obtained in this paper should be regards as the lowest estimate. Nevertheless, the analysis results of this paper clearly showed that urbanization played a significant impact on the RH change at the urban station. This conclusion is of great practical significance to further understand the characteristics and causes of RH change at a typical urban meteorological station in North China, and to detect the large-scale climatic and environmental change for assessing the impact of climate change on agricultural production and water cycle.

Under the background of global climate change and regional climate warming (Bian *et al* 2012) and drying (Bian *et al* 2016) in Shijiazhuang areas, the decrease of RH meant that the low-layer atmospheric condition in urban areas was more sensitive to precipitation change, and more frequent and severe droughts will occur when precipitation decreases. The drying trend in urban areas will also affect the urban ecosystem, air quality and human health. Our analysis showed that the annual and seasonal mean RH in the rural areas were not becoming significantly lower with time over the last 50 years. The previous notation that the low-layer atmosphere experienced an aridization was reached in analyses by applying the data of the urban stations, which, if applied in monitoring of large-scale climate change, should be regarded as non-representative for the region due to the urbanization effect existed in the data series. This may have been related to the decline of solar radiation and the increased irrigation over the last decades (Guo and Ren 2006), which may have offset the influence of the decreased precipitation in a large extent (Ren *et al* 2012).

5. Conclusions

Based on the monthly data of RH from Shijiazhuang city station and four rural stations during 1963–2012, and the urban-rural method, the urbanization effects on the series of the surface air RH at the urban station were analyzed with the following conclusions:

(1) In the 50 years, the annual mean RH at the urban station showed a significant decreasing trend at a rate of −0.74%/10 yr, with the more significant decrease after 1990s; the annual mean RH of the rural stations experienced a weaker decreasing trend at an average rate of −0.16%/10 yr.

(2) The effect of 'urban dryness island' at Shijiazhuang station was obvious, and the absolute values of difference of urban-rural RH experienced a significant increase over the half century. The annual mean RH difference of the urban-rural RH changed at a rate of −0.59%/10 yr, which was highly significant. The urbanization contribution to the overall trend was 78.7%.

(3) Urbanization effects on seasonal mean RH trends in spring, summer, autumn and winter were also significant or highly significant at the urban station, and the urbanization contributions were 45.1%, 88.7%, 84.3% and 100% respectively.

(4) The main factors affecting RH change were surface air temperature and precipitation days, in addition to the urbanization effect, in Shijiazhuang areas, and precipitation amount and wind speed also played a role in a less extent.

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