Responses of abrupt temperature changes/warming hiatuses to changes in their influencing factors: A case study of northern China

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Abstract
Determining the response of abrupt temperature changes/warming hiatuses to changes in their influencing factors can provide a reference for investigating their mechanism. The present study, using the Mann–Kendall test, based on data (including average minimum temperature ($T_{\text{min}}$), average temperature ($T_{\text{ave}}$) and average maximum temperature ($T_{\text{max}}$) recorded at 357 meteorological stations in northern China and its surrounding regions as well as large-spatial-scale data (e.g. Atlantic multidecadal oscillation (AMO), global radiative forcing of CO$_2$ (RF$_{\text{CO}_2}$) and radiative forcing of annual greenhouse gases (RF$_{\text{AGG}}$)) for the period 1951–2016, the characteristics of abrupt temperature changes/warming hiatuses and their response to their influencing factors were qualitatively and quantitatively determined. The following results were obtained. Overall, from the late 1970s to the 1990s, as the RF$_{\text{AGG}}$ continuously increased, the Pacific decadal oscillation (PDO) remained in a positive phase, the AMO and total solar radiation (SR) continuously increased, the multivariate El Niño southern oscillation (ENSO) index (MEI) changed abruptly, the wind speed (WS), atmospheric pressure (AP) and relative humidity (RH) in each zone continuously decreased/increased, their trends changing subsequently, and abrupt changes in the three temperature metrics (i.e. the $T_{\text{min}}$, $T_{\text{ave}}$ and $T_{\text{max}}$) occurred in each zone during the period 1977–2004. Similarly, in the 1990s, particularly after 1998, as the increase in the AMO slowed, the PDO was in either a positive phase but exhibited a decreasing trend or a negative phase, the MEI and SR decreased, the WS, AP and RH decreased/increased, with subsequent changes in trends, and warming hiatuses occurred. The sensitivities of the responses of the $T_{\text{min}}$ to changes in the three types of influencing factors were the highest, followed by those of the $T_{\text{ave}}$ and $T_{\text{max}}$. The effects of various influencing factors on the three kinds of temperature change and warming hiatus have strong spatial and temporal differences. As a
Abrupt temperature changes/warming hiatuses have a significant impact on humans’ living environment. However, influence factors were complex and their relative importance has not been quantified (Kosaka and Xie, 2013). A qualitative or quantitative (especially quantitative) understanding of the responses of abrupt temperature changes/warming hiatuses to changes in their influencing factors is of great significance.

An abrupt climate change is manifested by a sharp change in climate from one statistical characteristic to another on temporal and spatial scales (Rial et al., 2004). These statistical characteristics mainly include the mean, variance, phase change and transition. Natural evidence such as ice core (Gao et al., 2016) and pollen (Zhao et al., 2017) records demonstrates that abrupt climate changes are universal on a temporal scale (Alley et al., 2003) and have profound impacts on both the economy and ecology. For example, the decline of the Mayan (Hodell et al., 1995) and Mesopotamian (Weiss et al., 1993) civilizations might have been caused by prolonged droughts resulting from abrupt climate changes. The period since the 1950s has seen a significant temperature increase, frequent occurrence of extreme weather events, and a worsening uneven distribution of water resources on global and regional scales (Alley et al., 2003; Yang et al., 2015; Sun et al., 2016; Wang et al., 2016). In the first decade or so of the 21st century, a global warming hiatus occurred. Temperatures changes stagnated in some parts of the world in this century (Drijfhout et al., 2014; Yan et al., 2016), but warming hiatuses are also cyclical and overall, global temperatures are still on the rise, the adverse effects of climate warming are also continuing (Yang et al., 2015), and some extreme climate events are closely related to them, and are even more detrimental to changes in animal and plant phenology (Lempeuru et al., 2017; Prodon et al., 2017).

Abrupt temperature change occurs in many regions of the world. In recent decades, abrupt climate changes have occurred around the world, including in Asia (Hu et al., 2015; Dong et al., 2016) and Canada (Gavin et al., 2011; Ding et al., 2014), and on the Tibetan Plateau (Duan and Xiao, 2015; You et al., 2016) and Loess Plateau (Sun et al., 2016) in China. However, there is still a lack of key evidence supporting the interpretation of these rapid and intense climate changes. Research has found that the concentration curves of greenhouse gases (e.g. carbon dioxide (CO2)) for the past 420,000 years were consistent with the temperature time series (Petit et al., 1999), changes in sea surface temperature (SST) and sea-ice area could explain 76% of the summertime warming in northeast Asia (Dong et al., 2016); the coastal warming in Siberia was highly negatively correlated with sea-ice cover (Gavin et al., 2011); and the rapid droughts and warming on the Loess Plateau were consistent with the increase in the geopotential height of the Eurasian continent (Sun et al., 2016). On various scales, temperature is related to changes in each influencing factor, which, however, cannot be fully explained by any existing theory. This, in fact, is a result of the combined action of multifactor integration, multiscale superposition, human activity and natural factors.

There was a significant increase in global mean temperature within a certain period after its abrupt change. From 1998 to 2012, the rise in global average temperatures temporarily slowed, and in some regions even decreased (Luo et al., 2012; England et al., 2014). This phenomenon is referred to as a warming hiatus (Carter, 2006), which was chosen by Nature magazine as “one of the top 10 scientific discoveries of 2014” (Meehl and Teng, 2014; Morello et al., 2014). However, the global temperature is still showing an overall upward trend, and the hiatus of warming in some areas may be temporarily periodic. There are various explanations for the reasons for the hiatus of warming in some areas. For example, volcanic eruption, solar radiation (SR) change (Lean and Rind, 2009) and some human activities (Yang et al., 2015) lead to the decrease of temperature change, changes in deep-sea heat (Chen et al., 2015), the Pacific decadal oscillation (PDO), the Atlantic multidecadal oscillation (AMO) and interannual turbulence is also the main influencing factor of temperature warming hiatus (Yao et al., 2017; Zhang et al., 2018). Based on the most recent data, in some areas where a warming hiatus occurred, the temperature has continued to rise in recent years. For example, the temperature in the Arctic is rising sharply at a rate more than twice the global average heating rate. In 2014, a new record was set for global average surface temperatures, and again in 2015 and 2016. The year 2019
also saw near-record global average temperatures, close to those in 2016. Currently, research conducted in China and elsewhere on abrupt temperature changes/warming hiatuses mostly focuses on average temperature (T_{ave}) and neglects the relationships of the T_{ave} with average minimum temperature (T_{min}) and average maximum temperature (T_{max}) and the differences between the T_{ave} and T_{min} and between the T_{ave} and T_{max} (Guo et al., 2005). The change in the T_{ave} is affected by the T_{max} and T_{min}, and there are differences among three types of temperature. Comparing the papers only focused on the T_{ave} and studying three types of temperature can fully reveal their characteristics and make up for each other, which is good for obtaining a comprehensive understanding of the change of climate and its influencing factors. There are certain limitations to the research on the responses of abrupt temperature changes/warming hiatuses to changes in their influencing factors. Relevant studies on abrupt temperature changes are universally problematic due to low station densities and short data series. Most of the time series used in studies of warming hiatus take the global comprehensive warming stagnation year (1998) as the starting year, but the stagnation of warming occurs only in part of the region. There is no stagnation of warming in some regions, which still showed rising temperatures during the period of the temporary warming hiatus. Global average temperatures are still showing an upward trend, and there are differences in the years of warming hiatus in the areas where warming and where the hiatus occur, so regional heterogeneity is generally ignored. In addition, those studies mostly focus on characteristic analyses based on single factors and fail to provide clear responding relationships and mechanisms. In view of this, the responses of abrupt temperature changes/warming hiatuses to changes in multiple types of their influencing factors have been qualitatively and quantitatively analysed the present study.

To ensure high universality and representativeness, northern China (a region with a large number of climate types and a vast area) was selected as the study area. Amid global warming, overall, northern China has seen significant warming and abrupt temperature changes. Temperatures in northern China are affected by the East Asian or even global atmospheric circulations (Xiang and Chen, 2006). Climate varies significantly between different regions of northern China and between regions differing in climate type. Available research has shown that abrupt temperature changes in each region of northern China occurred mainly in the period 1980–1990s. Xie et al. (2017) noted that climate change in China is affected by atmospheric circulation. Chen et al. (2004) concluded that the increase of aerosol optical thickness (Li et al., 2016; Li et al., 2019), the change of CO₂ emission (Ren et al., 2017; Chongyin, 2019) and S emission (Kaufmann et al., 2011) caused by human activities and pollution have a great impact on temperature change. Cooling in the Sichuan Basin and warming on the north China Plain were both associated with increases in aerosols (Duo et al., 2016; Wang et al., 2017). Interdecadal changes in the circulation factor might have resulted in abrupt summertime temperature changes in northeast China (Li et al., 2016). A warming hiatus occurred in the Inner Mongolia section of the Yellow River Basin in 2007 (Huang et al., 2016). Relevant studies on northern China only use single influencing factors. Research results are lacking regarding the responses of abrupt temperature changes/warming hiatuses to changes in several influencing factors. The study was conducted based on annual and monthly data (including the T_{min}, T_{ave}, T_{max} and wind speed (WS)) collected at 357 meteorological stations distributed with a high density in northern China and its surrounding regions, as well as large-spatial-scale data (including the AMO and PDO) for the period 1951–2016 with a view to provide a reference for the study of the causes of abrupt changes in global temperature and the hiatus of warming.

2 | GENERAL INFORMATION ON THE STUDY AREA, DATA AND METHODS

2.1 | General information on the study area

Northern China encompasses a vast area that stretches over a great distance in both latitudinal and longitudinal directions (see its location (73 ° 40’–135 ° 2’ E, 31 °9’–53 °33’ N) in Figure 1) and it consists of three regions, namely, northwest (Qinghai, Gansu, Ningxia, Shaanxi, western Inner Mongolia and Xinjiang), north (Hebei, Shandong, Henan, Shanxi and central Inner Mongolia) and northeast (Heilongjiang, Jilin, Liaoning and eastern Inner Mongolia) (Chen et al., 1998). Northern China has complex and varied landforms (e.g. deserts, mountains, plains and basins), with a variety of climate types (e.g. monsoon, temperate continental and plateau/mountain climates). There are significant differences in surface relief, temperature (−13 to 23°C) and precipitation (50–1,200 mm) between west and east northern China.

2.2 | Data sources

Annual (monthly) data (including the T_{min}, T_{ave} and T_{max}) collected at 357 meteorological stations distributed over northern China and its surrounding regions
(Figure 1) in the period from the time of the establishment of the stations to 2016 were used. The data were obtained from the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA). The NMIC has conducted quality control on various types of temperature data collected at each meteorological station. Thus, these data are reliable and contain no notable abrupt-change points and random variations, but instead have relatively uniform and consistent variations, and they therefore can represent the temperature conditions in the study area.

To analyse the causes of temperature changes in the study area, climatic factors closely related to temperature changes were selected as driving factors for temperature changes. The annual/monthly data for the atmospheric pressure (AP), WS and relative humidity (RH) for the period 1951–2016 used the present study are measurements taken at the 357 meteorological stations, the temperature data of which were also used herein. The RFCO2 and RFAGG time series were unified such that they covered the period 1979–2016. Estimates for missing data were calculated by interpolation and extension using correlation and regression analysis methods based on data collected at nearby stations. Ultimately, uniform time series for the aforementioned climatic factors were obtained.

2.3 | Methods used for data processing

2.3.1 | Time-series data for the climatic factors

The time-series data for the climatic factors were unified. The temperature, AP, WS and RH data of each station as well as the global-scale MEI, PDO and AMO data were unified such that they all covered the period 1951–2016. The RFCO2 and RFAGG time series were unified such that they covered the period 1979–2016. Estimates for missing data were calculated by interpolation and extension using correlation and regression analysis methods based on data collected at nearby stations. Ultimately, uniform time series for the aforementioned climatic factors were obtained.

2.3.2 | Influencing factors for temperature

The influencing factors for temperature were classified. The currently highly accepted factors, namely the PDO, AMO and RFAGG (including RFCO2), were classified as definite influencing factors (Petit et al., 1999; Li et al., 2009; Steinman et al., 2015; Li et al., 2016; Antonello et al., 2017) (referred to as the first type of influencing factors). The second type of influencing factors are possible influencing factors, including the MEI and SR (Yang et al., 2015; Li et al., 2015a; Chang et al., 2017). The WS, AP and RH are closely related to temperature and may be affected by temperature and, in turn, affect temperature. They were classified as the third type of influencing factors (Dong et al., 2000; Jiang et al., 2010).
2.3.3 Testing the abrupt temperature changes and related influencing factors

Abrupt temperature changes and the related influencing factors were tested using the Mann–Kendall non-parametric statistical method as follows. Let $x_i$, where $i = 1, 2, 3, n$ is a time series of length $n$. For each $x_i$ the number $m_i$ of $x_j < x_i$ with $j < i$ is computed, and the sum is formed:

$$d_n = \sum_{j=1}^{n} m_j$$

$$E(H_0) = n(n-1)/4V(H_0) = n(n-1)(2n+5)/72$$

$$u(d_n) = (d_n - E(H_0))/V(H_0)^{1/2}$$

where $E(H_0)$ is the expect value; $V(H_0)$ is the variance; and $u(d_n)$ is the statistic. The statistic was compared with a standard normal distribution at the required significance level ($\alpha = 0.05$). The null hypothesis is then rejected when $u(d_n) > 1.96$.

$$d'_i = \sum_{j=1}^{n} m'_{j}$$

$$u\left(d'_i\right) = \left[ d'_i + ((n-i)(n-i+1)/4)/\left[ (n-i)(n-i+1)(2(n-i+1) + 5)/72\right]^{1/2} \right]$$

The sequential version consists of the graphical representation of all the $u(d'_i)$ along the time axis, denoting $C_1$ for the series and $C_2$ for the retrograde one. The intersection of both curves $C_1$ and $C_2$, between the critical values at the 5% level of significance, localizes the beginning of the change. See Esterban-Para et al. (1995) for details of the principle. When the point of intersection between the two lines was outside the confidence line or multiple abrupt-change points were detected, the abrupt-change points were further examined and determined using the Pettitt test.

2.3.4 Study area

The study area was regionalized based on the climatic factors using a central clustering algorithm. One point was selected as the centre, and the correlation co-efficients ($R_s$) between that point and its neighbouring points were calculated and subsequently transformed to distance co-efficients. In addition, the sample variable was also standardized. The results were examined using the chi-square distribution. When a result was smaller than the check number, the result was < 0.05 significance level. Stations of this type were classified as the same type (i.e. the same zone). Otherwise, the zone was expanded or contracted until the test was satisfied. Ultimately, regionalization maps for various types of climatic factors were obtained. See Yao (1994) for the detailed calculation process.

2.3.5 Average temperatures and average of the time series for each influencing factor

The average temperatures and average of the time series for each influencing factor were calculated for each zone using the inverse distance-squared method. Each zone was transformed to a $0.5 \times 0.5^\circ$ uniform latitude–longitude grid. Thus, grid points were generated. Climatic factor data for each grid point were determined based on the weight (distance factor) and comprehensive distance weight of each nearby station as well as the meteorological data for each nearby station. Afterwards, the arithmetic mean of the data at all the grid points within each zone (i.e. the annual average series for each zone) was calculated. See Jones and Hulme (1996) for the detailed calculation process.

2.3.6 Year when a warming hiatus started

The year when a warming hiatus started (WH year) after an abrupt temperature change was determined by analysing the temperature series and its stage-wise trend lines in combination with a sliding value series for three to five year and its stage-wise trend lines. If the climate tendency rate for a certain year after an abrupt temperature change was the highest, and the climate tendency rate for the period from the year in question to the end of the series (2016) was $\leq 0^\circ C \cdot 10^\alpha^{-1}$, then the year was considered to be a WH year.

2.3.7 Co-efficient of variation (CV)

The CV was used to indicate the intensity of the temperature change:

$$CV = SD/MN$$

where $SD$ is the standard deviation; and $MN$ is the mean. The higher the CV, the more violent the change in the climatic factor.
2.3.8 | Time-series trends of temperature and its influencing factors

The time-series trends of temperature and its influencing factors were analysed based on either the climate tendency rate alone or a combination of the climate tendency rate and the standardized temperature anomaly time series after subjecting the time series to minimum–maximum data normalization (Ma, 2000). The temperature variation trend is analysed by the climate tendency rate method, using the following formula:

\[ y = at + b \]

where \( y \) is one of the three temperature types; \( t \) is the time; and \( a \) is a positive value that indicates that the temperature \( y \) exhibits a linear upward trend in a statistical time period, and a negative value indicates a downward trend.

3 | RESULTS

3.1 | Regionalization of the study area based on the climate factors

The study area was large. To facilitate analysis, it was regionalized based on the \( T_{\text{ave}}, T_{\text{min}} \) and \( T_{\text{max}} \) (Figure 2). The study area was divided into a total of six level-1 climate zones (I–VI). These zones, to some extent, differed from those created by Shi et al. (2014), which might be a result of the difference in the length of the time-series data and the regionalization method. There is a certain difference within the level-1 zones associated with the variations in latitude and longitude and other geographical conditions. Therefore, level-2 regionalization was performed based on the level-1 regionalization (the study area was divided into a total of 15 level-2 zones).

The present analysis was conducted based on the annual \( T_{\text{ave}} \) time series for each level-2 zone. Because different central stations were selected when regionalizing the study area based on the three temperature metrics, there were some differences in area between the zones. Thus, the interannual average series for the three temperature metrics and each of their influencing factors were calculated for each zone. The large-spatial-scale annual series were used for the global-average-scale factors.

3.2 | Determination of the AC and WH years for each zone

The AC and WH years for each of the 15 level-2 zones were determined by examining the annual temperature \( (T_{\text{ave}}, T_{\text{min}} \text{ and } T_{\text{max}}) \) time series for the period 1951–2016. Figure 3 shows the results.

As shown, there was an abrupt change in each of the three temperature metrics for each zone, which occurred mostly in the 1990s (there were abrupt changes in the \( T_{\text{min}}, T_{\text{ave}} \text{ and } T_{\text{max}} \) in 10, eight and 10 level-2 zones, respectively), followed by the 1980s (there were abrupt changes in the \( T_{\text{min}}, T_{\text{ave}} \text{ and } T_{\text{max}} \) in four, six and two level-2 zones, respectively). In some zones, the abrupt changes occurred as late as the 2000s. For example, the abrupt change in the \( T_{\text{ave}} \) in zone VI. Overall, the abrupt change in the \( T_{\text{max}} \) occurred the latest (1988–2004), followed by that in the \( T_{\text{ave}} \) (1982–2002) and that in the \( T_{\text{min}} \) (1977–1998). The abrupt changes in each of the three temperature metrics occurred at an increasingly later time with decreasing latitude and increasing elevation (from east to west). In most zones, there was a hiatus in the increase in each of the three temperature metrics, which mainly occurred in 1998 and around 2007. Warming hiatuses never occurred in some zones, which were mainly distributed at lower latitudes, for example, zones II6, III, IV1 and V4.

FIGURE 2 Regionalization of the study area based on the three temperature metrics. The study area is divided into six first-level regions as I–VI region, and a first-level region may contain several second-level regions; second-level regions that belong to the same first-level region have the same colour (e.g. IV1 and IV2)
3.3 Responses of abrupt temperature changes/warming hiatuses to changes in their influencing factors

3.3.1 Analysis of the characteristics of temperature changes/warming hiatuses

Figures 4 and 5 show the distribution of the climate tendency rates and the CVs of the annual temperature series for all the level-2 zones in each period before and after the AC and WH years, respectively (period T1: 1951–AC year; period T2: AC year–WH year; and period T3: WH year–2016).

As shown, before the abrupt change, each of the three temperature metrics increased slowly but fluctuated most significantly; in addition, the $T_{\text{max}}$ also decreased slightly in some zones. In each zone, the rate of increase in the $T_{\text{min}}$ was the highest (0.19°C-decade$^{-1}$), followed by that in the $T_{\text{ave}}$ (0.14°C-decade$^{-1}$) and that in the $T_{\text{max}}$ (0.06°C-decade$^{-1}$). The three temperature metrics increased at a decreasing rate with increasing latitude. After the abrupt change, each of the three temperature metrics for each zone increased significantly and, overall, fluctuated to a smaller extent compared with before the abrupt change. Overall, the three temperature metrics for the southeastern zones (II6, III, IV1 and IV2) of the study
area increased slowly. Moreover, most of the zones where no warming hiatus occurred were also located in the southeastern study area. The three temperature metrics for the high-latitude (I) and high-elevation (VI) zones increased rapidly. The $T_{\text{min}}$ in zone I increased most rapidly (1.40°C-decade$^{-1}$). Each temperature metric fluctuated the least during the warming hiatus. Overall, the $T_{\text{max}}$ shows the strongest cooling ($-0.32^\circ$C-decade$^{-1}$) compared with the $T_{\text{ave}}$ and $T_{\text{min}}$. Overall, the temperature metrics for the zones where no warming hiatus occurred increased slowly in the 21st century, and the temperature metrics for their surrounding zones also decreased slowly (approximately $-0.1^\circ$C-decade$^{-1}$).

### 3.3.2 Response of abrupt temperature changes/warming hiatuses to changes in the first type of influencing factors

Figures 6 and 7 show the spatial distributions of the $Rs$ between the three temperature metrics and the RF$_{\text{AGG}}$ and RF$_{\text{CO2}}$ and between the three temperature metrics and the PDO and AMO for each zone, respectively (due to the difference in lengths between time series). Figure 8 shows the changes in the time series for the temperature in representative zones and the RF$_{\text{AGG}}$ (including RF$_{\text{CO2}}$), PDO and AMO. Due to the limited length of the present paper, only zones representative of general patterns and with strong correlations ($p < 0.5$) are presented as examples.

As shown in Figure 6, overall, the RF$_{\text{AGG}}$ and RF$_{\text{CO2}}$ were most strongly correlated with the $T_{\text{min}}$ in each zone ($R = 0.72$), followed by the $T_{\text{ave}}$ ($R = 0.64$) and the $T_{\text{max}}$ ($R = 0.55$). The correlations of the temperature metrics for each zone with the RF$_{\text{AGG}}$ and RF$_{\text{CO2}}$ increased with increasing latitude. Based on the changes in the time series for the RF$_{\text{CO2}}$ and RF$_{\text{AGG}}$ and the temperature metrics for each zone as well as the plot for a representative zone shown in Figure 8a, the RF$_{\text{CO2}}$ and RF$_{\text{AGG}}$ both had increased linearly since 1979, and the RF$_{\text{CO2}}$ accounted for approximately 62% of the RF$_{\text{AGG}}$ (multi-year average). CO$_2$ is a main component of greenhouse gases. The Antarctic Vostok ice core data have shown that temperature is closely related to changes in CO$_2$, thereby further demonstrating that greenhouse gases, particularly CO$_2$, play a vital role in global warming (Petit et al., 1999). The RF$_{\text{CO2}}$ increased at a higher rate (0.284 W·(m$^{-2}$·decade$^{-1}$)) in the period 1998–2016 than in the period 1979–1998 (0.224 W·(m$^{-2}$·decade$^{-1}$)), whereas the RF$_{\text{AGG}}$ increased at a lower rate (0.338 W·(m$^{-2}$·decade$^{-1}$)) in the period 1998–2016 than in the period 1979–1998 (0.371 W·(m$^{-2}$·decade$^{-1}$)).

In the period 1998–2016, there were either warming hiatuses or slowdowns in the increases in temperature in each zone.

The PDO has a direct impact on the climate in the Pacific region and its surrounding regions (Hodgkins et al., 2017; Park et al., 2017; Wu and Mao, 2017). As shown in Figure 7, overall, the PDO was most strongly correlated with the $T_{\text{min}}$ ($R = 0.22$), followed by the $T_{\text{ave}}$ ($R = 0.19$) and the $T_{\text{max}}$ ($R = 0.09$). The correlations between the temperature metrics for each zone and the PDO weakened with decreasing latitude. Based on the changes in the time series for temperature in each zone and the PDO as well as the plot for a representative zone shown in Figure 8b, the phase of the PDO alternated between positive and negative relatively notably three times (the PDO was in a negative phase in the periods 1991–1975 and 2008–2013 and in a positive phase in the periods 1976–2007 and 2014–2016). The PDO was in a positive phase (in the period 1976–2007) in the AC year for each zone (in the period 1980–2003). At the beginning of this phase, the PDO continuously increased and reached its maximum in 1987, and the temperature in each zone continuously increased. In the period 1987–2013, overall, the PDO decreased. As the PDO continuously decreased for three to 16 years, a warming hiatus occurred in each zone. In the period 2014–2016, the PDO was in a high positive phase, and, correspondingly, the temperatures in each zone increased significantly. Different regions have different degrees and speeds of temperature response to PDO changes. When the PDO is in the positive phase and continues to increase, it will cause an abrupt change in temperature; this temperature response to changes in the PDO in different regions lags between

![FIGURE 5](image-url)  
**FIGURE 5** Spatial distributions of variation co-efficients (CVs) of the three temperature metrics for each zone in periods T1–T3.
one and 27 years. When the positive phase of the PDO continues to decrease, or the PDO phase is negative, the temperature rate of change of temperature will slow down or a hiatus will be observed. Spatially, overall, a warming hiatus occurred at an increasingly later time with decreasing latitude, suggesting a delay in the response of temperature to changes in the PDO. This finding is consistent with the conclusion drawn by Park et al. (2017).

The AMO reflects interdecadal changes in the SST of the North Atlantic Ocean. Research has found that the AMO has a significant impact on the climate of the continents surrounding the North Atlantic Ocean (Meehl et al., 2011; Cristina et al., 2015; Yamamoto and...
Palter, 2016). While China is distant from the North Atlantic Ocean, there are similar changes in China and the AMO on a millennial scale (Wang et al., 2013). As demonstrated in Figure 7, overall, the AMO was most strongly correlated with the $T_{\text{max}}$ ($R = 0.44$), followed by the $T_{\text{min}}$ ($R = 0.42$) and $T_{\text{ave}}$ ($R = 0.39$). Overall, the correlations between the AMO and the temperature metrics for each zone of northeast China (I–IV) were the weakest ($R = |0.07|–|0.4|$) and increased with decreasing latitude. Based on the changes in the time series for the temperature in each zone and the AMO as well as the plot for a representative zone shown in Figure 8c, the AMO underwent three stages. Specifically, the AMO decreased at a rate of $-0.241$ decade$^{-1}$ in the period 1951–1974, increased rapidly at a rate of $0.143$ decade$^{-1}$ in the period 1974–1998, and increased at a slower rate of $0.063$ decade$^{-1}$ in the period 1998–2016. During the stage when the AMO decreased, the temperature in each zone either decreased or increased slowly. The AMO decreased to its minimum in 1974 and subsequently started to increase. After the AMO continuously increased for three to 29 years, abrupt temperature changes occurred in each zone. Except for some individual zones, the AC years for the three temperature metrics for all the zones were all within the stage when the AMO increased rapidly. The AMO increased to its maximum in 1998 and subsequently started to increase at a lower rate. Warming hiatuses occurred in some zones in the same year and approximately nine years later in the remaining zones. Clearly, after the AMO continuously increased for a certain period of time or its rate of increase reached a certain value ($0–0.143$-decade$^{-1}$), an abrupt temperature change occurred. After 1998, the AMO increased at a lower rate, thereby contributing significantly to warming hiatuses.

In summary, in each zone, the trend of abrupt temperature increases was consistent with that of the RF$_{\text{AGG}}$ (including RF$_{\text{CO2}}$); however, after a warming hiatus occurred, the trend of abrupt temperature increases was opposite to that of the RF$_{\text{AGG}}$ (including RF$_{\text{CO2}}$). This suggests that while greenhouse gases play a significant role in temperature increases, their effects may be offset by other factors. Abrupt temperature changes and warming hiatuses or slowdowns in the increases in temperature occurred in each zone at basically the same time as the AMO increased rapidly or at a lower rate. Overall, there was, to some extent, a delay in the response to the alternation between positive and negative phases of the PDO. Overall, the comprehensive response of temperature was most sensitive to changes in the AMO, followed by those in the RF$_{\text{AGG}}$ (including the RF$_{\text{CO2}}$) and those in the PDO.

### 3.3.3 Responses of abrupt temperature changes/warming hiatuses to the second type of influencing factors

Figure 9 shows the spatial distribution of the $R$s between the three temperature metrics and the MEI and SR.
Figure 10 shows the changes in the time series for the temperatures in representative zones and the MEI and SR. Due to the limited length of this paper, zones representative of general patterns and with strong correlations ($p < 0.5$) are presented as examples.

The MEI was calculated based on six main observable variables, including the SST of the tropical Pacific Ocean and total cloud cover. Positive and negative MEIs indicate warm ENSO (El Niño) episodes and cold ENSO (La Niña) episodes, respectively. As demonstrated in Figure 9, overall, the MEI was most strongly correlated with the $T_{\text{min}}$ ($R = 0.22$), followed by the $T_{\text{ave}}$ ($R = 0.18$) and the $T_{\text{max}}$ ($R = 0.09$). Based on the changes in the time series for the temperatures in each zone and the MEI as well as the plot for a representative zone shown in Figure 10a, overall, the interannual oscillations of the temperature metrics for each zone were consistent with that of the MEI (the MEI and temperature both increased or decreased year by year), with alternating stages where the interannual oscillations of the temperature metrics for each zone for a period of two to five years were opposite to that of the MEI (temperature increased (decreased) year by year when the MEI decreased (increased)). Abrupt changes in the MEI occurred in 1976 and 2007. After the first abrupt change, the MEI increased significantly. In the period 1976–1990, the MEI tendency rate was as high as 0.541 decade$^{-1}$, which was far higher than the overall rate of increase (0.113 decade$^{-1}$). Here, the $T_{\text{min}}$ in zone V3 is used as an example. The abrupt change in the $T_{\text{min}}$ in zone V3 occurred in a later year (1990) than the first abrupt change in the MEI (1976). For the period 1990–1998, the multi-year average $T_{\text{min}}$ in zone V3 was higher than the overall average by 0.6°C. In that period, the trends of the temperature metrics were consistent with that of the MEI. Overall, the period 1990–1998 was during an El Niño stage. The AC years for the temperature metrics for each zone were mainly within the period 1990–1998.
The MEI continuously decreased (−0.37-decade⁻¹) around its second AC year, particularly in the period 1998–2014. The trends of changes in the temperature metrics for each zone were basically consistent with that in the MEI. Evidently, the first abrupt change in the MEI and its decrease in the period 1998–2014 likely contributed significantly to the abrupt changes/slowdowns in the increases in temperature or warming hiatuses.

The SR is an important driving force for the Earth’s atmospheric circulations. Research has shown that temperature is significantly correlated with changes in the SR (Chang et al., 2017). As demonstrated in Figure 9, overall, the SR was most strongly correlated with the $T_{\text{min}}$ ($R = 0.3$), followed by the $T_{\text{ave}}$ ($R = 0.21$) > $T_{\text{max}}$ ($R = 0.13$). The SR was most strongly correlated with the temperature metrics for northeast China, followed by those for northwest China. Based on the changes in the time series for the SR and the temperature metrics for each zone as well as the plot for a representative zone shown in Figure 10b, the SR underwent five stages. Specifically, it increased slowly at a rate of 0.082 MJ·m⁻²·decade⁻¹ in the period 1959–1965, decreased rapidly at a rate of −0.261 MJ·m⁻²·decade⁻¹ in the period 1965–1985, increased rapidly at a rate of 0.227 MJ·m⁻²·decade⁻¹ in the period 1985–1997, decreased steadily and slowly at a rate of −0.004 MJ·m⁻²·decade⁻¹ in the period 1997–2010, and increased sharply at a rate of 0.394 MJ·m⁻²·decade⁻¹ in the period 2010–2016. In zone II5, the trend for the $T_{\text{min}}$ was consistent with that of SR in the period 1985–2006. In the period 1985–1997, after the SR continuously increased for two to 12 years, the temperature metrics for zones underwent abrupt changes. In the period 1997–2010, while the SR decreased, the increase in temperature in some zones slowed, and warming hiatuses occurred in some other zones.

In summary, overall, the abrupt change (increase) in temperature in each zone (in the 1977–1990s period) occurred basically at the same time as the MEI and SR increased. Except for zone I, hiatuses in the increases in each of the three temperature metrics for all the zones occurred in 1998 or later, and the trends of the changes in the three temperature metrics were, overall, consistent with those in the MEI and SR. Overall, the response of temperature was less sensitive to changes in the SR than the MEI. This phenomenon was most pronounced for the $T_{\text{min}}$.

3.3.4 Responses of abrupt temperature changes/warming hiatuses to the third type of influencing factors

When a climate system is forced to cross a certain stage, it will undergo an abrupt change at a higher rate than the forcing factors (Alley et al., 2003). Temperature might have affected and been affected by changes in the WS, AP and RH, which were classified as the third type of influencing factors. In addition, the responses of temperature to changes in these influencing factors were also qualitatively and quantitatively analysed. Each influencing factor might have maintained a certain trend of changes in the periods before and after an abrupt temperature change/warming hiatus (the trend lines for these trend stages are highlighted in red in Figure 11 and, for clear illustration, are translated to nearby blank areas). Figures 13 and 14 show the spatial distributions of climate tendency rates of the influencing factors during these trend stages. Figure 12 shows the spatial distributions of the $R$ between the three temperature metrics and the WS, AP and RH. Figure 15 shows the changes in the time series of temperature in each zone and the WS, AP and RH. Due to the limited length of the present paper, only zones representative of general patterns and with strong correlations ($p < 0.5$) are presented as examples.

Based on the changes in the temperature and WS time series for each zone (Figure 11 and the plots for representative zones shown in Figure 15a1 and a2), stages having interannual oscillations of temperature consistent with that of WS alternated periodically (three to 27 years) with stages having interannual oscillations of temperature opposite to that of WS. As demonstrated in Figure 12, the temperatures in more than half the zones were significantly negatively correlated with the WS ($p < 0.01$). The average absolute value (0.56; values are presented similarly hereinafter) of the $R$ between the $T_{\text{min}}$ and WS was the highest, followed by that (0.42) between the $T_{\text{ave}}$ and WS and that (0.35) between the $T_{\text{max}}$ and WS. Overall, in the approximate 1970–1990s period, the WS continuously decreased, which was closely related to the increase in temperature. In the period 1990s–2000s, except for some individual zones (e.g. zone I), the WS in each zone, overall, decreased at a lower rate or even increased. In the same period, temperature generally remained unchanged. As shown in Figure 13, as the WS decreased, the temperatures in most zones increased (the trend of the changes in temperature was opposite to that of the WS). After the WS continuously decreased for 5–30, 4–23 and 3–26 years, the tendency rate reached −0.94 to −0.11, −0.79 to −0.11, and −0.35 to −0.16 m·(s⁻¹·decade⁻¹), and abrupt changes in the $T_{\text{min}}$, $T_{\text{ave}}$ and $T_{\text{max}}$ occurred, respectively. Temperatures in the southeastern zones of the study area increased as the WS increased (the trend of changes in temperature was consistent with that of WS). For example, in zones II5, III and IV2, after the WS continuously increased for 4–24, 3–9 and 3–11 years and the tendency rate reached 0.12–1.21, 0.07–0.69, and 0.1–2.7 m·(s⁻¹·decade⁻¹), abrupt changes in the $T_{\text{min}}$, $T_{\text{ave}}$ and...
FIGURE 11  Changes in the normalized
time series for temperature and each
influencing factor

Legend:
- Wind speed
- Atmospheric pressure
- Relative humidity
- Trendline (T1,T2,T3 period)
- AC year
- Trend segment of each driver before temperature mutation or warming hiatus
- WH year
$T_{\text{max}}$ occurred, respectively. Similarly, as shown in Figure 14, the decrease in WS slowed before and after a hiatus in the increase in temperature. After the WS continuously decreased for 4–24, 4–18 and 4–16 years and the tendency rate reached −0.6 to −0.01, −1.12 to −0.02, and −1.63 to −0.02 m (s$^{-1}$-decade), hiatuses in the increases in the $T_{\text{min}}$, $T_{\text{ave}}$ and $T_{\text{max}}$ occurred, respectively.

Based on the changes in the temperature and AP time series for each zone (Figure 11 and the plots for representative zones shown in Figure 15b1 and b2), peak (valley) temperature was strongly correlated with peak (valley) AP. For some zones, the AP time series for a one to five years later period was most strongly correlated with the temperature time series. For example, for zone IV2 shown in Figure 15b1, the AP time series for a five years later period was most strongly correlated with the temperature time series ($R = 0.81$) and was stage-wise symmetrically distributed. The temperatures in each zone were generally negatively correlated with AP. The average $R$ (0.32) between the $T_{\text{min}}$ and AP was the highest, followed by that (0.29) between the $T_{\text{ave}}$ and AP and that (0.23) between the $T_{\text{max}}$ and AP. Before and after an abrupt temperature change or warming hiatus, the AP in some zones, overall, decreased, and the trends of their changes were opposite to that of temperature; an opposite
phenomenon was observed for some other zones. Based on Figure 13, during a stage where the trend of changes in temperature was opposite to that in AP, after AP continuously decreased for 3–14, 3–11 and 4–15 years and the tendency rate reached −0.25 to −0.03, −0.67 to −0.07, and −0.36 to −0.01 hPa-decade$^{-1}$, abrupt changes in the $T_{\text{min}}$, $T_{\text{ave}}$ and $T_{\text{max}}$ occurred, respectively. During a stage where the trend of changes in temperature was consistent with that in AP, after AP continuously increased for 5–35, 3–20 and 5–29 years and the tendency rate reached 0.02–0.39, 0.02–1.18, and 0.01–4.63 hPa-decade$^{-1}$. Similarly, as shown in Figure 14, before a warming hiatus, the AP in each zone generally decreased, except for some individual zones. After the AP continuously decreased for 5–15, 4–19 and 4–19 years and the tendency rate reached −0.94 to −0.04, −0.63 to −0.04, and −1.56 to −0.05 hPa-decade$^{-1}$, hiatuses in the $T_{\text{min}}$, $T_{\text{ave}}$ and $T_{\text{max}}$ occurred, respectively. Based on the changes in the temperature and RH time series for each zone (Figure 11 and the plots for representative zones shown in Figure 15c1 and c2), for most zones, overall, the trend of changes in temperature was opposite to that in RH, and the interannual oscillation of temperature was also opposite to RH. In the 1950s and 1985–2000s period, the trend of changes in temperature was consistent with that in RH.

Overall, the RH was most strongly correlated with the $T_{\text{max}}$ ($R = 0.44$), followed by the $T_{\text{ave}}$ ($R = 0.42$) and $T_{\text{min}}$ ($R = 0.27$). Similar to the WS, there were stages where the trend of changes in RH was consistent with that in temperature as well as stages where the trend of changes in RH was opposite to that in temperature. Based on Figures 13 and 14, during a stage where the trend of changes in RH was opposite to that in temperature, after the RH continuously decreased for 3–15, 2–8 and 3–10 years and the tendency rate reached −1.19 to −0.31, −2.26 to −0.49, and −1.12 to −0.28%·decade$^{-1}$, abrupt changes in the $T_{\text{min}}$, $T_{\text{ave}}$ and $T_{\text{max}}$ occurred, respectively. During a stage where the trend of changes in RH was consistent with that in temperature, after the RH continuously increased for 2–9, 3–10 and 3–9 years and the tendency rate reached 0.08–1.89, 0.12–2.56, and 0.06–1.01%·decade$^{-1}$, abrupt changes in the $T_{\text{min}}$, $T_{\text{ave}}$ and $T_{\text{max}}$ occurred, respectively. Similarly, before and after a warming hiatus, overall, the RH decreased. After the RH continuously
decreased for 4–18, 7–17 and 4–16 years and the tendency rate reached −1.85 to −0.11, −0.41 to −0.11, and −0.66 to −0.07%·decade⁻¹, hiatuses in the increases in the \( T_{\text{min}} \), \( T_{\text{ave}} \) and \( T_{\text{max}} \) occurred, respectively. Dong et al. (2000) found that the absorption capacity of aerosols for visible radiation (the main component of SR) decreases with decreasing RH. Therefore, an abrupt temperature change might be indirectly related to a decrease in RH.

In summary, before and after an abrupt temperature change/warming hiatus, the trend of changes in temperature was either consistent with or opposite to those in the WS, AP and RH; in addition, stages where the trend of changes in temperature was consistent with those in the WS, AP and RH periodically alternated with stages where the trend of changes in temperature was opposite to those in the WS, AP and RH. This suggests that these three influencing factors might have contributed insignificantly to changes in temperature. Overall, the response of temperature was most sensitive to changes in the WS, followed by those in the RH and AP.

Overall, from the late 1970s to the 1990s, as the RF\(_{\text{AGG}}\) continuously increased, the PDO was in a positive phase, the AMO and SR continuously increased, the WS, AP and RH in each zone continuously decreased/increased and subsequently their trends changed, and abrupt temperature changes occurred in each zone. Before an abrupt temperature change, the trend of changes in temperature in each zone was either consistent with or opposite to that in each influencing factor. Overall, the trend of changes in temperature was consistent with that in the global averages of each influencing factor. In the 1990s, particularly after 1998, as the increase in the AMO slowed, the MEI and SR decreased, the PDO continuously decreased or was in a negative phase, the WS, AP and RH in each zone continuously decreased/increased, and subsequently their trends changed, and the increase in temperature slowed or a warming hiatus occurred in each zone. Overall, abrupt changes/hiatuses in the increases in the three temperature metrics in each of zones were affected by a combined action of the influencing factors.
4 | DISCUSSION

Abrupt temperature changes mainly occurred in each zone of northern China in the period 1980s–1990s. Warming hiatuses occurred in most zones in the 1990s or around 2007. Continuous increases in temperature occurred in some zones. Overall, warming hiatuses occurred in northern China at a later time than the global warming hiatus (1998) (Carter, 2006). Abrupt temperature changes and warming hiatuses both occurred on a global scale. For example, a notable warming occurred in France in the spring of 1987/1988 (Brulebois et al., 2015), abrupt temperature changes occurred in Central Asia (Hu et al., 2015) and northeast Asia (Dong et al., 2016) in the 1980s and after the mid-1990s, respectively, and the increase in the global temperature was close to zero in the period 1999–2008 (Wang et al., 2010). Overall, global-scale abrupt temperature changes and warming hiatuses occurred at basically the same time as those in the study area.

Overall, temperature in each zone of northwest China was strongly correlated with the RFAGG, MEI and AP, temperature in each zone of north China was strongly correlated with the RFAGG and AMO, and temperature in each zone of northeast China was strongly correlated with the PDO, SR, WS and RH. Before an abrupt temperature change or warming hiatus, the trend of changes in temperature was either consistent with or opposite to that in each influencing factor. After each influencing factor continuously increased/decreased and its rate of change reached a certain value, an abrupt temperature change or warming hiatus occurred. This also suggests that more than one factor affects abrupt temperature changes or warming hiatuses. In addition, the effects of different influencing factors on temperature changes might be cancelled out or superimposed. Abrupt changes in temperature and hiatus of warming are the result of a combination of human activities (Frolischer et al., 2014) and natural factors (Chen et al., 2015). Abrupt temperature changes are also a result of human and natural factors. For example, the notable wintertime warming in China was related to a natural factor, the warm phase of the AMO (Li et al., 2009); greenhouse gases, particularly CO₂, which are human factors, contribute significantly to global warming (Petit et al., 1999), and the response of temperature to the increase in the atmospheric CO₂ concentration is not overestimated (Ma et al., 2017). Currently, there are two main theories regarding the warming hiatus mechanism, namely external forcings and natural variability. In recent years, there have been many explanations for the hiatus of temperature warming in some areas. In terms of internal climate system variability, El Niño and La Niña (Banholzer and Donner, 2014; Chen et al., 2015), and the AMO are closely related to the stagnation of temperature warming (Chylek et al., 2014), and external variables such as volcanic eruption (Hawkins et al., 2014) and S emission (Kaufmann et al., 2011) also play an important role. In the present study, the responses of abrupt temperature changes and warming hiatuses to changes in a range of influencing factors were quantitatively and qualitatively analysed. The results obtained can provide a reference for investigating the climate change mechanism.

Due to the limited length of the data series used the present study, there are limitations and deficiencies in the analysis of the responses of long-term abrupt temperature changes/warming hiatuses to changes in their influencing factors. There are certain limitations or uncertainties in regard to treating cooling stages as warming hiatus stages. In other words, a slight decreasing trend of a temperature series within a short period of time is not a sufficient indication of a warming hiatus. Some researchers are sceptical of this view (Kerr, 2009; Beniston et al., 2015; Karl et al., 2015; Wei et al., 2015). Due to the limited length of the present paper, analysis was only conducted based on interannual series. Some influencing factors might have more significant effects on temperature on a seasonal (monthly) scale. Therefore, this affected the results to some extent. In addition, the incomprehensiveness of the selected influencing factors also affected the results to some extent. In view of this, more in-depth research focusing on temperature and several its influencing factors on seasonal and monthly scales will be conducted in future based on physical and chemical mechanisms.

5 | CONCLUSIONS

- Overall, the abrupt change in the average minimum temperature (Tmin) in each zone occurred earliest (1977–1998), followed by the average temperature (Tave) (1980–2002) and average maximum temperature (Tmax) (1988–2004). Abrupt changes occurred at increasingly later times in the zones from north to south and from west to east. Warming hiatuses occurred mainly in 1998 and around 2007. Overall, the response of the Tmax to cooling was the most pronounced (−0.32°C·decade⁻¹). Zones where no warming hiatus occurred were mainly distributed at low latitudes.

- The radiative forcing of annual greenhouse gases (RFAGG), Pacific decadal oscillation (PDO), multivariate El Niño southern oscillation (ENSO) index (MEI), total solar radiation (SR), wind speed (WS) and atmospheric pressure (AP) were most strongly correlated
with the $T_{\text{min}}$, but least strongly correlated with the $T_{\text{max}}$. The relative humidity (RH) was most strongly correlated with the $T_{\text{max}}$, followed by the $T_{\text{ave}}$. Temperature in northwest China was strongly correlated with the RFAGG, MEI and AP, whereas temperature in north China (northeast China) was, overall, strongly correlated with the RFAGG and AMO (WS, PDO, SR and RH).

- Overall, from the late 1970s to the 1990s, the RFAGG continuously increased, the PDO was in a positive phase, the AMO and SR continuously increased, the MEI changed abruptly, and the WS, AP and RH in each zone continuously decreased/increased, and their trends changed subsequently. After each influencing factor continuously increased/decreased for a certain period of time and the tendency rate reached a certain value, an abrupt temperature change occurred. In the 1990s, particularly after 1998, the increase in the AMO slowed, the PDO certain value decreased or was in a negative phase, the MEI and SR decreased, and the WS, AP and RH in each zone continuously decreased/increased, and their trends changed subsequently. After each influencing factor continuously increased/decreased for a certain period of time and the tendency rate reached a certain value, a warming hiatus occurred. For example, after the AMO and WS continuously increased for 3–29 and 4–24 years, respectively, and the tendency rate reached 0.12–1.21 m/(s$^{-1}$.decade), an abrupt change in the $T_{\text{min}}$ occurred in each zone.

- The sensitivity of responses of $T_{\text{min}}$ to changes in the three types of influencing factors was the highest, followed by those of the $T_{\text{ave}}$ and $T_{\text{max}}$. Overall, the temperature response in each zone was most sensitive to changes in the first type of influencing factors (particularly the AMO), followed by those in the second type of influencing factors (particularly the MEI) and those in the third type of influencing factors (particularly the WS).

- There is a strong spatial–temporal difference in the effects of various influencing factors on the three types of temperature, which leads to the great spatial difference in the three types of temperature abrupt change and the year of warming hiatuses, which provides a reference for the study of regional temperature mutation and the mechanism of stagnation of warming and the prediction of future temperature.

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