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Article *in* Theoretical and Applied Climatology · March 2019

DOI: 10.1007/s00704-019-02820-0

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https://doi.org/10.1007/s00704-019-02820-0

ORIGINAL PAPER

Long-term change in surface air temperature over DPR Korea, 1918–2015

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Received: 4 October 2018 / Accepted: 18 February 2019

Abstract

Land surface air temperature (SAT) change is one of the core issues in monitoring and assessing regional climate change. In this study, the characteristics of SAT change over DPR Korea for the period 1918–2015 were investigated using a high-quality historical dataset. Results show that the region-averaged annual mean SAT increased 0.21 °C/decade for the period 1918–2015 on the basis of data from four stations and 0.19 °C/decade for the period 1941–2015 as estimated based on data from nine stations. Before the 1970s, Pyongyang station in the central region experienced the largest warming trend. Linear trends of seasonal mean SAT during 1941–1970 were negative for all seasons in eastern coast and for summer and autumn in western coast and northern inland areas. Since 1971, however, the annual and seasonal mean SAT trends have shifted to positive values in all regions, with winter experiencing the most rapid warming. During the period of global warming slowdown since 1998 or 2000, no significant seasonal warming trend of wintertime was detectable, and this caused the smallest winter warming for the last 45 years. Other seasons also witnessed a generally weakened warming during 1971–2015 compared to that of 1971–2000. The results of the study will help in understanding regional climate change and in assessing the impacts of climate change on economic and natural ecosystems in the country.

1 Introduction

Land surface air temperature (SAT) is a key climatic variable, and the observations and analyses of the SAT series are of major significance in the monitoring, detection, and assessment of global and regional climate change (Jones 1994; Jones and Hulme 1996; Hulme et al. 2010).

Previous studies have analyzed the characteristics of global and regional surface temperature changes (e.g., Chung et al. 2004a, b; Hansen et al. 2006; Jones et al. 2012; Ren et al. 2012, 2017; IPCC 2013). Comprehensive studies of global land SAT change during the last century and since the 1950s have been recently published (e.g., Kosaka and Xie 2013; Fyfe et al. 2016; Kim et al. 2016a, b; Sun et al. 2017a). Jones et al. (2012) showed, for example, that the annual mean SAT in the northern hemisphere and the southern hemisphere increased by as much as 1.12 and 0.84 °C, respectively, between 1901 and 2010.

Many works have been also published for regions and countries surrounding the Korean peninsula, particularly in Northeast China and southern Korean Peninsula. Tang and Ren (2005) showed that annual mean SAT in mainland China experienced an increase of 0.08 °C/decade for 1905–2001, which is larger than the global or northern hemispheric changes reported by the Inter-governmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) during the same time period. Zhao et al. (2009) analyzed the annual mean temperature, maximum temperature, and minimum temperature changes in Northeast China since 1956, and found that the increasing trend of annual mean SAT was 1.5 °C or about 0.3 °C/decade, much higher than the mainland China average.

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Sun et al. (2006) used data from 74 observational stations in Northeast China to evaluate the surface air temperature changes, showing a remarkable decrease from the mid-1960s to the mid-1970s and a strong increase since the mid-1970s. Wang and Liu (2016) used a dataset of 90 stations in Northeast China to analyze the SAT change of the warmest month (July) and coldest month (January) between 1961 and 2010, showing that the rate of increase was 0.46 °C/decade in January and 0.19 °C/decade in July, respectively. Dong et al. (2009) reported that northeastern China had experienced a marked increase in temperature since 1982, and Hokkaido of Japan had also shown a significant upward trend since 1988. They pointed out that the annual mean temperature increase rate for the period 1909–2003 was 0.18 °C/decade in northeastern China and 0.12 °C/decade in Hokkaido, both of which are much higher than the global average (0.07 °C/decade) during the same period. Zhao et al. (2009) reported a significant temperature increase in Northeast China began from 1988 and the more evident increase in winter mean minimum temperature. Wang and Liu (2016) showed that the upward trend of winter mean temperature in Northeast China was higher than those in other seasons.

In southern part of the Korean Peninsula, some analyses were reported on the trend of regional SAT changes for the past decades. Chung and Yoon (2000) used data from 20 observational stations in South Korea to analyze temperature trends from 1974 to 1997 and found that the rate of increase was more pronounced in winter. They also showed that the boundary of the subtropical region in South Korea shifted northward by about 250 km due to the climatic warming. Kim et al. (2011) used data from 27 (DPR Korea) and 17 (Korea) weather stations to analyze the temperature trends of the Korean Peninsula since the 1970s, and found a more prominent increase in spring and fall in DPR Korea. Jung et al. (2002) reported that the warming trend in South Korea from 1954 to 1999 was about 0.23 °C/decade based on the analysis of data from 12 observatories.

Bao and Ren (2014) reported their analysis results for the marginal seas of China during the period 1870–2011, and they indicated that the sea surface temperature had a significant upward trend, with mean increases more obvious in autumn and winter. In addition, studies from other regions of East Asia have also confirmed that the increase of SAT is significant and also higher in winter than in summer (e.g., Zhao et al. 2009).

Therefore, detailed analyses of the SAT changes have been conducted for East Asian countries and other regions, which are very important for our understanding of regional climate change and for coping with the impacts of climate change and variability. However, to our knowledge, no effort has been reported so far to exclusively investigate the long-term temperature change over the northern part of the Korean Peninsula (PDRK hereafter). This paper made a first attempt to analyze the SAT changes for the last century and the early-twenty-first century over the region, applying a high-quality surface observational dataset. The objective of the analysis is to understand the spatial and temporal pattern of regional climate change in northern part of the Korean Peninsula, and to provide robust scientific information for validating regional climate models and assessing climate impact in PDRK.

2 Study region, data, and methods

The geographical positions of the stations used in the study, and the topographical condition and provincial position, are shown in Fig. 1a. PDRK is located in East Asia between 37.7° N–43° N and 124° E–131° E and is encompassed by the Yellow Sea in the west and the East Sea (Sea of Japan) in the east. The Korean Peninsula is located in middle-latitude zone, under the influence of the East Asian Monsoon, with wet and hot southerly flow from subtropical high which moves northward during summer. In contrast, the effects of the continental anti-cyclone in Siberia and Mongolia in the winter cause the cold and dry weather to be maintained over the study region.

The quality control and homogenization of the long-term observational data are important, and these have already been studied by a number of groups (e.g., Boulanger 2010; Moberg and Alexanderson 1997; Vincent et al. 2012). Two data sets from 179 surface stations were used in the current study: monthly average temperature and annual mean temperature data (Table 1). All the stations are located at the elevations less 800 m above sea level, with most of them between 0 and 400 m above sea level. The monthly and annual temperature data as used in this work were provided by the State Hydro-Meteorological Administration of DPR Korea (SHMA), and they have been quality-controlled by the SHMA referring to the recommendations from the World Meteorological Organization (WMO) (WMO 1993, 2004).

There are only a small number of stations registering the missing monthly records, and the data missing rates are far less than 1.0% for most of the stations. For the data from the stations with missing observations, we conducted the Pearson correlation (bivariate correlation) analysis to select the neighboring stations that had the best relationships with the target station and to estimate the average difference from the target station during the overlap period. The missing monthly data were then supplemented by adding or subtracting this value. For Sehong station, for example, the data for January and February 1951 were absent and thus we interpolated the missing values by using temperature records from Pyongyang and Haeju stations, which have high correlation coefficients with Sehong station (0.92 and 0.95, respectively). Similar approaches were used in previous studies (Brandsma and Können 2006; Aguilar et al. 2003), and they were proved to be effective. Collectively, the missing data represented less

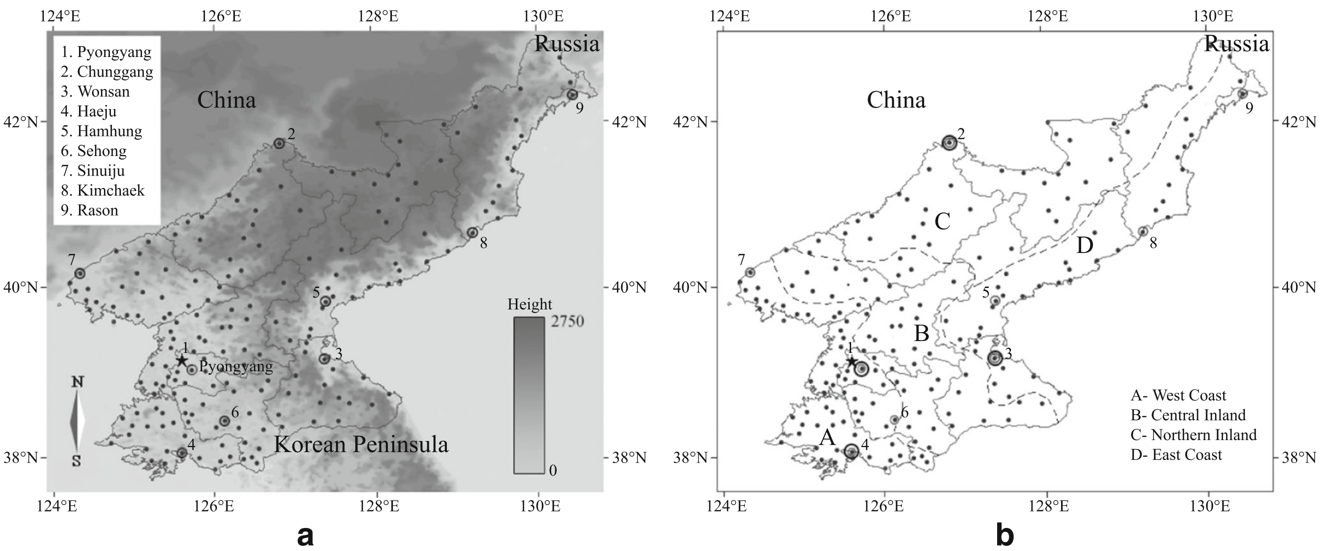

Fig. 1 **a** Study region with the geographical locations of 179 surface observational stations (37–43° N and 124–131° E) and boundaries between provinces of PDR Korea (black star indicates the capital). **b** Division of climatic zones and the representative observational stations for each of the zones. Gray solid line, boundary of provinces; black dashed line, boundary of climate zones; double black circle, stations for 1918–2015; single black circle, stations for 1941–2015; numbers 1–9, code of the 9 stations (see **a** for names)

than 3.2% of the total records in our study, and all of them were adjusted. The data set is thus more suitable for studies of regional climate change.

For the period from 1941 to 2015, the nine stations used (Table 1) had not experienced any relocation, and the possible inhomogeneities probably caused by relocation of the stations were not considered in this analysis. Compared with those in other developing countries of Asia, the data inhomogeneities related to the station relocations would not be serious in the study region due to the relatively slow urbanization processes which would result in the gradual worsening of observational settings around the grounds of the stations as occurred in mainland China and southern Korean Peninsula (Ren et al. 2015).

As shown in Table 1, SAT data from four stations for the period 1918 to 2015, nine stations for the period 1941 to 2015, and 179 stations for the period 1971 to 2015 were used for this study.

The correlations of the SAT between the 4 stations and the 179 stations since the 1970s were calculated. The correlations are highly significant, showing that the characteristics of SAT change over the study area can be well represented by using SAT records of the only four stations for the pre-1970s period in which the overall observations

Table 1 Information of SAT observations from stations used in the study

Zone	Station	Temperature data used		Geographic position		Size of city
		Annual	Monthly	Longitude	Latitude	
Country-averaged		1918–2015				
The central plain	Pyongyang	1907–2015	1907–2015	E 125° 47′	N 39° 02′	Large
The northern inland	Chunggang	1915–2015	1941–2015	E 126° 53′	N 41° 47′	Small
The central east coast	Wonsan	1905–2015	1941–2015	E 127° 26′	N 39° 11′	Medium
The central west coast	Haeju	1918–2015	1941–2015	E 125° 42′	N 38° 02′	Medium
The northern east coast	Hamhung		1941–2015	E 127° 33′	N 39° 56′	Large
The central inland	Sehong		1941–2015	E 126° 13′	N 38° 25′	Small
The northernmost west coast	Sinuiju		1941–2015	E 124° 23′	N 40° 06′	Medium
The northern east coast	Kimchaek		1941–2015	E 129° 12′	N 40° 40′	Medium
The northernmost east coast	Rason		1941–2015	E 130° 24′	N 42° 19′	Small
	Other stations		1956–2015 1971–2015			

The classification of city is based on urban population. Large city: ≥ 500,000; medium city: < 100,000, ≥ 500,000; small city: < 100,000, ≥ 10,000 were insufficient. The 1981–2010 was used as the most recent climatological reference period for calculating annual mean and monthly average temperature anomalies of individual stations.

In order to investigate the regional representativeness of the four stations with data from 1918, we divided the climate zones of the study area based on the SAT data from 1971 to 2015. In the classification of the climate zones, we used the continentality as an indicator, referring to the usual practice in climatic classification in PDRK (Yun 1996). Continentality could be calculated by using the following equation:

$$K = (A_\mathrm{T} + A_\mathrm{t} + A_\alpha)/(0.36\varphi + 14) \times 100(\%) \tag{1}$$

where A_T, A_t, and A_α are the intra-annual, diurnal temperature ranges, and the intra-annual range of the saturation deficiency, respectively, and φ is the latitude. Saturation deficiency (d) is a measure of the "dryness" or "wetness" of the air, generally expressed by the difference between saturated vapor pressure (E) and actual vapor pressure (e). Four climatic zones could be divided referring to the spatial distribution of continentality values. The climatic zones and the stations in each of the zones are shown in Fig. 2.

Five time periods were analyzed for liner trends of temperature. They are the periods of 1918–2015, 1941–2015, 1941–1970, 1971–2015, and 1971–2000. The division was mainly based on the observational lengths of the stations available (e.g., critical years 1918, 1941, 1971, and 2015) and also on the shifting of climatic regime (e.g., shift years 1971 and 2000) (Fyfe et al. 2016; Sun et al. 2017a, b).

Simple arithmetic averages of temperature anomalies of all stations were made for obtaining regional average annual and monthly average temperature anomaly series due to the relatively even distributions of the stations in the study region and the climatic zones (Fig. 1 and Fig. 2), especially for the recent period of 1971–2015 which owns a denser observational network. Significance of the linear trends was examined by using a two-tailed Student's t test. A trend is considered statistically significant if it is significant at the 95% ($p < 0.05$) confidence level. Serial correlation in temperature data series may significantly affect the estimate of trends and the confidence test (von Storch 1982; Zhang and Zwiers 2004). However, this issue has not been considered because there is a controversy about whether to prewhiten the autocorrelation of original monthly average temperature data (Yue and Wang 2004).

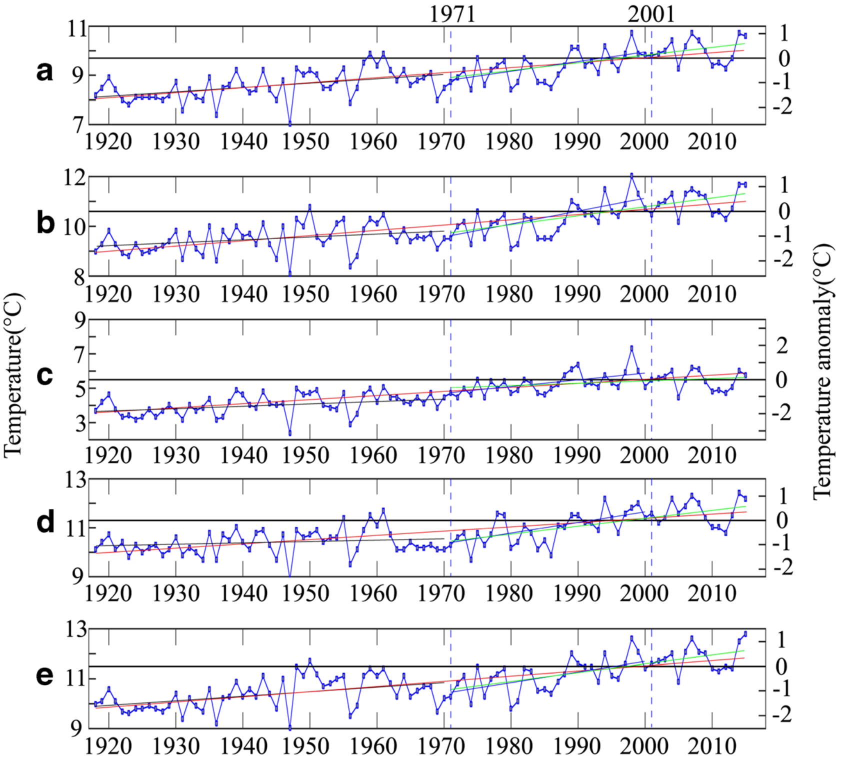

Fig. 2 Region-averaged and station annual mean SAT anomalies in PDR Korea during 1918–2015. **a** Region-averaged. **b** Pyongyang station. **c** Chunggang station. **d** Wonsan station. **e** Haeju station. Red solid line, linear trends for 1918–2015; green solid line, linear trends for 1971–2015; black solid line, linear trends for 1918–1970; blue solid line, linear trends for 1971–2000; blue dashed line, 1971 when the regime of annual temperature change shifted; black dashed line, 2001 when the regime of seasonal temperature change shifted for most stations

3 Results

3.1 Representativeness of long-term records

The boundary lines of the climate zones are shown in Fig. 1b. The boundary between the coastal zone and the central inland zone, for example, is indicated by the 180% isogram line of continentality.

Table 2 shows the number of stations for each of the climate zones and observation periods. There were no data for the stations belonging to zone B (Central Inland) before the 1970s. Moreover, there is only one station in each of the Northern Inland zone and the Eastern Coast zone. Therefore, the regional and temporal representativeness of the SAT data of the nine stations before 1970s is not as good as that afterward. Table 3 presents the correlation coefficients of annual mean temperature of the nine stations and four stations with that of the total stations (excluding the nine stations or four stations) for each climate zone and the whole study region during the period 1971–2015. The correlation coefficients for both the nine stations and the four stations are generally very high (> 0.91). All of the correlations are highly significant, indicating the good representativeness of the nine stations and the four stations for the climate zones and the whole region.

It is rational to assume that the average annual and seasonal mean temperature anomaly series as obtained from the data of the four stations (Pyongyang, Chunggang, Wonsan, and Haeju stations) are able to represent the "real" mean SAT changes as estimated from a dataset of denser observational stations for different periods. We therefore analyze the long-term changes in SAT in PDRK in the next subsection by using the monthly average temperature data of the abovementioned four and nine stations.

3.2 Annual mean SAT change

The annual mean temperature anomalies and SAT trends for the whole region and the four representative stations are shown in Fig. 2. A temperature increase rate of 0.21 °C/decade during 1918–2015 has been experienced in the whole region studied, with an overall warming of almost 2.0 °C for the whole time period. Based on a comprehensive consideration of variations in the regional average annual mean temperature, the numbers of stations applied, and the previous studies of climate warming slowdown (Kosaka and Xie 2013; Sun et al. 2017a, b), 1971 and 2001 were chosen as shifting points, and different periods were divided to examine their respective trends.

The most rapid warming, 0.41 °C/decade for 9 stations and 0.41 °C/decade for 179 stations, occurred during 1971–2000, followed by the periods of 1971–2015 and 1941–2000 (Table 4). Moreover, 1998, 2007, and 2014 are the three warmest years for the past 98 years, all registering an anomaly of 1.0 °C. The coldest year during the whole period is 1947, when the average annual mean temperature anomaly reached − 2.7 °C. Three stagnate periods, 1920–1934, 1960–1974, and 1998–2015, are detectable from the region-averaged annual mean temperature anomaly series. The temperature underwent no significant upward trends during the hiatus periods, with period 1960–1974 even experiencing an obvious decrease.

The temperature differences among the stations of the inland zones and coastal zones are significant in the study area. In particular, Chunggang is in the inland zone and represents one of the regions with the strongest impacts of the continental climate. The annual mean temperature at this station is about 4.0 °C lower than the country average (about 5.0 °C lower than Pyongyang and 6.0 °C lower than Haeju and Wonsan of the coastal zones). It is clear that temperatures have increased overall over the last century including the period since 1998 at all stations despite the large climatic and geomorphological differences among the observational stations. Table 4 shows SAT trends and the significance level in different zones during different periods. The large and significant increase in annual mean SAT can be seen for the period 1971–2000, and the rates of temperature increase for the period are two to six times higher than those for period 1918–1970. However, the SAT trends for the nine stations from 1941 to 1970 are not statistically significant (data not presented), indicating that no significant increasing or decreasing SAT for this period was detectable over the study area.

It is noteworthy that there were large differences of trends for the various periods of the last century among the different zones. Generally, West Coastal zone and North Inland zone have larger and more significant warming than East Coastal zone. The largest increase in temperature appeared at

Table 2 Number of stations for different climatic zones and observational periods

Period	Climatic zone			
	A (West coast)	B (Central inland)	C (Northern inland)	D (East coast)
1918–1940	2		1	1
1941–1970	4		1	4
1971–2015	60	44	36	39

Table 3 Assessment of representativeness of observational sites for individual climatic zones and the study region on a whole (shown are the correlation coefficients of annual mean temperature of the observational stations with those of region-averaged annual mean temperature for the period 1971–2015)

Station	Zone	A-average	B-average	C-average	D-average	Total
Pyongyang	A	*0.98*	0.93	0.91	0.91	0.93
Chunggang	C	0.91	0.91	*0.95*	0.90	0.91
Wonsan	D	0.94	0.91	0.92	*0.94*	0.93
Haeju	A	*0.96*	0.93	0.90	0.93	0.91
Average (4 stations)						0.92
Hamhung	D	0.93	0.90	0.93	*0.96*	0.93
Sehong	A	*0.96*	*0.95*	0.90	0.92	0.91
Sinuiju	A	*0.97*	0.94	0.92	0.92	0.94
Kimchaek	D	0.93	0.90	0.92	0.94	0.91
Rason	D	0.92	0.90	0.93	0.94	0.91
Average (9 stations)						0.91

A, west coast; B, central inland; C, northern inland; D, east coast. Italics, the correlation coefficients are significant at $p < 0.01$ level. All the correlations are significant at $p < 0.05$ level

Chunggang station of North Inland zone for the period 1918–2015, reaching 0.24 °C/decade, and the weakest warming, 0.17 °C/decade, is seen at Wonsan station of East Coastal zone. For the periods 1971–2000 and 1971–2015, Pyongyang experienced the most rapid warming in terms of annual mean temperature change. Chunggang station of North Inland zone had the lowest warming rate during 1971–2015, however, obviously different from that of Pyongyang station. Sehong station of West Coastal zone shows the second highest SAT increase rate for the period 1971–2000.

Haeju, Wonsan, Kimvhaek, and Rason are all located in coastal zones, and the climate warming at the stations might have been buffered in certain extents by a marine climate. Previous works have analyzed the temperature rise of the northern hemisphere and the southern hemisphere for the last century, showing that the northern hemisphere experienced a higher temperature rise than the southern hemisphere, which are mostly oceans (Jones and Moberg 2003; IPCC 2013). The results of the larger temperature rise in northern inland areas and the smaller warming along the coastal zones especially the East Coastal zone for the period 1918–2000 are approximately in agreement with those for larger-scale analyses.

Despite warming trends had been weakened over all the regions since 2001, the annual mean temperature at each of the zones experienced large and significant increasing trends for the period since 1971. The warming was much larger than that for the period 1918 to 1970 or for the period 1941–2000 at Wonsan, Haeju, Hamhung, Sehong, and Pyongyang stations, with Pyongyang and Haeju stations seeing the first and second largest increase in temperature among all the nine observational sites. The sustaining and larger temperature increasing trend at the urban stations including Pyongyang station (large city

Table 4 Linear trends of annual temperature anomalies and their significance level in different climatic zones during different periods (unit—°C/decade)

Region (climate zone)	1918–1970	1918–2015	1941–2000	1971–2000	1971–2015
Country-averaged	0.126**	0.208***	0.213***	**0.411***** (**0.398****)	0.294*** (0.280**)
	4 stations	4 stations	9 stations	9 (179 stations)	9 (179 stations)
Pyongyang (A)	0.116*	0.220***	0.223***	***0.505******	*0.370****
Chunggang (C)	*0.159***	*0.238****	*0.328****	**0.402****	0.159*
Wonsan (D)	0.071	0.165***	0.174***	**0.439*****	0.331***
Haeju (A)	0.157***	0.212***	0.159**	**0.438*****	0.361***
Hamhung (D)			0.180***	**0.472*****	0.338***
Kimchaek (D)			0.175**	0.217	**0.269*****
Sehong (A)			0.192***	**0.484*****	0.333***
Sinuiju (A)			0.214***	**0.392****	0.249***
Rason (D)			0.279***	**0.350*****	0.235***

Italics: maximum value on each column (for the same period). Bold: maximum value on each row (for the same station). A, C, and D denote the different climatic zones as indicated in Fig. 1b

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$

station) and Haeju station (medium-size city station) (Table 1) since 1971 needs to be further examined for the possible reasons, but it might be related to the enhanced UHI (urban heat island) effect due to urbanization, as happened in most parts of mainland China over the last decades (Ren et al. 2008, 2015).

3.3 Seasonal mean SAT change

Region-averaged seasonal mean SAT trends during the last three periods are shown in Fig. 3. The seasonal trends during the period from 1971 to 2000 in West Coast zone were not much different, but there was a large negative SAT trend in summer and autumn during the period 1941–1970. Likewise, in North Inland zone, a negative trend in SAT for the pre-1970 summer was obvious (Fig. 3b). In Eastern Coastal zone, 1941–1970 underwent an obvious drop of temperature for all the seasons, with the largest negative trend appearing in the fall (Fig. 3c). For the period 1971–2000, winter of all the climatic zones witnessed a large increase in seasonal mean temperature, and spring, summer, and autumn of West Coastal and East Coastal zones also experienced large and significant warming. It is interesting to note that all the seasons of East Coastal zone experienced a significant cooling during 1941–1970 (Fig. 3c).

These results indicate that all climatic zones (excluding Central Inland zone) experienced large changes in seasonal mean SAT for most of the seasons, generally a significant warming trend. Specifically, the winter mean temperature showed the largest increase during the period from 1971 to 2000 for all climatic zones.

Comparing the periods 1971–2000 and 1971–2015, the seasonal trends in SAT showed some noticeable changes over

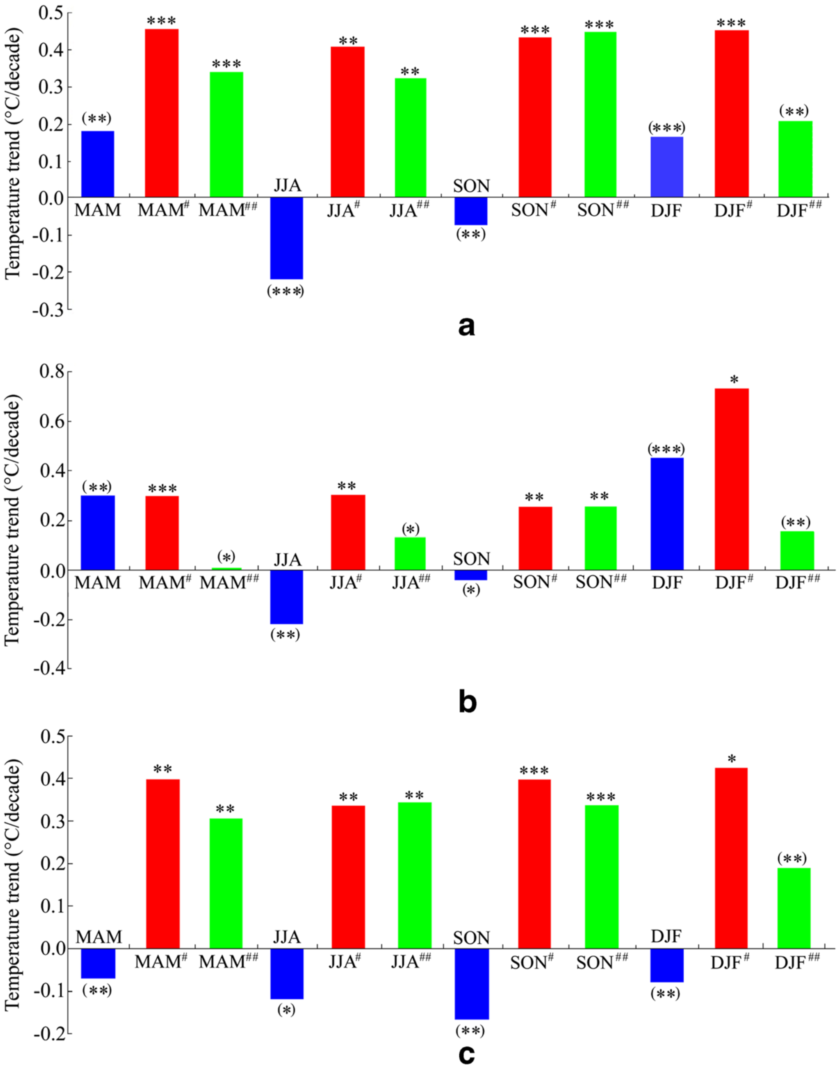

Fig. 3 The region-averaged seasonal mean SAT trends for spring (MAM), summer (JJA), autumn (SON), and winter (DJF) during 1941–1970 (blue), 1971–2000 (red), and 1971–2015 (green) for different climatic zones. **a** A zone (west coast), four stations. **b** C zone (northern inland), one station. **c** D zone (east coast), four stations. $***p < 0.001$, $**p < 0.01$, and $*p < 0.05$. Parenthesized asterisks indicate the significance level after 3-year running mean

the whole region (Fig. 3). However, most of the regions and seasons experienced weakening positive trends in 1971–2015 as compared to the period 1971–2000, implying the influence of regional climate warming slowdown in the study region. The phenomenon is especially remarkable in the wintertime in two coastal zones. The northern inland area also saw a stagnating warming for the past 45 years compared to the period 1971–2000 during wintertime. An important reason for this to occur would be the strengthening of East Asian winter monsoon after 1998 or 2000, and the increase of seasonal mean temperature in Northeast Asian region might have been offset by the naturally induced cooling due to the increasing intensity of winter monsoon (Sun et al. 2017a, b). These results also coincided with the previous studies which reported the global warming slowdown after 1998 or 2000 and generally attributed it to the multi-decadal variability related to PDO (Pacific Decadal Oscillations), AMO (Atlantic Multi-decadal Oscillations), and ENSO (El Niño–Southern Oscillation) modes (e.g., Kosaka and Xie 2013; Fyfe et al. 2016).

4 Discussion

An attempt was made in this work to analyze the change in surface air temperature for the period 1918–2015 for PDRK by using a high-quality surface observational dataset.

The results show a significant change in SAT in PDRK for the first time, with some exhibiting distinctive features from those reported in other regions of the globe. The temperature increasing rates of 0.21 °C/decade for the last 98 years and 0.19 °C/decade for the last 74 years are higher than those of the globe and northern Hemisphere, and also higher than that estimated for mainland China and Northeast China over similar periods (Table 5) (Qian and Zhu 2001; Tang and Ren 2005; IPCC 2013; Sun et al. 2017a, b). However, the annual mean warming trends of the recent periods (1941–2015 and 1971–2015) in PDRK seem to be obviously lower than Korea, Northeast China, and mainland China as a whole, but comparable to the warming of the Bohai Sea and the Yellow Sea (West Sea) (Table 5).

Major uncertainties with the analysis would be the possible effect of urbanization (or UHI) on the linear trends of surface air temperature at the urban stations and the error resulting from the insufficient coverage of data in early decades.

The coldest year over PDRK for the last century appeared in 1947, with the average annual mean temperature anomaly of − 2.7 °C. This is different from the analysis by Tang and Ren (2005) which indicated the coldest year in 1969 after 1918, but in better similarity to that by Cao et al. (2013) which reported the approximately similar negative temperature anomalies for 1947 and 1969 after 1918, for mainland China. The analysis results from PDRK seem to support the homogenized data series by Cao et al. (2013) in inter-annual temperature variability pattern, but the latter also results in a recovery of urbanization effect at the urban stations of eastern China as indicated by Zhang et al. (2013) and Ren et al. (2017). Removing the urbanization biases in the temperature series of the urban stations would produce a different rank of the extreme cold years in mainland China. Further works are obviously needed to solve the issue.

According to the studies conducted for mainland China, southern Korean Peninsula, and Japan, the urbanization effects in the regional average long-term temperature series are generally large and significant (e.g., Chung et al. 2004a, b; Ren et al. 2008; Fujibe 2009; Zhou and Ren 2014; Park et al. 2017). In mainland China, for example, the urbanization effect on the annual mean temperature trend of the national stations over the last five decades accounts for at least 27% of overall

Table 5 A comparison of linear trends of annual mean surface air temperature (°C/decade) estimated for regions of East Asia

Study area	Data used	Period analyzed	Linear trend	Reference
PDR Korea	4 stations	1918–2015	0.21	This study
PDR Korea	9 stations	1941–2015	0.19	This study
PDR Korea	179 stations	1971–2015	0.28	This study
Korea	12 stations	1960–2010	0.29	Kim et al. (2016a, b)
Korea	12 stations	1961–1990	0.23	Jung et al. (2002)
Japan	Stations with low population density	1979–2008	~ 0.30	Fujibe (2009)
Northeast China	6 stations	1905–2001	0.16	Sun et al. (2005)
Northeast China	103 stations	1956–2005	0.30	Zhao et al. (2009)
China	291	1901–2015	0.10	Tang and Ren (2005)
China	730 stations	1951–2001	0.25	Ren et al. (2005)
Bohai and Yellow Seas	HadISST	1870–2011	0.06	Bao and Ren (2014)
Bohai and Yellow Seas	HadISST	1962–2011	0.18	Bao and Ren (2014)

The trends shown in the table are all significant at the 95% confidence level increase in annual mean temperature (Zhang et al. 2010; Ren et al. 2015), which most probably contributes one-third of the regional average warming as estimated by using the national observational stations (Sun et al. 2016). Therefore, it would be interesting to further investigate the possible impact of urbanization on the estimated long-term trends of surface air temperature in the study region, especially for the urban stations which usually own the longer data series, despite the fact that the urbanization process in the study region may be slow compared to mainland China and Korea.

In addition, the early year observations are relatively sparse, and this may cause a larger uncertainty in the calculated trends of the last 98 years and 74 years. The exact errors due to the sparse observational sites in early years and the increased coverage of observations with time should also be estimated in future analyses.

The more rapid warming in PDRK in the last century, like those found in other regions of East Asia, may have been related to the weakening East Asian Winter Monsoon, in addition to the possible urbanization effect as mentioned above. The strength of the East Asian winter Monsoon experienced a declining trend over the past more than half century, especially from the 1950s to 1990s, and this may have caused a more rapid warming in winter and spring in East Asian countries including PDRK (Chung et al. 2004a, b; Ding and Ren 2008; Zhao et al. 2014). Recent two decades witnessed a re-strengthening of the winter monsoon, which have partially contributed to the regional warming slowdown since 1998 (2000) (Kosaka and Xie 2013; Sun et al. 2017b), and may not have changed the significant long-term warming trends in PDRK and other Eastern countries over more than half a century.

The results of the study would help to deepen our understanding of regional climate change and increase our ability to verify regional climate models usually used for projecting future climate in East Asia including the Korean Peninsula, and they will also be of key reference to the assessments of regional climate change on natural and human systems in the northern part of the peninsula, which, like other developing regions, is highly sensitive and vulnerable to climate change and variability.

5 Conclusions

This paper analyzed the long-term changes in temperature in PDR Korea. The main conclusions were drawn as follows:

1. The region-averaged annual mean SAT showed an increase of 0.21 °C/decade for 1918–2015 on the basis of four stations, and 0.19 °C/decade for 1941–2015 based on the data from nine stations.
2. The inland areas generally had a higher warming trend than the coastal areas. The linear trends of seasonal mean temperature were negative in all seasons on the eastern coast and in summer and autumn in the western coast and northern inland area during the 1941–1970.
3. Since 1971, the annual and seasonal mean SAT trends in all regions shifted to positive, with winter and inland areas experiencing the larger and more significant warming.
4. The annual mean temperature increase obviously weakened after 1998 or 2000 compared to the periods 1971–2000 and 1971–2015, with winter mean temperature exhibiting almost no trend, indicating a remarkable climate warming slowdown in the study region.

Acknowledgments We would like to thank the State Hydro-Meteorological Administration (SHMA) of PDRK for providing the observed monthly temperature data and the topographical map data of the study region. The first author shows his gratitude to many teachers and students in the School of Environmental Studies of China University of Geosciences, Wuhan, who gave their selfless helps to him during his stay in China. He also appreciates the help from his colleague Kum-Su Li from Kim Il Sung University.

Funding information This work is supported by the National Key R&D Program of China (no. 2018YFA0605603).

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