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Long-term change in relative humidity across China from 1961–2018

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ABSTRACT: Using observational data of daily relative humidity obtained from 2479 meteorological stations from 1961–2018 and the homogenized monthly data set of national ground meteorological stations, this paper analyzes the climate change characteristics of average relative humidity across China as well as in 9 individual regions. From 1961–2018, the climate change trend in annual average relative humidity across China was negligible, but there were large differences among different regions. Overall, annual relative humidity in the Qinghai-Tibet Plateau and Xinjiang area showed a significant increase, while Northwest China, Northeast China and northern North China showed a significant decrease. Seasonally, average relative humidity in China chiefly decreased in spring, and there was no discernable trend in other seasons. The Qinghai-Tibet Plateau showed a significantly increasing trend in winter, spring and summer, especially in spring; Xinjiang exhibited a significant increasing trend in winter, summer and autumn; Northeast China presented a significantly decreasing trend in winter; Northwest China, North China, Central China and East China witnessed a significantly decreasing trend in spring; and South China and Southwest China showed a slightly decreasing trend across all 4 seasons. Large urban agglomerations exert an influence on relative humidity to some degree, with urban areas experiencing lower relative humidity than rural areas.

KEY WORDS: Relative humidity · Region · Climate change trends · Urbanization · China

1. INTRODUCTION

As a physical quantity to measure the content of atmospheric water vapor, relative humidity exerts a vital influence on the greenhouse effect, the water cycle, climate feedback, cloud microphysics, aerosols, smog formation, disease transmission and human health (Yang et al. 1999, Ding & Liu 2014). In the context of global warming, regional precipitation and air temperature have changed to varying degrees over the past century. As an important factor to adjust the balance of surface water and energy, changes in relative humidity are closely bound to precipitation and air temperature. Changes in precipitation and air temperature will inevitably result in a response and adjustment of relative humidity (Gaffen & Ross 1999). Thus, it is of enormous practical significance to study the distribution pattern and change in trends of relative humidity in the context of global climate change (Vicente-Serrano et al. 2018). Such information may not only reduce the uncertainty arising from relative humidity in the prediction of future climate change but also has important practical significance for understanding how changes in the environment will affect agricultural production (Lu 2013).

Surface relative humidity typically exhibits relatively little spatial and interannual variation, with a mean value of 75–80 % over most oceans in all seasons and 70–80 % over most land areas (except for deserts and high terrain, where relative humidity is 30–60 %) (Dai 2006). The fourth IPCC report stated that relative humidity is constant on large spatial and time scales (Randall et al. 2007). Some studies hold that the climate change trend of relative humidity is negligible (Vincent et al. 2007, Willett et al. 2010). Despite global average changes in relative humidity being rather small superficially, these changes can be quite large both at a regional scale and between different regions

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(Fatichi et al. 2015). At the regional scale especially, changes in relative humidity are more complicated. The sixth IPCC Assessment Report pointed out that since 2000, relative humidity in most parts of the world has decreased, especially in the middle latitudes of the Northern Hemisphere, whereas it has increased in the high latitudes of the Northern Hemisphere (IPCC 2021). Relative humidity has generally decreased in the western USA, South America, North Africa, eastern Australia and eastern China (Simmons et al. 2010). In most parts of China, relative humidity has exhibited a downward trend (Wang & Gaffen 2001, Ma et al. 2014), and the relative humidity has decreased significantly in the north of Huaihe River in the Qinling Mountains, chiefly owing to the decrease in relative humidity; the change in relative humidity in the south of Qinhuai River is not distinct in the region (Lu 2013). From 1951–2000, relative humidity exhibited a distinct upward trend in the plateau and northwest regions and a significant downward trend in Northeast China, whereas in other regions there was no obvious trend (Wang et al. 2004). Researchers analyzing the surface data of China in a recent 50 yr period (1961–2010) discovered that relative humidity in most areas of eastern China has significantly decreased (Song et al. 2012). In long-term observations of relative humidity, there have been many breakpoints in the humidity time series, as well as changes due to station relocations and different observation methods. After revision using the Multiple Analysis of Series for Homogenization (MASH) method, researchers discovered that there was almost no long-term trend (0.006 % decade^{-1}) in the regional average relative humidity in China from 1960–2017, whereas the original sequence showed a false downward trend of −0.414 % decade^{-1} (Li et al. 2020). Many scholars in China have conducted immense amounts of research on the characteristics of changes in relative humidity in different regions. In a recent 50 yr period (1953–2002), the annual average relative humidity along with the relative humidity across 4 seasons decreased in fluctuation in semi-arid areas of western Jilin Province, but the downward trend was not significant (Jin et al. 2009). The principal factors influencing changes in relative humidity were air temperature and precipitation, with wind speed also playing a role. Relative humidity near the surface of the Qinghai-Tibet Plateau exhibited a significant downward trend from 1961–2013, especially in summer and autumn, corresponding to a significant increase in air temperature in the plateau region; this trend was associated with a lack of ocean water vapor transport (You et al. 2015). The annual relative humidity in the middle reaches of the Yangtze River showed a decreasing trend (Yang et al. 2013). Average annual relative humidity in northern Xinjiang generally decreased from 1955–2012, while that in southern Xinjiang generally increased; overall, relative humidity in northern and southern Xinjiang has undergone a series of ‘increase–decrease–increase–decrease’ fluctuations. Across the whole region, relative humidity in northern and southern Xinjiang has decreased drastically since the beginning of the 21st century (He et al. 2015).

Since the 1980s, China has experienced rapid urbanization. Numerous studies have indicated that rapid urbanization exerts a great influence on relative humidity (Yao et al. 2019), with most urbanization producing a ‘dry island’ effect (Yang et al. 2017). As the cities in the Yangtze River Delta expanded, a marked dry island effect developed in these cities. During the period from 1961–2014, relative humidity in urban and rural areas decreased by 1.629 and 0.888 % respectively every decade; thus, due to urbanization, the relative humidity decreases by 0.741 % every decade, making up 45.5 % of the overall trend in urban areas (Luo & Lau 2019). The same conclusion was drawn in a study of South China, with an estimated contribution rate of urbanization to the drying trend in Guangdong urban areas of around 50 % (Lin et al. 2020). The dry island intensity in Beijing has increased by 1.3 % every decade since 1995, which is significantly and highly correlated with the urban heat island intensity in Beijing, with a correlation coefficient as high as 0.86. The increasing rate of dry island intensity with heat island intensity in Beijing is around 4.7 % °C^{-1} (Zheng & Ren 2018).

Owing to the enormous spatial and temporal differences in climate distribution and change across China, the variation characteristics of relative humidity differ distinctly in different regions (Lu & Xiong 2013). Therefore, more than 2400 meteorological stations across China have been classified into 9 regions with reference to the latest homogenized data set of relative humidity (Zhu et al. 2015), to investigate the variation characteristics of relative humidity in each region along with the principal climate factors influencing relative humidity change, with the goal to enhance our understanding of the scientific issues concerned.

2. DATA AND METHODS

2.1. Regional division and station selection

China is conventionally divided into regions encompassing Northeast China, North China, Northwest

China, East China, South China, Central China and Southwest China. Owing to the large area covered by Northwest and Southwest China and the enormous difference in topography between those 2 regions, Xinjiang, Tibet and Qinghai are separately recognized as Xinjiang and the Qinghai-Tibet Plateau, creating 9 regions in total. Please refer to Table 1 and Fig. 1 for the regional distribution and information on meteorological observation stations. The meteorological data comes from the National Meteorological Information Center, in which relative humidity is a daily value data set of homogenized relative humidity from national ground meteorological stations (v.1.0). From 1961–2018, there were 2479 meteorological stations in China. We checked whether the daily observation data of each meteorological station was missing: if there were more than 3 days missing within a month, the average value of that month was recorded as missing; if the monthly value was missing for 2 or more months, the annual average value was recorded as missing. A total of 2047 stations with no missing years from 1961–2018 were selected as calculation stations. Please refer to Table 1 and Fig. 1 for regional distribution and site conditions.

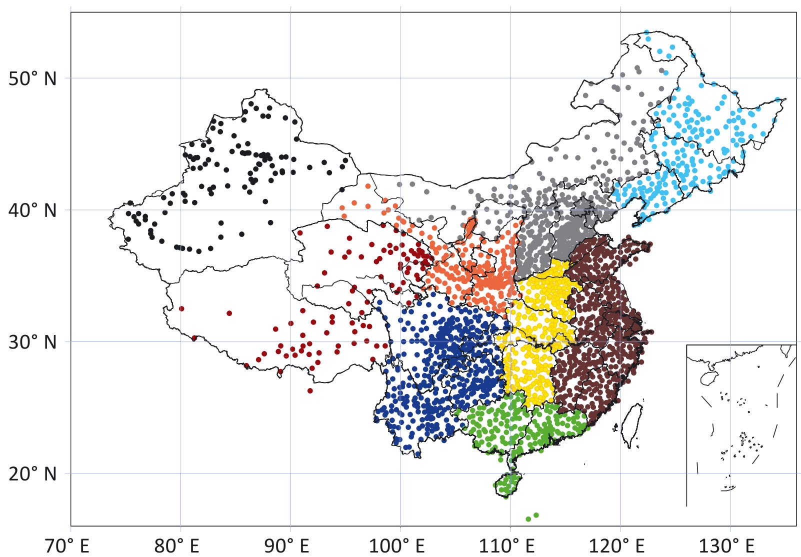

Fig. 1. Distribution and zoning of meteorological stations across China. See Table 1 for region-color explanations

2.2. Introduction of daily data sets of homogenized relative humidity at national ground meteorological stations

During the past 60 yr, most meteorological stations in China have been moved, with some stations being relocated many times. As a result, several changes have occurred in the instruments recording relative humidity, with observation modes alternating from manual to automatic. These factors make the time series of relative humidity non-uniform, with breakpoints chiefly concentrated in the period from 2001–2010 (Zhu et al. 2015). Homogeneous neighboring stations were selected as reference stations, and the reference sequence was constructed by averaging the weight of the correlation coefficient. A heterogeneity test and correction of the relative humidity data from 2413 stations in China was carried out based on the penalty maximum *F*-test and the penalty maximum T-test (Cao & Yan 2011) in combination with the metadata information from the stations and the rationality of temporal and spatial distributions of climate elements. We found that 68% of the stations had breakpoints; the proportion of negative correction was high and the correction range was mainly between −5 and 0%. See Fig. 2 for the change in annual average relative humidity in China before and

Table 1. Regional divisions of meteorological stations across China

Region	Included provinces	No. of stations used	Color in Fig. 1
Northeast China	Heilongjiang, Jilin, Liaoning	169	• Light blue
North China	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia	287	• Dull grey
Northwest China	Gansu, Ningxia, Shaanxi	176	• Orange
East China	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong	446	• Dark brown
Central China	Henan, Hubei, Hunan	269	• Yellow
South China	Guangdong, Guangxi, Hainan	164	• Emerald
Southwest China	Sichuan, Guizhou, Yunnan, Chongqing	370	• Dark blue
Qinghai-Tibet Plateau	Qinghai, Tibet	68	• Ruby red
Xinjiang area	Xinjiang	98	• Black

after revision. It can be seen that after 1961, the significant low during the period 2004–2014 was chiefly corrected, and the revised annual average relative humidity in China showed no obvious increasing or decreasing trend (Zhu et al. 2015).

2.3. Methods

The national and regional average relative humidity series are calculated as per the arithmetic average, chiefly by the following formula:

$$\mathrm{RH}_{jk} = \frac{1}{m}\sum_{i=1}^{m}\mathrm{RH}_{ijk} \quad (1)$$
$$(j = 1, 2, \ldots, 9;\ k = 1961, 1962, \ldots, 2018)$$

where j represents the region, k is the year, m is the number of weather stations in a certain region, RH_{ijk} is the relative humidity of station i in the k^{th} year of the j^{th} region and RH_{jk} is the average relative humidity in the k^{th} year of the j^{th} region. The seasons are winter (December–February of the next year), spring (March–May), summer (June–August) and autumn (September–November).

The least square method is used to calculate the linear regression coefficient (o) of sample and time when calculating the variance tendency of climate, namely:

$$\alpha = \frac{\sum_{i=1}^{n}(t_i\,y_i) - \frac{1}{n}\sum_{i-1}^{n}y_i\sum_{i=1}^{n}t_i}{\sum_{i=1}^{n}t_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n}t_i\right)^2} \quad (2)$$

where y_i is the sequence of meteorological elements and t_i is the time ($t_i = 1, 2, \ldots, n$), and n is the number of years (from 1961 to 2018) which equals 58, $10 \times \alpha$ (linear regression coefficient) is taken as the variance tendency of climate, y_i is relative humidity (% decade^{-1}) for $10 \times \alpha$, and the p-value of a paired t-test was used to indicate significance. When $p < 0.001$, the variance tendency of climate is considered to be highly significant, while when $p < 0.01$, the variance tendency of climate is considered to be significant.

3. RESULTS

3.1. Temporal and spatial climatic characteristics of relative humidity

Over the study period from 1961–2018, the annual average relative humidity in China gradually decreased from southeast to northwest (data not shown). The regions with relative humidity <40% were chiefly situated in southeast Xinjiang, central and western Inner Mongolia, western Gansu, northwestern Qinghai and central and western Tibet. The relative humidity in the Yangtze-Huaihe river basin and most regions in the south was relatively high, with a range of 70–80%, among which relative humidity in eastern Sichuan, Chongqing, most of Guizhou, Guangdong and Hainan was >80%. Table 2 presents the relative humidity of each region: South China had the highest levels, with an annual average of 77.8%. East, Central and Southwest China were also above 70%, whereas Qinghai-Tibet had the lowest relative humidity levels at merely 48.2%. The spatial distribution characteristics of relative humidity across the 4 seasons basically coincided with the annual average distribution. Relative humidity in East, Central, South and Southwest China was comparatively high, while that in Xinjiang and the Qinghai-Tibet Plateau was comparatively low. Regarding changes in the 4 seasons (Table 2), the different regions were not consistent. Relative humidity in Northeast, North and Northwest China was lowest in spring at about 50% and highest in summer at about 70%. In Central, East and South China, relative humidity throughout the 4 seasons was above 70%, slightly lower in winter, with little difference in the other 3 seasons. Relative humidity in Southwest China was also the lowest in spring but higher in summer and autumn.

Table 2. Annual and seasonal average relative humidity (%) in different regions of China from 1961–2018

	Northeast China	Northwest China	North China	Central China	East China	South China	Southwest China	Qinghai Tibet	Xinjiang China	Whole
Year	65.0	62.6	57.0	72.3	72.9	77.8	74.3	48.2	52.4	64.7
Winter	64.1	57.9	53.8	69.5	70.3	75.0	72.0	37.6	64.8	62.8
Spring	54.2	56.1	46.8	71.2	71.1	80.2	68.4	42.5	44.8	59.5
Summer	75.4	66.5	65.5	74.9	76.9	80.7	78.0	60.1	45.4	69.3
Autumn	66.3	70.0	61.9	73.8	73.4	75.5	78.7	52.4	54.7	67.4

The relative humidity of the Tibetan Plateau was only 37.6% in winter and highest in summer at 60%. Xinjiang is completely different from other regions: there, relative humidity was highest in winter (64.8%) and lowest in spring and summer (45%).

3.2. Climate variation characteristics of relative humidity

From 1961–2018, national average annual relative humidity was 64.5%, with no tendency change. As can be seen from Fig. 2, from the 1960s to the early 1980s, except for the abnormal high in 1964, annual relative humidity changed around the mean value, slightly high from the mid-1980s to the early 2000s, above the mean value in most years, low from 2004–2014 and then increasing again. The national average relative humidity in winter was 62.5%, which was similar to the annual average relative humidity (Fig. 3a), and there was no trend change. Relative humidity was generally low from the 1960s to the 1980s. From the 1990s to the 2000s, relative humidity was generally high except for a low period in the late 1990s. In the first decade of the 21st century, it began to turn negative and was in a low value stage. The average relative humidity in spring was 59.1%, and the variance tendency of climate was −0.22% decade^{-1}, which was not significant. Except for the large interannual variation in the early 1960s, it fluctuated around the mean value in the 1960s–1980s, became larger in 1990s, smaller at the start of the 21st century and has presented a steady upward trend in recent years (Fig. 3b). The average relative humidity in summer was 69%, the climate change trend was 0.12% decade^{-1}, which failed the significance test. It continued to rise from a minimum in the 1960s to a maximum at the end of the 1990s and then presented a downward trend. It turned to a negative anomaly at the beginning of the 21st century and was relatively low in the first decade of the 21st century. In recent years, the average relative humidity in summer has exhibited an upward trend and exceeded the mean value (Fig. 3c). The average relative humidity in autumn was 67.1%, and there was no tendency change. The relative humidity varied greatly from the 1960s to the 1970s; it started to decrease in the 1980s and remained low until the end of the 20th century, then exhibited an upward trend and entered a high stage (Fig. 3d).

From the point of view of spatial distribution (Fig. 4a), most of the Qinghai-Tibet Plateau and Xinjiang increased in annual average relative humidity, with the southeastern part of Qinghai-Tibet exhibiting a significantly increasing trend ($p < 0.001$). Northwest China, North China, Northeast China and other regions presented a decreasing trend in annual average relative humidity, among which the eastern part of Northwest China and the northwest part of Northeast China presented a significantly decreasing trend ($p < 0.001$). Most of Southwest China and southern South China presented a decreasing trend. The number of stations in East China and Central China increased and were reduced by half, respectively, during the study period. From the spatial distribution of relative humidity changes in each season, the areas with a decreasing trend in relative humidity in winter were mainly concentrated in Northeast China, north and west of North China, east of South China and south of Southwest China. There was an increasing trend in the central and southern parts of the Qinghai-Tibet Plateau, Xinjiang and southern parts of East China, especially in the southern parts of the Qinghai-Tibet Plateau, with the maximum variation in relative humidity reaching > 2% decade^{-1} (Fig. 4b). Relative humidity in spring increased only in the large part of the Tibetan Plateau and the northern part of Northeast China, but decreased in other areas, especially in the east of Northwest China, the west of North China, the central part of East China and the central part of Central China, which all exceeded −1% decade^{-1} (Fig. 4c). In summer, the relative humidity decreased in North China, Northwest China, south of Northeast China, south and

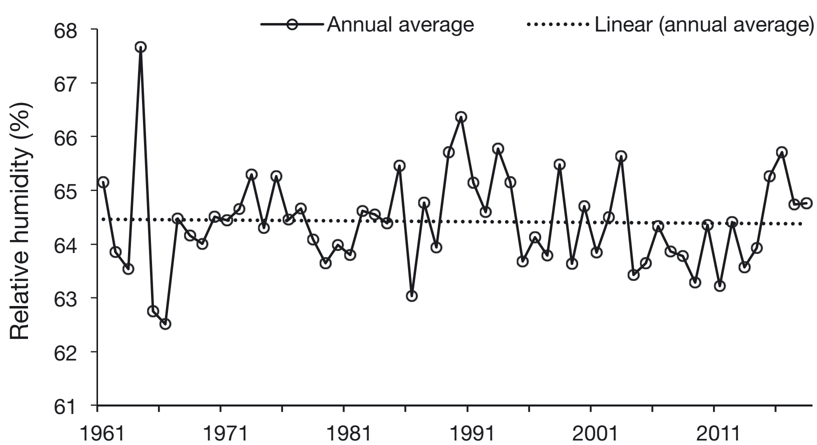

Fig. 2. Variation in national annual average relative humidity across China from 1961–2018

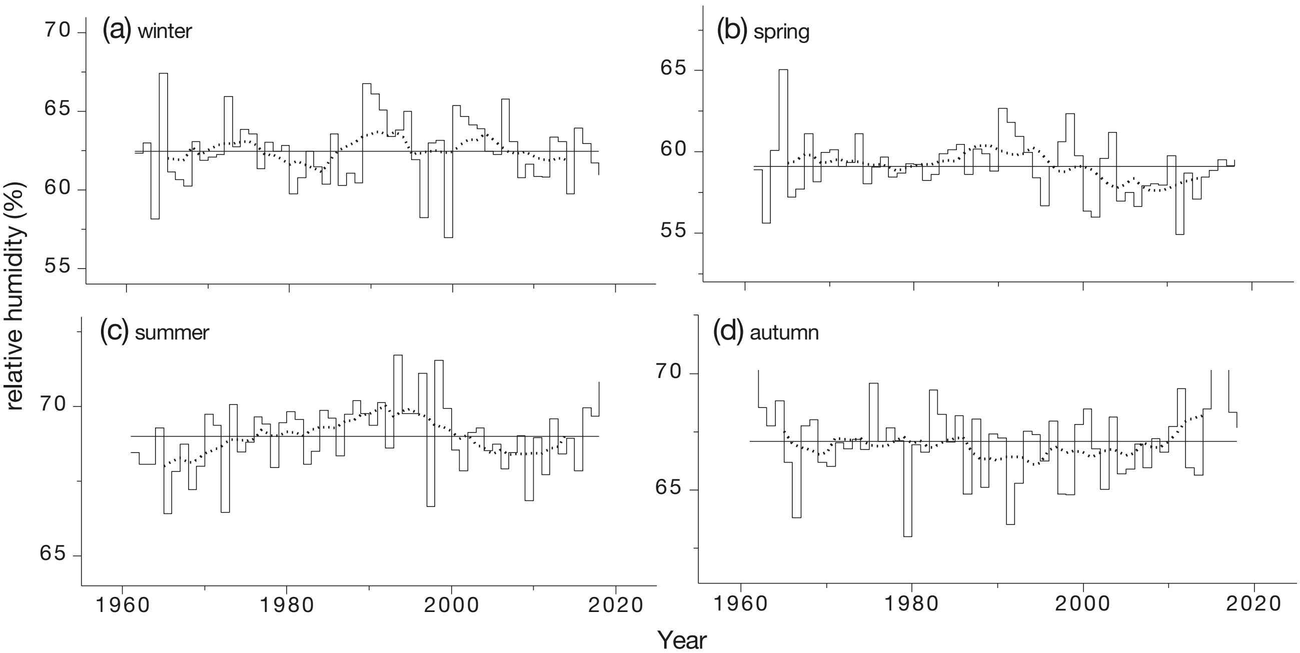

Fig. 3. Variation in national average relative humidity across (a) winter, (b) spring, (c) summer and (d) autumn in China from 1961–2018. Stepped line: seasonal relative humidity from 1960–2020; dotted line: 9 yr moving average of seasonal relative humidity; horizontal line: average seasonal relative humidity

west of Southwest China and south of South China, and increased in East China, Central China, northeast of Southwest China, the Qinghai-Tibet Plateau and Xinjiang, among which the increase in Xinjiang was most obvious (Fig. 4d). In autumn, relative humidity decreased in the north of North China, Northeast China, east of Northwest China, south of Southwest China and most of South China, and increased in the Qinghai-Tibet Plateau, Xinjiang and west of Northwest China to the west of 110° E (Fig. 4e).

Fig. 5 shows the change in annual average relative humidity in the 9 regions from 1961–2018. Northeast China displayed a weak decreasing trend (Fig. 5a2); 66.8% of the stations in that region exhibited a decreasing trend, principally distributed in the eastern areas of Jilin and Liaoning Province. The annual average relative humidity in most areas of Heilongjiang Province exhibited a weak increasing trend, and the increasing trend in the western part of Liaoning was distinct.

Overall, the annual average relative humidity in North China generally showed a weak decreasing trend (Fig. 5b2), in which 70.3% of the stations presented a declining trend. The stations with a range decreasing beyond −0.3% decade^{-1} are distributed throughout Inner Mongolia, the central part of Beijing-Tianjin-Hebei and the eastern part of Shanxi. The remaining 30% of stations showed a slight increasing trend, principally distributed in the southern part of North China.

The annual average relative humidity in Northwest China displayed a decreasing trend, and the climate change tendency rate was −0.25% decade^{-1} (which failed the significance test) (Fig. 5c2). About 63.2% of the stations presented a decreasing trend, distributed in the south of Gansu, the north of Ningxia and the north of Shaanxi, and the annual relative humidity of 22.6% of the stations decreased by more than 0.3% decade^{-1}. About 36.8% of the stations showed an increase, principally distributed in the south of Shanxi and the middle and west of Gansu.

There was no trend change in annual average relative humidity in East China (Fig. 5d2). With regard to spatial distribution (Fig. 5d1), the number of stations with increasing and decreasing relative humidity was approximately equal, among which the central part of East China (the Yangtze River Delta urban agglomeration) and the northern part of Shandong presented decreasing trends. The climate trend of most stations decreased by over 0.3% decade^{-1}. In the southern part of East China (Fujian, Jiangxi and southern Zhejiang), the annual relative humidity of most stations exhibited an increasing trend, especially most stations in Jiangxi, which increased by over 0.3% decade^{-1}.

There was no trend change in the annual average relative humidity in Central China (Fig. 5e2). With respect to spatial distribution (Fig. 5e1), 40.5% of the stations presented a decreasing trend, with those stations principally distributed in the central part of

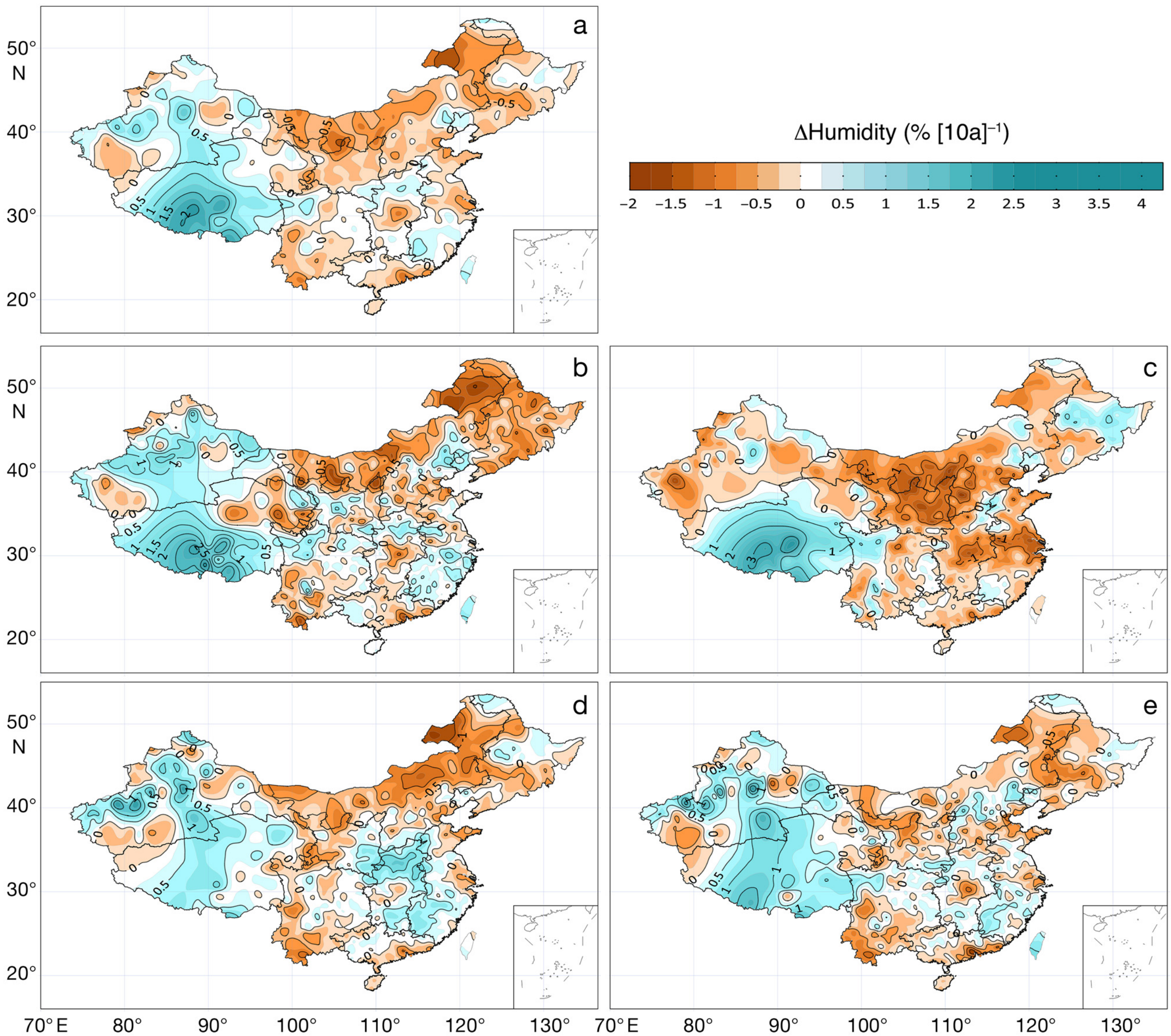

Fig. 4. Climate change trend in relative humidity across China from 1961–2018: (a) year, (b) winter, (c) spring, (d) summer, (e) autumn

Central China (Wuhan urban agglomeration). The variance tendency of climate of most stations decreased by more than 0.3 % decade^{-1}. In contrast, the annual relative humidity of most stations in Henan Province in the northern part of Central China exhibited an increasing trend, especially in the central and southern parts of Henan, with an increase of more than 0.3 % decade^{-1}. The annual average relative humidity of most stations in Jiangxi Province in the south of Central China increased, with the stations with the most obvious humidity increases mainly distributed in the south of Jiangxi Province.

The annual average relative humidity in South China presented a small decreasing trend, and the variance tendency of climate was −0.13 % decade^{-1}, which failed the significance test (Fig. 5f2). With respect to spatial distribution (Fig. 5f1), the Pearl River Delta urban agglomeration and Chaoshan area showed a significant decreasing trend, and the variance tendency of climate of most stations decreased by more than 0.3 % decade^{-1}. The annual relative humidity of most stations in Guangxi and Hainan exhibited an increasing trend, but few stations showed a significant increase.

The annual average relative humidity in Southwest China showed a small decreasing trend, and the variance tendency of climate was −0.13 % decade^{-1}, which failed the significance test (Fig. 5g2). With regard to spatial distribution (Fig. 5g1), the number of stations with increasing or decreasing annual average relative humidity was approximately equal, among which the annual average relative humidity in most areas of Yunnan Province, southwestern Guizhou Province and central Sichuan Province exhibited a decreasing trend. The annual relative humidity of most stations in eastern and western Sichuan, most of Chongqing and eastern Guizhou showed an increasing trend.

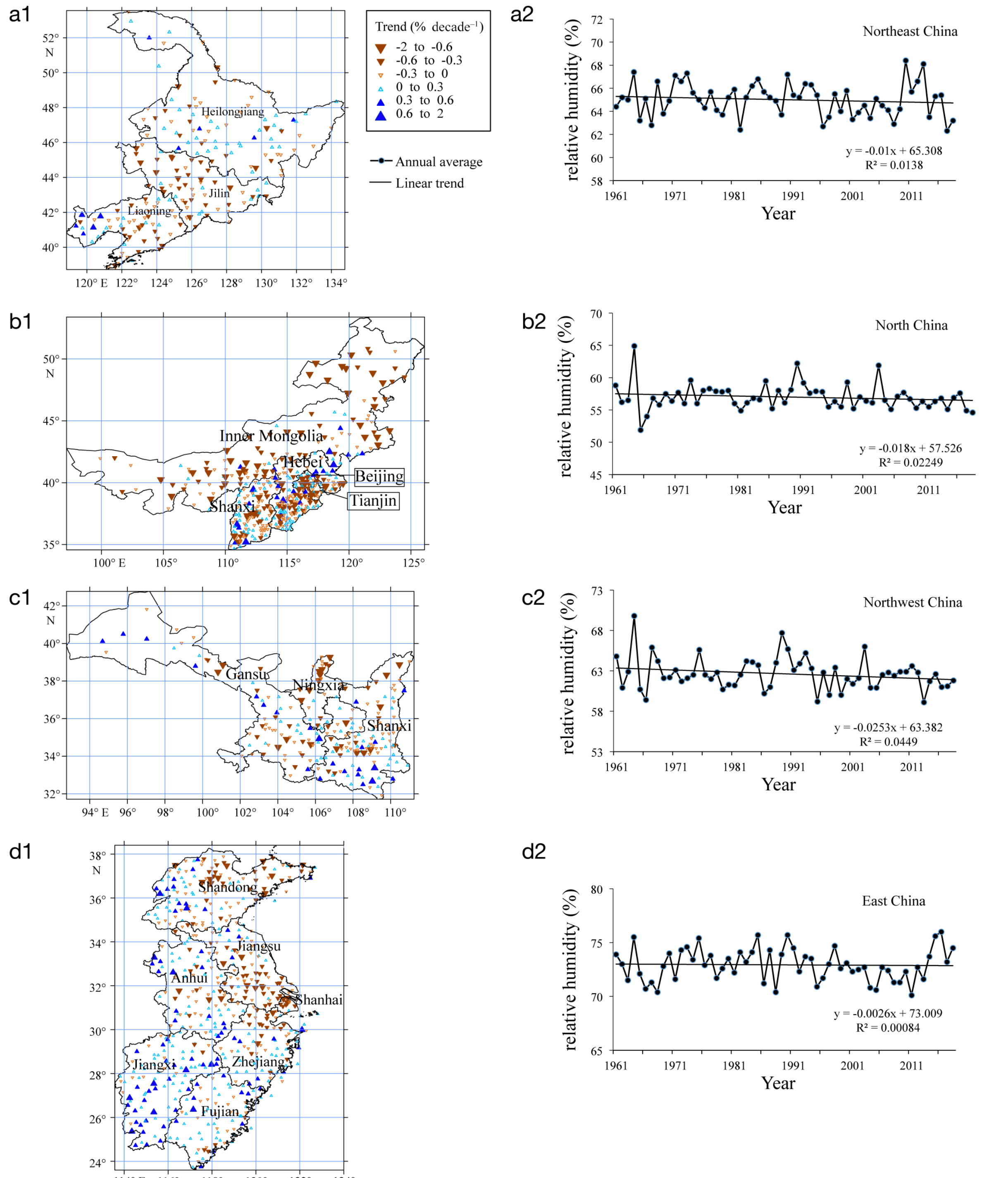

Fig. 5 (continued on next page).

Fig. 5. Climate change trend in annual relative humidity at each station in each region (a1, b1, c1, d1, e1, f1, g1, h1, i1) and annual average relative humidity change in each region (a2, b2, c2, d2, e2, f2, g2, h2, i2) from 1961–2018

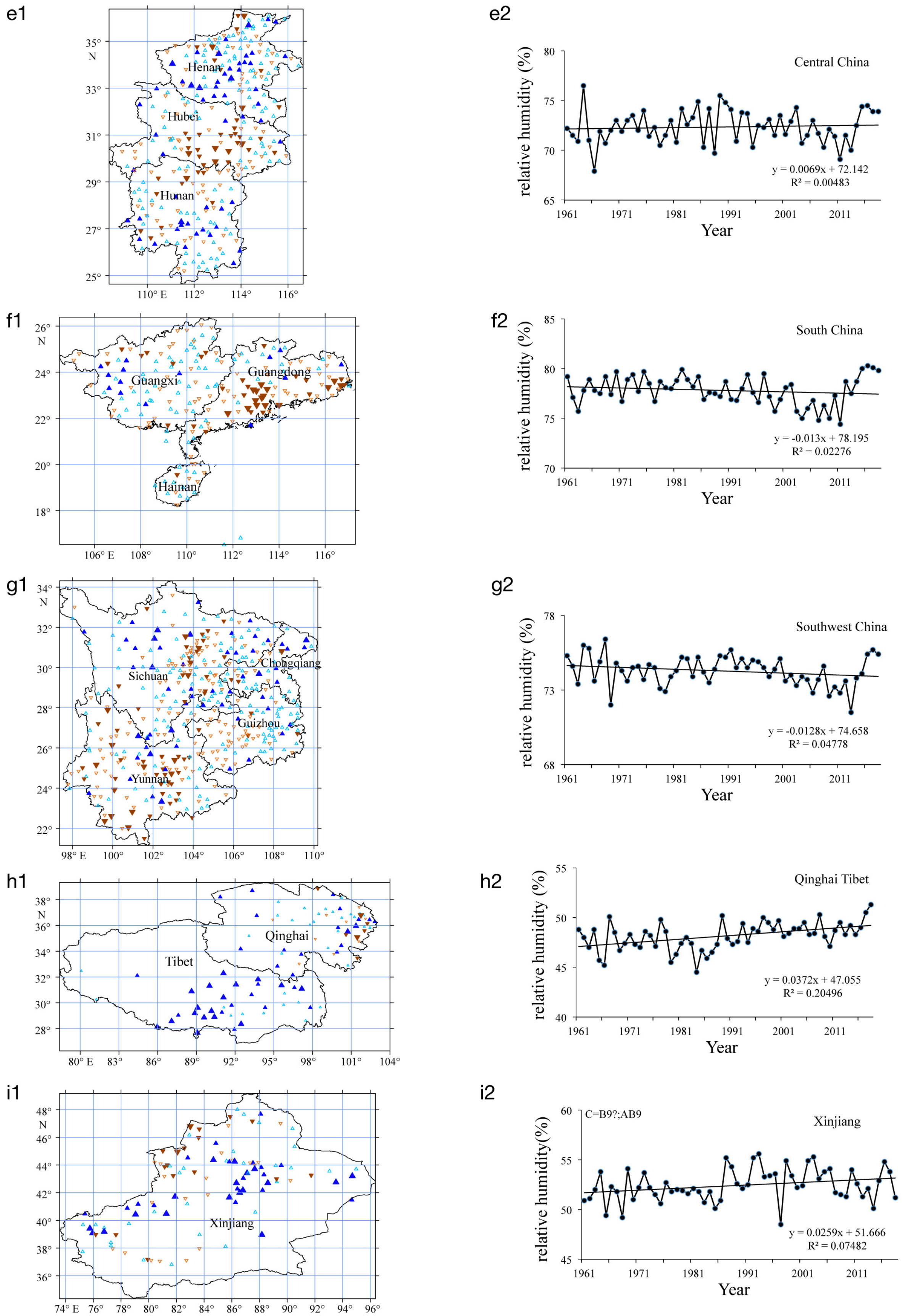

Fig. 5 (continued).

In the Qinghai-Tibet Plateau, annual average relative humidity showed a significant increasing trend, and the variance tendency of climate was 0.37% decade $^{-1}$ ($p < 0.001$) (Fig. 5h2). As far as spatial distribution (Fig. 5h1) is concerned, except for a few stations in the northeast of Qinghai, the annual average relative humidity at stations in other areas all increased, and the annual average relative humidity in central Tibet exhibited a significant increasing trend, with an increasing range of >0.3% decade^{-1}.

The annual average relative humidity in Xinjiang exhibited a significant increasing trend, and the variance tendency of climate was 0.26% decade^{-1} ($p < 0.001$) (Fig. 5i2). With respect to spatial distribution (Fig. 5i1), the annual average relative humidity at 36.2% of the stations decreased, chiefly concentrated in the northern part of Xinjiang. Annual average relative humidity at stations with increasing trends made up 63.8%, among which, central and western Xinjiang presented a significant increasing trend. The increase at most stations was more than 0.3% decade^{-1}.

Regarding seasonal changes, the average relative humidity of the 4 seasons in South and Southwest China showed a slightly decreasing trend, while the change characteristics of average relative humidity of 4 seasons in the other regions was variable (Table 3). The average relative humidity of the Qinghai-Tibet Plateau showed an increasing trend in all seasons, with a significantly increasing trend in winter, spring and summer, and the largest increasing rate in spring (up to 0.67% decade^{-1}; $p < 0.001$). Unlike the Qinghai-Tibet Plateau, the relative humidity in Xinjiang decreased in spring, significantly increased in the other 3 seasons and attained a maximum of 0.46% decade^{-1} in summer. The relative humidity in Northeast China decreased chiefly in winter, and its variance tendency of climate was –0.38% decade^{-1} ($p < 0.01$). Relative humidity tended to increase in spring and decrease in summer and autumn; the seasonal changes in Northwest China and North China were comparatively consistent. In spring, relative humidity decreased significantly ($p < 0.001$), up to –0.96 and –0.45% decade^{-1}, respectively. Relative humidity decreased in winter, but there was no trend in summer and autumn. The change characteristics of relative humidity in Central China and East China were similar but the amplitude was quite different, resulting in relative humidity that decreased significantly in spring ($p < 0.001$) and increased in the other 3 seasons, especially during summer in Central China, with a variance tendency of climate as high as 0.56% decade^{-1} ($p < 0.001$).

3.3. Effects of topographic height and urbanization on relative humidity

Studies have shown that the spatial distribution of relative humidity is not only affected by water vapor but also topographic height and latitude (Liu et al. 2016). The annual average relative humidity of all stations in the country and the height of stations are clustered. Since the height of most stations is below 3000 m, only stations below that height are shown in Fig. 6. Overall, there is a significant negative correlation between annual average relative humidity and the height of the station, with a correlation coefficient of –0.37 ($p < 0.001$). For every 100 m increase in topographic height, the relative humidity decreases by 0.6%. Due to the variation in height among regions, the relationship between relative humidity and height in each region also has its own characteristics. For instance, the annual relative humidity in North, northwest and southwest China has a very significant negative correlation with height, with correlation coefficients of –0.51, –0.33 and –0.61 respectively ($p < 0.0001$). Areas with higher annual relative humidity, such as East China and Central China, are positively correlated with height. There is no correlation between annual average relative humidity and height in Northeast China, South China and

Table 3. Climate change trends in annual and seasonal average relative humidity in different regions of China from 1961–2018 (units: % decade^{-1}). *$p < 0.01$; **$p < 0.001$

	Northeast China	Northwest China	North China	Central China	East China	South China	Southwest China	Qinghai Tibet	Xinjiang	Whole China
Year	–0.10	–0.26	–0.18	0.07	–0.03	–0.13	–0.13	0.37**	0.26	–0.02
Winter	–0.38*	–0.06	–0.22	0.01	0.16	–0.07	–0.10	0.35**	0.39**	0.01
Spring	0.15	–0.96**	–0.45**	–0.34*	–0.45**	–0.17	–0.18	0.67**	–0.20	–0.22
Summer	–0.03	0.11	–0.12	0.56**	0.14	–0.07	–0.13	0.29*	0.46**	0.12
Autumn	–0.13	–0.08	0.08	0.04	0.05	–0.19	–0.09	0.20	0.38**	0.03

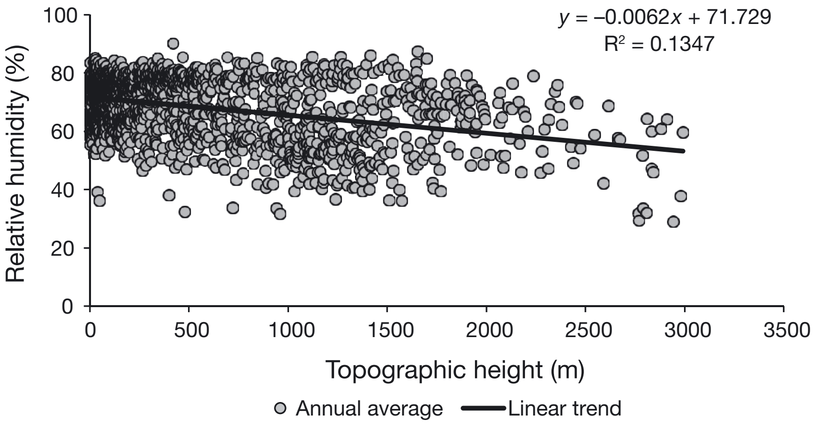

Fig. 6. Relationship between annual average relative humidity and topographic height across China

Xinjiang. There are great differences in the topographic height of the Qinghai-Tibet Plateau. The relative humidity of stations below 5000 m has no significant relationship to topographic height, but there is a significant negative correlation above 5000 m.

Climate observations and studies (e.g. Shi et al. 2011, Suonan et al. 2018) from many large and medium-sized cities have shown that, due to the special underlying surface of the city and the influence of human factors, the urban dry island effect shows an obvious enhancement trend with the development of the city. The urban heat island increases urban air temperature and saturated water vapor pressure under conditions of constant water vapor content, resulting in a decrease in urban relative humidity. Urban stations with meteorological observations constructed only in the cities above prefecture level in each province are usually located in economically developed areas with a high degree of urbanization. Rural stations with both meteorological observations and some agrometeorological observations (such as crop growth and development, yield, etc.) are generally observation stations set up in the counties dominated by agriculture, and their urbanization degree is relatively low. The difference in relative humidity between urban and rural areas (ΔRH) is used to determine the impact intensity of urbanization on relative humidity. From 1961–2018, the annual average relative humidity of national urban stations was 62.8%, while that of rural stations was 64.6%. Thus, national ΔRH was 1.8% (Table 4). In Northeast China, Northwest China, Central China and Xinjiang, ΔRH was >3.0%, and in East and North China ΔRH was ≥1.0%. In South China, ΔRH is small; however, the annual average relative humidity in cities in Southwest China and Qinghai-Tibet Plateau was higher than that in rural areas, with a ΔRH of about 1.0% (Table 4).

Fig. 7 shows the annual average relative humidity of urban and rural stations in China. In the last 60 yr, interannual changes were small. There was no trend change in the relative humidity of rural stations, but urban stations showed a decreasing trend, resulting in a significantly increasing trend of the absolute value of ΔRH by 0.19% decade^{-1} ($p < 0.001$). Especially since 2000, the impact intensity of urbanization has ranged from −1.8 to −2.8%. Fig. 8 shows the annual changes in relative humidity and ΔRH in each region from 1961–2018. It can be seen that the climate change trend of relative humidity in cities and villages is small in Northeast China, North China, the

Table 4. Annual average relative humidity difference between urban and rural stations (ΔRH), and ΔRH climate change trend from 1961–2018. *$p < 0.01$; **$p < 0.001$

Region	No. of urban stations (units)	No. of rural stations (units)	Average annual urban relative humidity (%)	Average annual rural relative humidity (%)	ΔRH (%)	ΔRH climate change trend (% decade^{-1})
Northeast China	29	49	63.0	66.2	−3.2	−0.09
North China	22	40	56.3	57.3	−1.0	0.04
Northwest China	19	41	58.1	61.3	−3.2	−0.53**
East China	73	69	71.8	73.9	−2.1	−0.28**
Central China	38	33	71.1	74.9	−3.8	0.17*
South China	30	28	77.5	77.8	−0.3	−0.24**
Southwest China	34	51	75.8	74.7	1.1	−0.70**
Qinghai-Tibet Plateau	8	12	45.0	44.1	0.9	−0.09
Xinjiang area	4	23	46.7	50.6	−4.2	−0.01
Nationwide	257	346	62.8	64.6	−1.8	−0.19**

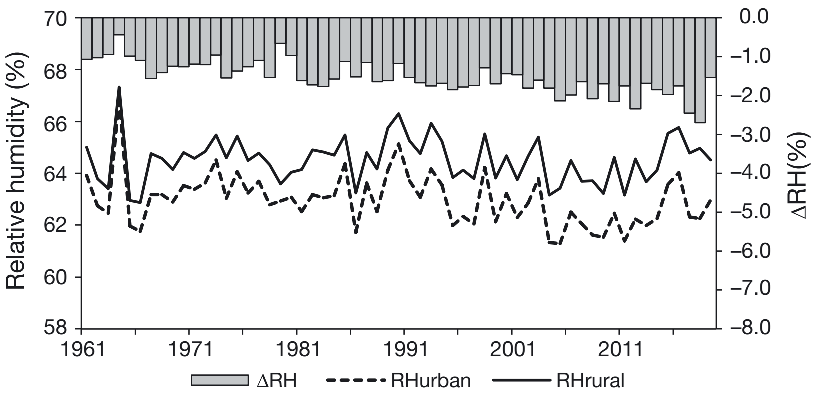

Fig. 7. Annual average relative humidity at urban (RHurban) and rural (RHrural) meteorological stations in China from 1961–2018 as well as the difference in relative humidity between the two areas (ΔRH: impact intensity of urbanization on annual average relative humidity)

Qinghai-Tibet Plateau and Xinjiang, and there is no trend change of ΔRH. In Central China, there is no trend change in urban relative humidity, and rural relative humidity shows an increasing trend, so ΔRH shows an increasing trend ($p < 0.01$). Urban relative humidity in Northwest China, East China, South China and Southwest China shows a decreasing trend, and there is no trend change in rural areas, resulting in a significant decreasing trend of ΔRH — that is, the impact of urbanization in these areas increases, and the urban dry island effect increases, resulting in a decreasing trend of relative humidity in this area.

4. DISCUSSION AND CONCLUSIONS

Based on the homogenized daily relative humidity data set (v.1.0) of national surface meteorological stations, we found that the change in national annual average relative humidity across China from 1961–2018 was only −0.02% decade^{-1}, without trend change. After correction by the MASH method, Jin et al. (2009) also showed that there was almost no long-term trend in regional average relative humidity across China from 1960–2017 (0.006% decade^{-1}). Although their conclusions were essentially the same, the climate change trend was slightly different, mainly because Jin et al. (2009) used data from 746 meteorological stations while in this paper we used data from 2479 stations, which indicate that the homogenized relative humidity data set used in this study is of good quality. Due to the revision of the breakpoint of significantly low relative humidity at meteorological stations during 2004–2014, the changes of relative humidity in various regions obtained in this paper are significantly different from previous research results, especially in the Qinghai-Tibet Plateau and Xinjiang. You et al. (2015) found that relative humidity in the Qinghai-Tibet Plateau showed a significant downward trend from 1961–2013, which is contrary to the conclusions of this paper. This discrepancy is mainly because the relative humidity data used by You et al. (2015) and others had not been uniformly revised, and the relative humidity was obviously low around 2004. Similarly, He et al. (2015) found that relative humidity in Xinjiang decreased sharply at the beginning of the 21st century.

Rapid urbanization leads to obvious dry island effects. In Northeast China, Northwest China, East China, Central China and Xinjiang, urban relative humidity has always been lower than that in rural areas; the difference is currently increasing. Therefore, the reduction of regional average relative humidity and urbanization also plays a role. However, the selection of rural stations in this paper did not strictly follow the urbanization standard; rather, we used the areas where agrometeorological observation stations were located as the rural stations, which will also cause some errors in the intensity of urban dry islands.

In general, 3 main conclusions can be drawn from this study: (1) from 1961–2018, the national average annual relative humidity was 64.5%, and overall, the national spatial distribution decreased gradually from southeast to northwest. The spatial distribution of relative humidity across all 4 seasons was consistent with that of the annual average distribution: relative humidity in East China, Central China, South China and Southwest China and other regions south of the Huaihe River was comparatively high, while that in Xinjiang, the Qinghai-Tibet Plateau and other areas was comparatively low.

(2) From 1961–2018, annual average relative humidity across China changed relatively little, but there were large differences within and among individual regions. Overall, annual relative humidity in the Qinghai-Tibet Plateau and Xinjiang area increased significantly, while that in Northwest China, Northeast China and the northern part of North China decreased significantly.

(3) Seasonally, average relative humidity in China showed a decreasing trend in spring but did not change in other seasons. In the Qinghai-Tibet Plateau,

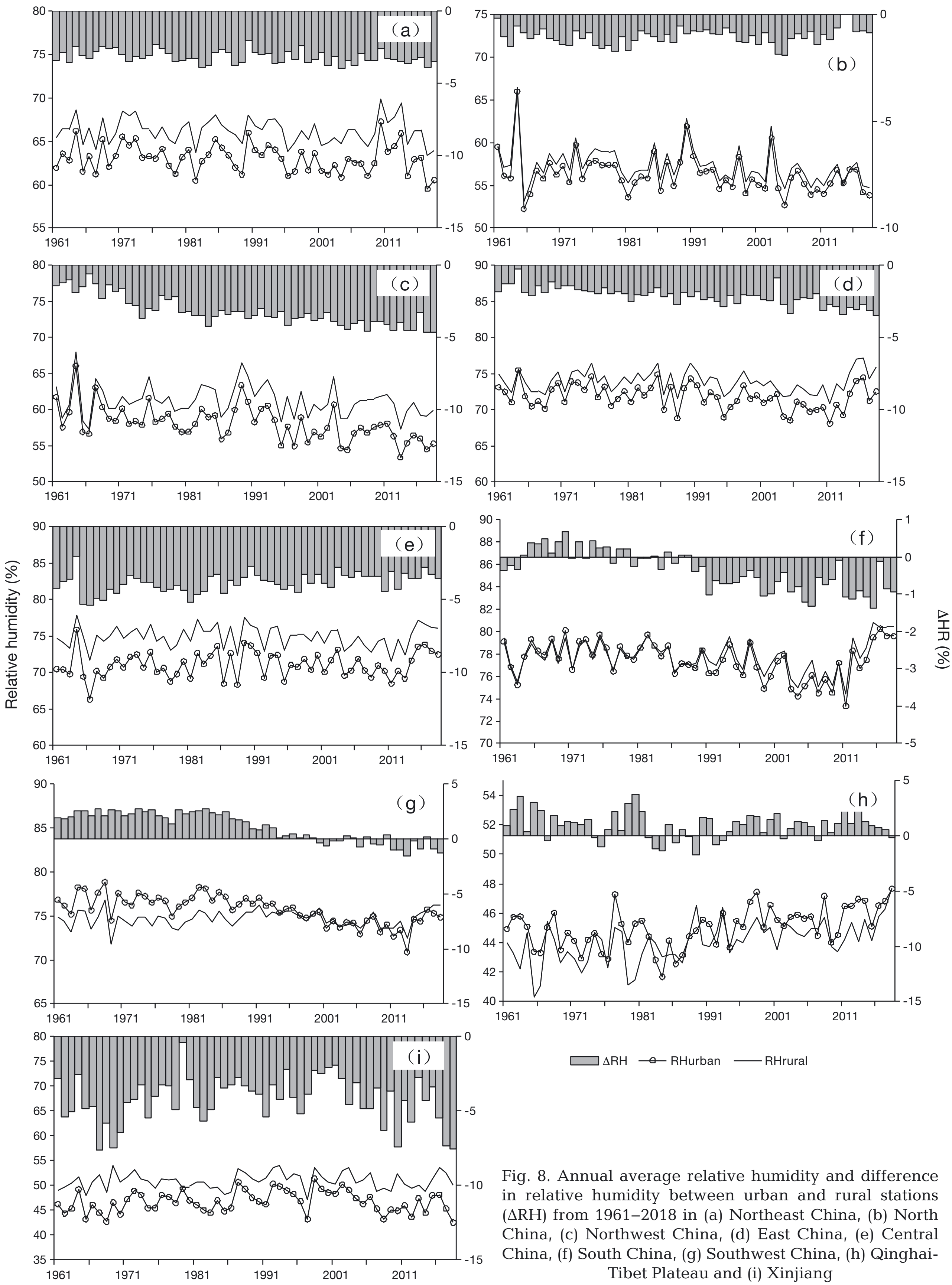

Fig. 8. Annual average relative humidity and difference in relative humidity between urban and rural stations (ΔRH) from 1961–2018 in (a) Northeast China, (b) North China, (c) Northwest China, (d) East China, (e) Central China, (f) South China, (g) Southwest China, (h) Qinghai-Tibet Plateau and (i) Xinjiang

annual relative humidity increased significantly in winter, spring and summer, with the most pronounced changes occurring in spring. The annual average relative humidity in Xinjiang increased significantly in winter, summer and autumn, while that in Northeast China decreased significantly in winter; in Northwest China, North China, Central China and East China, annual average relative humidity decreased significantly in spring; whereas in South China and Southwest China it exhibited only a slight decreasing trend across all 4 seasons.

In brief, in the context of climate change, the annual average relative humidity in Xinjiang, the Qinghai-Tibet Plateau and the western part of Northwest China has generally shown an increasing trend, suggesting that the vast areas in the western region are exhibiting a 'warming and wetting' trend. East of 110° E, relative humidity is generally decreasing, especially in Northeast China and North China. Expansive urbanization within East China and Central China has exerted a distinct influence on relative humidity.

Data availability. Data sets are available in a funder-mandated or from the website of China Meteorological Data Network http://data.cma.cn/en.

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