Development of a Winter Abnormal Cold Climate Index and Its Influencing Factors

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Research Article

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Posted Date: March 22nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-312902/v1

Development of a Winter Abnormal Cold Climate Index and Its Influencing Factors

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Abstract: The prediction of extreme weather and climate events is a difficulty in the field of climate prediction. In practice, seasonal and monthly mean temperature has been used as the climate prediction index. However, the mean temperature forecast on seasonal and annual time scales cannot truly reflect the real climate situation as the mean temperature on a certain time scale smoothes abnormal cold and warm climate events. For instance, an abnormal cold climate event may occur even if the winter mean temperature is forecasted to be normal in a certain year. An abnormal warm climate event may also occur at the same time. Both affect the accuracy of climate prediction. Based on extreme weather events, this paper constructs a winter abnormal cold climate index, named WACCI, to represent the characteristics of extremely low temperature events. The index is composed of three factors, including cold duration, extremely cold temperature anomaly, and temperature cumulative anomaly. Taking Heilongjiang Province in China as the study area, relationships between WACCI and winter mean temperature, atmospheric circulation, and sea surface temperature (SST) are analyzed and compared. The analysis shows that the polar and mid-high latitude circulations have a significant impact on WACCI. The meridional circulation is dominant in the mid-high latitudes of Eurasia when the polar vortex area in the Northern Hemisphere is large, the intensity of the polar vortex is weak, and the polar vortex splits southward. Additionally, the intensity of the East Asian trough is strong and arctic oscillation (AO) is in an abnormal negative phase, which tends to result in a large WACCI. According to those atmospheric circulation factors, the regional and even global abnormal cold climate can be predicted in practice instead of using the prediction of winter mean temperature. The abnormal cold climate index proposed in this paper provides a new way for the extreme climate event occurrence trend, mechanism research, and short-term climate prediction (i.e., monthly or seasonal).

Key words: abnormal cold climate index, atmospheric circulation factors, sea surface temperature index of key regions, Heilongjiang Province

1 INTRODUCTION

Under the background of global warming, there are various types of short-term and regional abnormal changes in the global climate system. In recent years, regional low temperature extreme events (RELTEs) occur frequently in the Northern Hemisphere with large impact range and long duration. For example, an extremely rare national low temperature extreme event occurred in China in January 2011. The wide range and long duration of the event made it the most significant event since 1977 (Hu et al., 2007). Since RELTEs occur more frequently and can result in huge disasters, better methods to detect RELTEs are needed. (Wu et al., 2017; Zhai et al., 2007; Wang et al., 2013; Gong and Wang, 2010; Zhai and Pan, 2003; Wang et al., 2004; Katz and Brown, 1992). At present, the prediction of long-term temperature change on seasonal and annual scales is mainly based on the seasonal and annual mean temperature which, however, can only reflect the average situation in a certain period. If there are strong low and high temperature extreme events in this period, the mean temperature would smooth out the extreme temperature signal. Therefore, the mean temperature cannot truly reflect the occurrence of extreme climate events. There are many past studies on the detection, diagnosis, and analysis of extreme climate events in China and abroad (Alexander et al., 2006; Soltani et al., 2016; Fu et al., 2011; Wang et al., 2014; Li et al., 2014; Wang and Ding, 2006). Nevertheless, the prediction of extreme climate events is still weak, especially for the seasonal and annual low temperature extreme events with long time scales. Meanwhile, the atmospheric circulation situation of cold and warm extreme events are different in the atmospheric circulation system. If the mean temperature is taken as the prediction index of extreme climate events, two possibly opposite atmospheric circulation index signals would be mixed and make it difficult to reveal the mechanism of atmospheric circulation affecting extreme climate events. Hence, if an abnormal extreme climate index could be constructed to separate low temperature extreme events from high temperature extreme events, it should realize the forecast and prediction of extreme climate events and promote the progress of climate operations. Furthermore, it should be able to objectively reflect the distribution and change of extreme climate events and reveal the occurrence mechanism of extreme climate events.

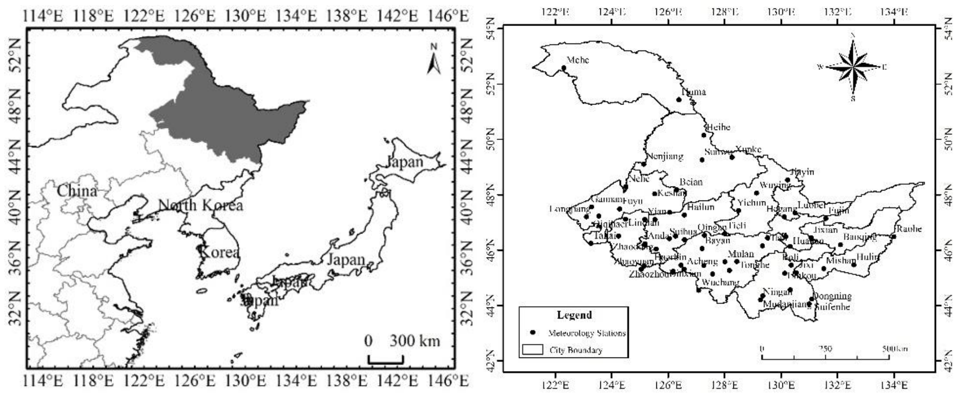
An extreme climate event refers to the occurrence of an abnormal climate variable value which is higher (or lower) than a certain threshold near the upper (or lower) end of the observation range of the variable (Stocker et al., 2013). Extreme temperature events are one kind of extreme climate events. There are currently three main types of detection and diagnosis of extreme temperature events, including absolute critical value method (Zhou and Ren, 2011), percentile method (Li et al., 2011; Sun et al., 2016; Wei et al., 2016; Choi et al., 2009), and standard deviation method (Qian et al., 2007; Pan et al., 2020). The absolute critical value method is to select a certain critical meteorological element value which affects human or living things. For instance, if the daily maximum temperature is higher than 35°C, it is defined as a high temperature extreme event. If the daily minimum temperature is lower than 0°C, it is defined as a low temperature extreme event. The percentile method is defined relative to the percentile critical values of the local climate state, that is, the small probability events counted from the perspective of probability distribution (Bonsal et al., 2001). To be specific, this method is to arrange the mean temperature of a certain period in an ascending order and take the 90th and 10th percentiles as the threshold values of extreme temperature events. If the temperature is greater than the 90th percentile value, it is considered that there is a high temperature extreme event in that year. If it is less than the 10th percentile value, it is considered that there is a low temperature extreme event in that year. Last but not least, the standard deviation method uses the standard deviation of $\pm n$ times of the mean value of regional temperature to determine the threshold value. The value of n depends on the distribution of specific values (Qian et al., 2007). The three methods have a common feature where they all can diagnose the frequency of extreme temperature events but cannot express the degree of extreme temperature events. Therefore, in addition to frequency, the abnormal extreme climate index should include the degree of abnormal extreme climate events.

The paper constructs a comprehensive extreme climate event based on the frequency and degree of extreme weather events. The extreme cold climate events are separated from the extreme warm climate events. The seasonal scale is defined to represent the WACCI of winter low temperature extreme events. Besides, the paper analyzes the long-term change trend of low temperature extreme event index, reveals the impact mechanism of atmospheric circulation factors and external forcing of SST on the index, provides a new idea to realize monthly and seasonal short-term climate prediction, and promotes the climate prediction operations. Also, the paper provides a new method to study the distribution and change trend of extreme climate events under the background of climate change and to reveal its mechanism. Moreover, the paper illustrates the advantage of WACCI, taking Heilongjiang Province in China as an example.

2 BRIEF INTRODUCTION OF HEILONGJIANG PROVINCE IN CHINA

Heilongjiang Province, located in northeastern China (121°11’–135°05’E, 43°26’–53°33’N), is the most northerly territory of the country (Fig. 1). It borders Russia in the north along Heilongjiang River.

Characterized with a temperate continental monsoon climate. Impacted by the geographical environment, sea-land air mass, and monsoon alternation, it has long, cold winters and short summers. The annual average temperature ranges from −4°C and 5°C from north to south of the study area. Its annual total precipitation is around 400–650 mm that gradually decreases from east to west. Relevant research shows that cold winters frequently occur in Heilongjiang Province in recent ten years. There are five consecutive years of cold winters in Heilongjiang Province from 2009 to 2013 (Song et al., 2011; Li et al., 2010; Li et al., 2011). In the winter of 2017, there were multiple cold wave weather. Besides, the lowest temperature in the same period since records was recorded at several stations (Ban et al., 2019).



(a) (b)

Fig. 1 Maps showing the location of Heilongjiang Province within northeastern China (a) and its administrative subdivisions (b).

3 DATA

Below are data used in this study:

(1) Daily mean temperature, provided by the Heilongjiang Meteorological Observatory first established in 1951. Since then, 83 stations have been built, which are divided into the national standard meteorological observation stations, national basic meteorological observation stations, and general meteorological observation stations. According to the requirements of data continuity and the number of stations needed for analysis, 61 stations with continuous and complete observation data since 1961 are selected. The spatial distribution is shown in Fig. 1b. The basic data used in the study are daily temperature data. The time scale is from January 1961 to February 2018. Plus, the research period is winter which is defined as November of the current year to February of the next year.

(2) Global grid data of 500 hPa geopotential height field on monthly scale, using the NCEP/NCAR reanalysis data, resolution of 2.5° × 2.5°, and time scale from December 1961 to February 2019. Data are from the U.S. National Oceanic and Atmospheric Administration. Registered download at website https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html.

(3) Global grid data of SST on monthly scale, utilizing the NOAA extended reconstruction of SST data set (ERSSTv4), resolution of 2.0° × 2.0°, and time scale from December 1959 to February 2019. Data are from the U.S. National Oceanic and Atmospheric Administration. Registered download at website https://psl.noaa.gov/data/gridded/data.noaa.ersst.v4.html

(4) Arctic oscillation index (AO). Data are from the U.S. Climate Prediction Center (CPC) with a time scale from December 1961 to February 2019. The data download address is as follows: https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii.table.

(5) Monthly atmospheric circulation index, derived from the National Climate Center of China Meteorological Administration. Circulation indices include the area and intensity of polar vortex in the Northern Hemisphere and Asia, the zonal circulation index in Eurasia, and the position and intensity of the

East Asian trough. The time scale is from December 1961 to February 2019.

4 RESEARCH METHOD

4.1 Pearson correlation coefficient

The Pearson correlation coefficient is a commonly used indicator to describe the degree of correlation between climate variables (Jia, 2018). Let $(x_1, y_1),(x_2, y_2)...(x_n, y_n)$ be the n pairs of observation values of the two-dimensional climate variable (X, Y), then their Pearson correlation coefficient r is

$$r = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n} (Y_i - \bar{Y})^2}} \quad (1)$$

where $\bar{X}$ and $\bar{Y}$ are the mean values of sequences X and Y, respectively. The value range of r is $0 \leq |r| \leq 1$. The size of r reflects the strength of the linear relationship between two variables. The larger $|r|$, the closer the linear correlation; the smaller $|r|$, the weaker the linear correlation. In addition, if r is positive, it means positive correlation; if r is negative, it means inverse correlation.

4.2 Trend analysis

Trend analysis on the time series of snowfall amount was carried out by the linear trend estimation method:

$$y = ax + b \quad (2)$$

where a and b are constants, and x represents the year. The trend coefficient a and the regression coefficient b are obtained by least squares. The value of a being positive or negative represents the direction of the data series change with time, and the absolute value of a represents the rate of change.

5 RESULTS

5.1 Construction of WACCI

In the paper, the cold duration days (τ, *d*), extremely cold temperature anomaly (t_m, °C), and temperature cumulative anomaly (t_a, °C) were selected to construct the WACCI.

(1) Determination method of cold duration days (τ) in a certain year: τ was based on historical long sequences of daily temperature data. First, the standard deviation method was used to select the winter abnormal cold climate events in Heilongjiang Province. Next, the accumulated days of winter abnormal cold climate events were calculated. The specific method was to calculate the daily mean temperature and standard deviation of the historically recorded daily mean temperature sequences (from 1961 to 2018 in the paper). The mean value was subtracted from daily temperature values in order to obtain the anomaly sequence (Δt) and calculate the sequence standard deviation (σ). In the sequence, an abnormal cold climate event was defined if the negative anomaly was more than 1 time of standard deviation ($\Delta t > \sigma$) in the daily mean temperature anomaly sequence for 5 consecutive days. If there were multiple winter abnormal cold climate events in a certain year, the accumulated days of all abnormal cold climate events were calculated. If there was no abnormal cold climate event, the one with the longest duration of negative daily temperature anomaly was selected as the general cold climate event and the duration days were calculated. Lastly, the duration was 0 if the winter mean daily temperature anomaly was positive.

(2) Determination method of extremely cold temperature anomaly t_m in a certain year: In winter abnormal cold climate events in a certain year, the temperature anomaly on the day with the lowest daily temperature

was selected as the extremely cold temperature anomaly. If there was no winter abnormal cold climate event, the temperature anomaly was calculated on the day when the temperature was the lowest in the same period of history and was defined as an extremely cold temperature anomaly. Lastly, the term was 0 if the winter mean daily temperature anomaly of a certain year was positive.

(3) Determination method of temperature cumulative anomaly t_a in a certain year: The temperature cumulative anomaly of all the days in a winter abnormal cold climate event was calculated. If there was no winter abnormal cold climate event, the days of a general cold climate event were selected to calculate the temperature cumulative anomaly. The term was 0 if the winter daily temperature anomaly was positive.

S_t, S_{tm}, and S_{ta} were obtained after standardizing τ, t_m, and t_a. The WACCI was constructed as follows:

$$\text{WACCI}=S_{\tau}-S_{tm}-S_{ta} \quad (3)$$

It can be seen from Equation (3) that the greater the WACCI in a certain year, the greater the intensity of winter abnormal cold climate events in that year.

5.2 Application of WACCI

The WACCI was an important indicator of climate change. Fig. 2 shows the variation trend of WACCI and winter mean temperature in Heilongjiang Province from 1961 to 2018, taking Heilongjiang Province as an example. As can be seen in Fig. 2, the WACCI of Heilongjiang Province appears to have had a very significant downward trend from 1961 to 2018 with a trend value of −0.56/10 a ($P < 0.01$). A very significant upward trend was observed for the winter mean temperature in Heilongjiang Province from 1961 to 2018 with a trend value of 0.258°C/10 a ($P < 0.01$). It can be seen that the winter mean temperature in Heilongjiang Province increased significantly from 1961 to 2018. The winter mean temperature in recent 10 years rose by 1.29°C compared with that in the 1960s, while the WACCI dropped significantly with a decline of 2.8 in recent 10 years compared with that in the 1960s. The correlation coefficient was −0.79 ($P < 0.05$) which was a significantly negative correlation. Therefore, the accelerated reduction of abnormal cold climate events was one of the reasons for the significant increase of winter temperature. In other words, the winter temperature warming in Heilongjiang Province was caused by the reduction of extreme cold climate events. Hence, the WACCI constructed in the paper is an important indicator of climate change.

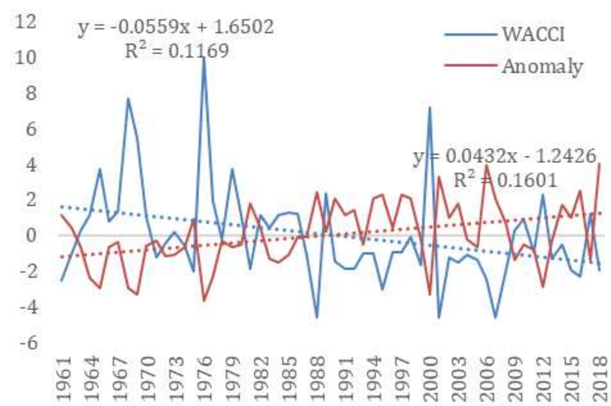


Fig. 2 Change chart of WACCI and winter temperature in Heilongjiang Province from 1961 to 2018

The WACCI and temperature anomaly values were further compared. It can be seen from Fig. 3 that the temperature in the 1960s and 1970s was low in winter and the WACCI appeared to be large for multiple consecutive years. Starting from the mid-1980s, the winter temperature in Heilongjiang Province turned to a warm background. Meanwhile, the corresponding WACCI turned to a small trend. Besides, the interdecadal variation trends of the two were consistent while there were certain differences in the interannual changes. It can be seen from the regression equation:

$$\Delta T=-0.523+0.031WACCI,\ R^2=0.629,\ P<0.01 \tag{4}$$

It indicated that WACCI determined 63% of ΔT. However, 37% of ΔT was not determined by WACCI, which meant it may occur that ΔT was small in the year of large WACCI. For example, the WACCI values in 1989 and 1982 were 2.33 and 1.16 respectively, ranking the 7th and 14th in history. It showed that the strong cold air activity led to the strong intensity of abnormal cold climate events in Heilongjiang Province. Yet the winter temperature was 0.2°C and 0.4°C respectively, which belong to years with normal to slightly high winter temperature. The WACCI values in 2005, 2011, and 1999 were all less than −0.9, which were weak years of abnormal cold climate events in Heilongjiang Province. However, the winter temperature was slightly low or low. Furthermore, the WACCI value was −0.45 in 1972, indicating that the occurrence of abnormal cold climate events in Heilongjiang Province was weak while the winter temperature anomaly in that year was −1.2°C. It can be concluded that the WACCI constructed in the paper did not completely match the winter temperature. Therefore, it revealed that there may be abnormal warm events in mismatched years. The abnormal warm events offset the impact of abnormal cold events. Another possibility is that the intensity and frequency of abnormal warm events were weaker than the intensity and frequency of abnormal cold events, which further proved that it was unscientific to use winter mean temperature to express winter abnormal cold and warm events. The degree and trend of temperature extreme change can be objectively reflected if abnormal cold events were separated from abnormal warm events.

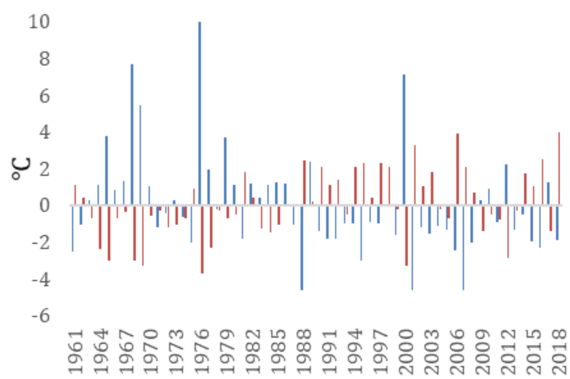


Fig. 3 WACCI and temperature anomalies

5.3 Relationship between WACCI and atmospheric circulation field

5.3.1 Relationship comparison between WACCI and 500 hPa winter height field

Fig. 4(a) shows the distribution of correlation coefficients between WACCI and the intensity of the 500 hPa height field in the same period. A correlation distribution pattern of "−, +, −" in the mid-high latitudes of Eurasia and a positive correlation in the Arctic polar region is shown. In addition, most regions except the North Pacific and Ural Mountains had a negative correlation between 40°N and 60°N. The majority of the regional correlation coefficients passed the significance test ($P < 0.05$). The analysis explained that the intensity of the polar vortex center was weak when the positive altitude anomaly occurred at 500 hPa in the Arctic. The polar vortex center was easy to split southward, which led to the anomaly distribution pattern of "positive in the North and negative in the South" in the height field. At this time, frequent cold air activities easily resulted in strong cooling in Heilongjiang Province.

Fig. 4(b) shows the distribution of correlation coefficients between winter mean temperature and 500 hPa height field in the same period. The correlation between the distribution characteristics and WACCI was consistent in the mid-high latitudes. However, the correlation coefficients in subtropical low latitudes were quite different than those in Fig. 4(a), i.e., the correlation between the winter mean temperature and most regions north of the equator passed the significance test ($P < 0.05$). This result indicated that the low latitude system also had an impact on the temperature, in addition to the mid-high latitude circulation system. However, the low latitude system had small impact on WACCI. Therefore, compared with winter mean temperature, factors affecting the WACCI were fewer and WACCI prediction is less difficult.

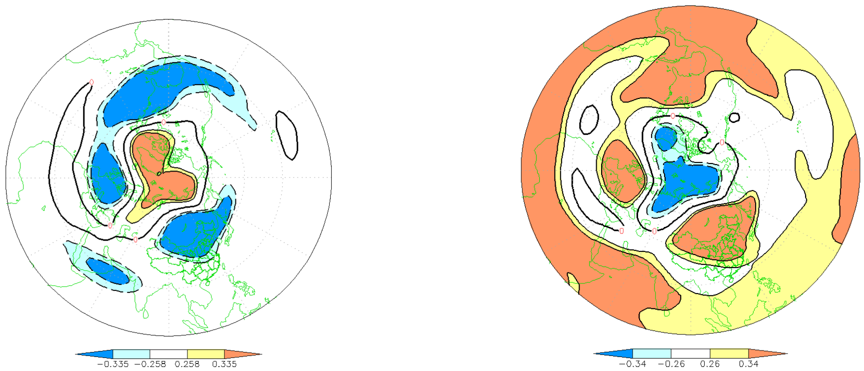


Fig. 4 Correlation distribution between 500 hPa height field and WACCI (a), temperature (b) in Heilongjiang Province during 1961–2018

5.3.2 Relationship comparison between WACCI and AO

AO reflects the reverse variation of sea level pressure over the Arctic and middle latitudes. After AO was proposed by Thompson and Wallace in 1998 (Thompson and Wallace, 1998), many scholars studied the climate in East Asia (Gong and Wang, 2010; Song et al., 2011; Li et al., 2010; Li et al., 2011; Ban et al., 2019; Shen, 2013; Qiao et al., 2014). It was concluded that AO affected the East Asian monsoon by affecting the Siberian high, though East Asia is far away from the north pole. In terms of dynamic mechanism, when the AO phase was positive, the polar vortex was strengthened and the westerly belt in the middle latitudes was strengthened and northerly. The cold air was confined in the polar region, which was easy to cause a warm winter in East Asia. When the AO phase was negative, the corresponding polar vortex weakened and the westerly belt in the middle latitudes weakened and moved southward. The Arctic cold air easily erupted southward, affecting North America, Europe, and Asia.

It can be seen from Fig. 5 that WACCI and AO had a significant negative correlation. The correlation coefficient was −0.61 ($P < 0.01$). AO was significantly in the negative phase and WACCI was in a strong stage from the 1960s to the middle and late 1980s. From the middle and late 1980s to the end of 1990s, AO was mainly in the positive phase while WACCI correspondingly appeared in a weak stage. After the 21st century, AO fluctuated significantly. There was a reverse relationship between WACCI and AO in 15 a of the total 19 a from 2000 to 2018. It can be seen that the variation of the mid-high latitude circulation system was an essential factor affecting WACCI in Heilongjiang Province. When AO was in the negative (positive) phase, the distribution pattern of geopotential height field in the mid-high latitudes of the Northern Hemisphere was the opposite. That is, the polar region was positive (negative) and negative (positive) height anomaly occurred from the south of the polar region to the subtropical zone. This distribution pattern was beneficial (unfavorable) to the transportation of cold air to Heilongjiang Province, which led to the occurrence (no occurrence) of abnormal cold climate events.

The relationship between WACCI, winter mean daily temperature, and AO was further compared. The AO was divided into strong and weak degrees. AOs greater than 1 (less than −1) were marked as abnormal positive (negative) phase and the rest were normal positive (negative) phase. From 1961 to 2018, there were 8 a with the abnormal positive phase of AO. In the 8 a, WACCI was less than −2 for 6 a while the winter mean temperature anomaly was more than 2°C for only 3 a. There were 14 a with the abnormal negative phase of AO. In the 14 a, WACCI was greater than 2 for 6 a while the winter mean temperature anomaly was less than −2°C for 8 a. It can be seen that when AO appeared in the abnormal positive phase, its indicative significance for WACCI was stronger than that for winter temperature. In the special six years (1989, 1982, 2005, 2011, 1999, and 1972) that had large differences between WACCI and temperature anomaly, both AO and WACCI showed a significant reverse relationship in 2011, 1999, and 1972. Specifically, AO was positive while WACCI was negative, which further indicated that the positive phase of AO had a strong indicative significance for the negative WACCI.

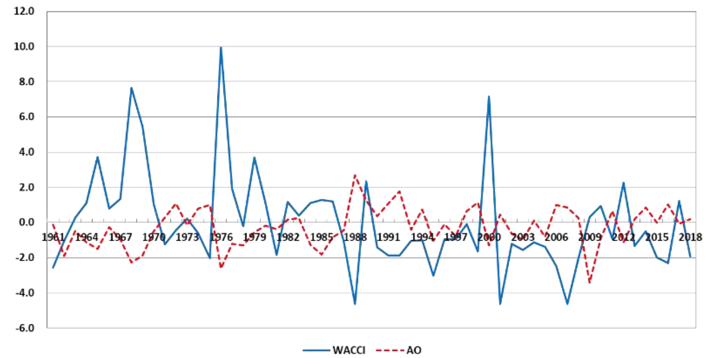


Fig. 5 Annual change curve of AO and WACCI in Heilongjiang Province from 1961 to 2018

5.3.3 Relationship comparison between WACCI and the atmospheric circulation indexes

Based on the correlation analysis of 88 atmospheric circulation indices and WACCI, several atmospheric circulation indices were selected ($P < 0.01$), including polar vortex area index in the Northern Hemisphere, polar vortex center intensity index in the Northern Hemisphere, Eurasian zonal circulation index, and East Asian trough intensity index. Their correlation coefficients with WACCI were 0.51, 0.41, −0.42, and −0.46, respectively. In addition, the correlation coefficients between winter mean temperature and four indices were −0.48, −0.34, 0.57, and 0.48, respectively. It can be seen that the correlation between WACCI and the polar vortex area index and the polar vortex center intensity index was better than that of temperature. The correlation between temperature and Eurasian zonal circulation index was stronger than that of WACCI. Moreover, correlations between the East Asian trough intensity index and WACCI and temperature were similar. From the perspective of physical mechanism, when the polar vortex area in the Northern Hemisphere was large, the polar vortex center intensity was weak, the meridional circulation was dominant in the mid-high latitudes of Eurasia, and the intensity of East Asian trough was strong. As a result, it was conducive to a large WACCI. Specifically, when the polar region was controlled by positive height anomaly, the polar vortex intensity was weak and the polar vortex split southward. At this time, the meridional circulation appeared in the mid-high latitudes of Eurasia and the East Asian trough was significantly established. Heilongjiang Province was located behind the ridge front trough and controlled by the northwest airflow, which were conducive to the transportation of cold air to Heilongjiang Province. Consequently, it caused strong abnormal cold climate events and made WACCI large. Hence, the corresponding relationship between WACCI and atmospheric circulation index was better than that of mean temperature.

The responses of WACCI and winter temperature to the above circulation indices (the polar vortex area index in the Northern Hemisphere, the polar vortex center intensity index in the Northern Hemisphere, the zonal circulation index in Eurasia, and the East Asian trough intensity index) were analyzed by using specific examples. As shown in Table 1, except for the East Asian trough intensity index, the corresponding relationships between WACCI and the other three factors in abnormal years were better than that of winter temperature. Through the analysis of special years (1989, 1982, 2005, 2011, 1999, and 1972), it was found that the polar vortex area index in the Northern Hemisphere corresponded to WACCI for 5 a in those 6 a. Furthermore, the corresponding relationship was better than that of winter temperature.

Table 1 Years of the relationship between the winter abnormal cold climate index (WACCI) and atmospheric circulation

Factors	Abnormal	Years corresponding	Years corresponding

	years (a)	to WACCI (a)	to temperature (a)
Polar vortex area index in the Northern Hemisphere	11	5	4
Polar vortex center intensity index in the Northern Hemisphere	8	6	3
Eurasian zonal circulation index	11	4	3
East Asian trough intensity index	11	8	7

5.3.4 Relationship comparison between WACCI and SST field

The correlation coefficients of WACCI, winter mean temperature, and moving mean SST field every three months in the previous year (starting from December last year, December to February, January to April, and so on) were calculated. The correlation coefficient of WACCI, winter temperature, and mean SST field in summer (June to August) was the highest. Fig. 6 shows regions where the correlation coefficients were significant for WACCI, winter temperature, and summer mean SST field. It can be seen that WACCI was negatively correlated with summer mean SST field. Winter mean temperature was positively correlated with summer mean SST field.Meanwhile, the spatial distribution of the correlation coefficients was also different. As shown in Fig. 6(a), regions of good correlation with WACCI ($P < 0.01$) were located in the South Pacific, the West Pacific warm pool to the offshore China, and sea waters of Northwest Australia. Fig. 6(b) shows that regions of good correlation between winter temperature and summer SST were also located in the South Pacific, Northwest Pacific, and offshore China. In addition, there were high correlation regions in waters of North Australia and East Indian Ocean. The greatest difference occurred in the Indian Ocean, comparing the two figures. Compared with the two charts, the biggest difference of correlation coefficient is in the Indian Ocean area. The correlation coefficient between the Indian Ocean SST and WACCI in the Indian Ocean area is greater than that with winter average temperature.

In Fig. 6(a), 330 grids with negative correlation between summer mean SST and WACCI and passing 99% significance test were selected. Besides, the key SST index (KSI) with significant impact on WACCI was calculated. The correlation coefficient between KSI and WACCI was −0.49 ($P < 0.01$). In Fig. 5(b), 330 grids with negative correlation between summer mean SST and winter mean temperature passed the 99% significance test. The correlation coefficient between KSI and winter mean temperature was −0.49 ($P < 0.01$). Therefore it can be seen that the relationship between wacci and mean sea surface temperature in summer is greater.

Based on the analysis of the special years (1989, 1982, 2005, 2011, 1999, and 1972), the corresponding relationship between KSI and WACCI was consistent in 5 a out of 6 a. There was only 1 a when KSI was consistent with the winter temperature anomaly. It revealed that the impact of KSI on WACCI was better than that of winter temperature. For most years, the abnormally low summer key SST was significantly corresponding to the high WACCI in Heilongjiang Province.

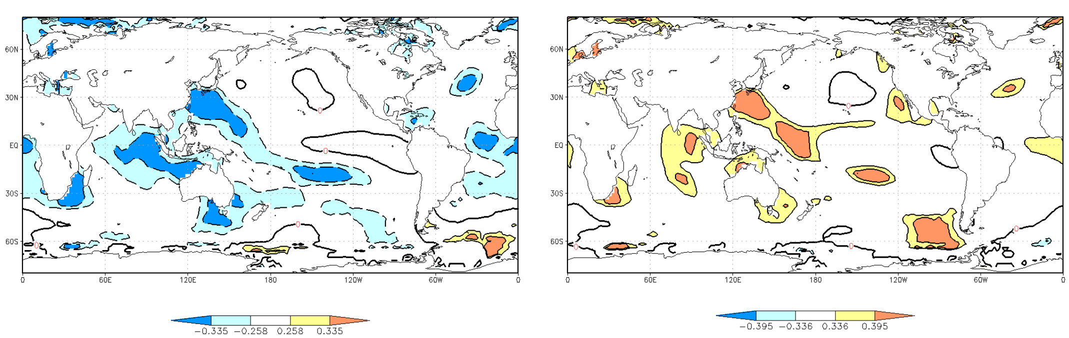


Fig. 6 Correlation distribution between summer sea surface temperature and WACCI (a), temperature (b) in Heilongjiang Province from 1961 to 2018

It can be concluded from analyses of 5.3.1 to 5.3.4 that the correlation between WACCI and 500 hPa height field, AO, the polar vortex area index in the Northern Hemisphere, the polar vortex center intensity index in the Northern Hemisphere, and the summer mean SST were significantly higher than that of winter mean temperature. Hence, it was advantageous and indicative to predict WACCI based on the 500 hPa height field, AO, the polar vortex area index in the Northern Hemisphere, the polar vortex center intensity index in the Northern Hemisphere, and the summer SST. These results further indicated that WACCI can be separated from the mean temperature to have better predictability.

6 DISCUSSION

1) To date, the definition of extreme climate events in China and abroad reflects the characteristics of a single extreme climate event and rarely reflects the intensity and frequency of extreme climate events on a seasonal scale. The WACCI constructed in the paper can reflect the real situation of extreme cold climate events on the seasonal scale and separate the abnormal cold climate events from the mean state.

2) In practice, the seasonal mean temperature is still used as the index for the prediction of long series (seasonal scale) extreme climate events. Extreme cold and warm climate events are mixed to smooth out the signal of extreme climate events. The results show that the relationship of either atmospheric circulation index or KSI with WACCI is closer than that of those with winter mean temperature in Heilongjiang Province. It is proved that the construction of WACCI can better reflect the influence of atmospheric circulation factors and SST on the weather and climate process. WACCI is more predictive than mean temperature and the prediction mechanism description is more convincing than that of mean temperature. Moreover, the accuracy of prediction results may be relatively high. This is a new idea to promote the improvement of short-term climate prediction ability.

3) Based on the WACCI proposed in the paper, the abnormal warm climate index can be constructed to represent the intensity of abnormal warm climate events. Thus, the mixed cold and warm states can be separated to further reveal the characteristics of temperature variation in the local area. Meanwhile, the WACCI proposed in the paper can improve the prediction accuracy of extreme climate events. This research idea can not only be applied to climate prediction, but also has positive significance for the analysis of extreme weather and climate events. Separating the extreme events from the mean value can clearly demonstrate the real spatiotemporal evolution trend of the extreme weather and climate process.

4) The study suggests that the two extremes can be separated in the process of monthly, seasonal, or any time scale mean temperature. The monthly, seasonal, or any time scale index describing the extreme of the predicted object can each be constructed. Then, the mean state or total amount is predicted based on the forecast of those two indices. This research concept can be extended to other abnormal climate factor events and used in the analysis and prediction of other abnormal extreme events such as abnormal precipitation events and abnormal wind events.

7 CONCLUSIONS

1) WACCI is constructed, which consists of three factors including the winter cold duration days, the extremely cold temperature anomaly, and the temperature cumulative anomaly.

2) The decreasing rate of WACCI was 0.56/10 a from 1961 to 2018, which was higher than the winter warming rate (0.258/10 a) in the province. It indicates that the accelerated reduction of severe abnormal cold climate events has made a principal contribution to the winter warming in the province.

3) Only the mid-high latitudes are correlated to WACCI in the correlation diagram of 500 hPa height field, which are less than those regions correlated to temperature. The prediction effect of WACCI is better than that of temperature. When AO appears in the abnormal positive phase, WACCI corresponds to more abnormal years than that of temperature. At the same time, the correlation between WACCI and AO is better than that of winter mean temperature. In the special years when the difference between WACCI and winter temperature is

large, the relationship between the polar vortex area index in the Northern Hemisphere and WACCI is better than that of winter temperature. Besides, the relationship between SST and WACCI is closer than that of winter temperature. For most years, the abnormally low summer key SST is significantly corresponding to the high WACCI in Heilongjiang Province. Therefore, WACCI performs better than winter mean temperature in indicating extreme cold events.

Conflict of Interest Statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript.

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Funding Statement

Financial support for this study was provided by the National Natural Science Foundation of China (Grant No. 41771067). Project supported by the Natural Science Foundation of Heilongjiang Province, China (Grant No. ZD2020D002).

Author's Contribution

Li Chen: Conceptualization, Methodology, Software, Formal analysis, Writing - Original Draft
Lijuan Zhang: Conceptualization, Methodology, Writing - Review & Editing
Jin Ban: Methodology, Software, Formal analysis
Dong Liu: Resources, Formal analysis
Jiaying Zhao: Resources
Yongsheng Li: Formal analysis
Tao Pan: Writing - Editing

Zhang Lijuan

Ban JIN

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Zhao Jiaying

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Availability of data and material: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request

Code availability: Not applicable

Ethical Approval: Not applicable

Consent to participate: All authors have read and approved the manuscript being submitted,and agree to its submitted to this journal

Consent for publication: Not applicable

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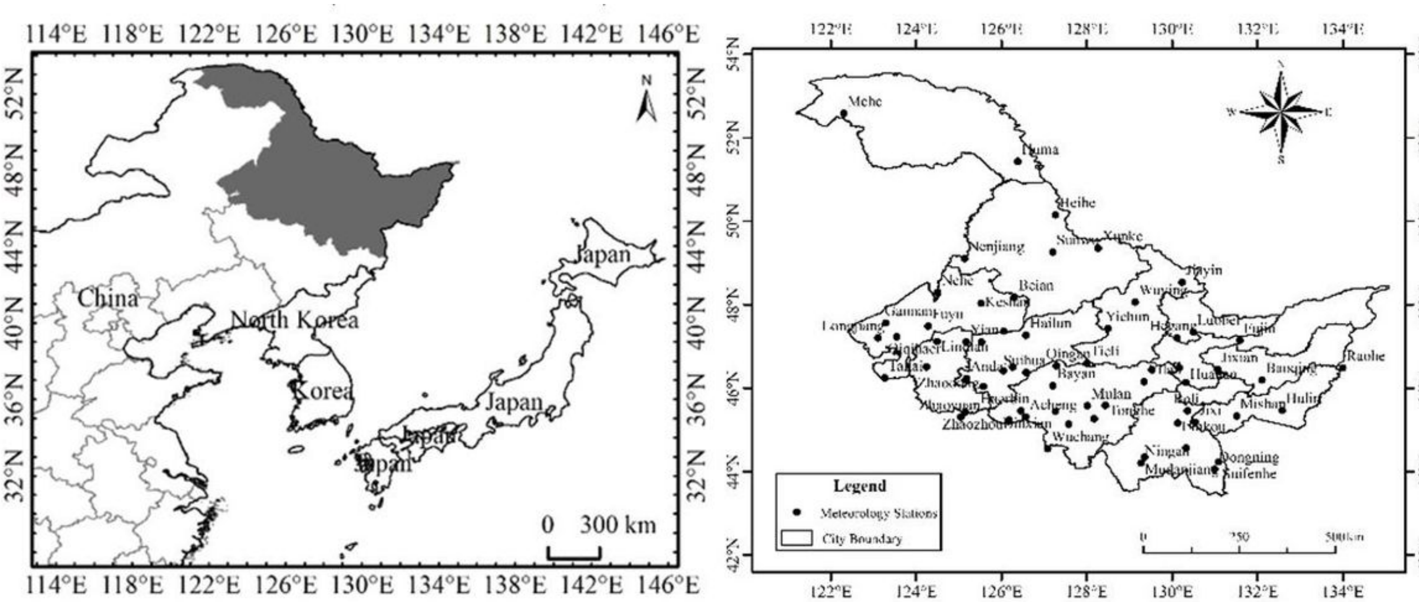
Figures



(a) (b)

Figure 1

Maps showing the location of Heilongjiang Province within northeastern China (a) and its administrative subdivisions (b). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

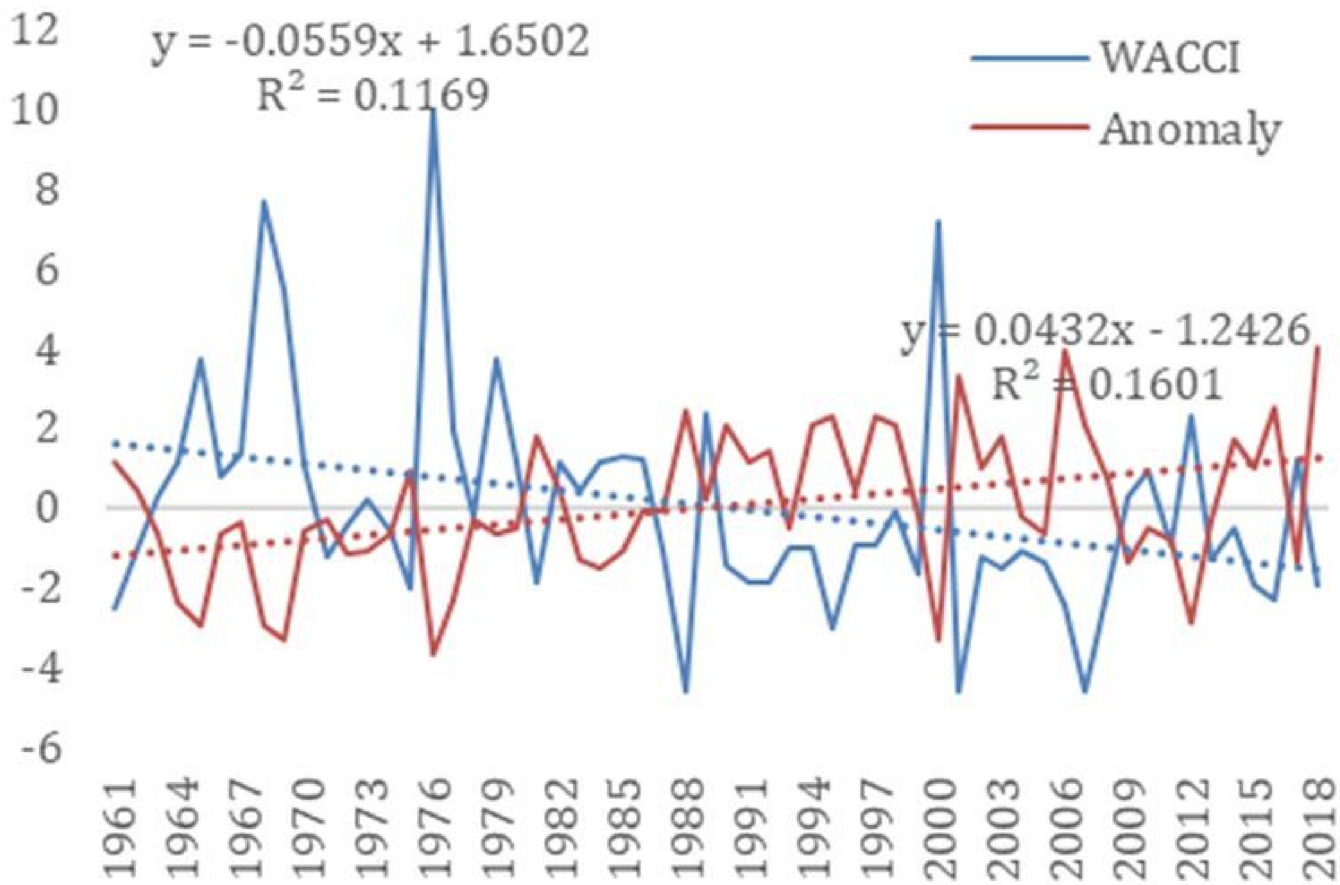


Figure 2

Change chart of WACCI and winter temperature in Heilongjiang Province from 1961 to 2018

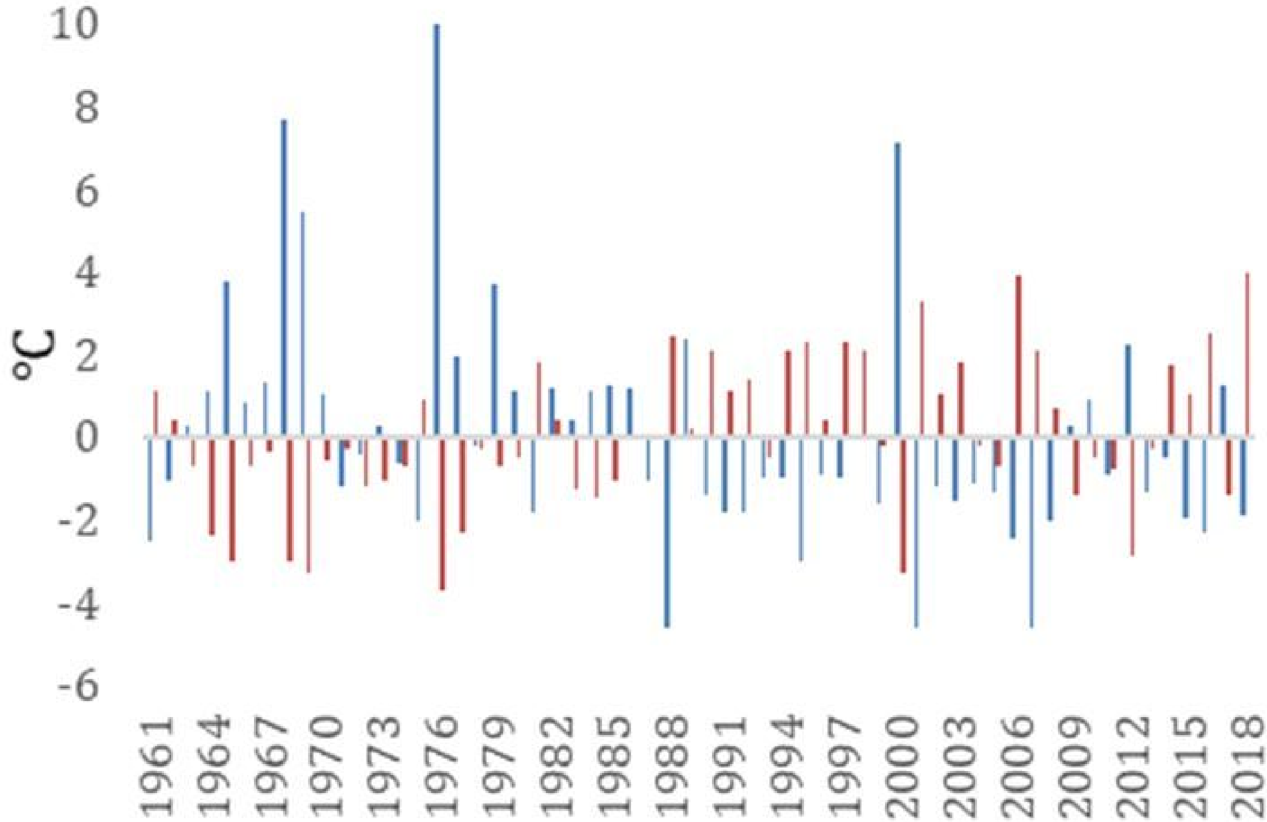


Figure 3

WACCI and temperature anomalies

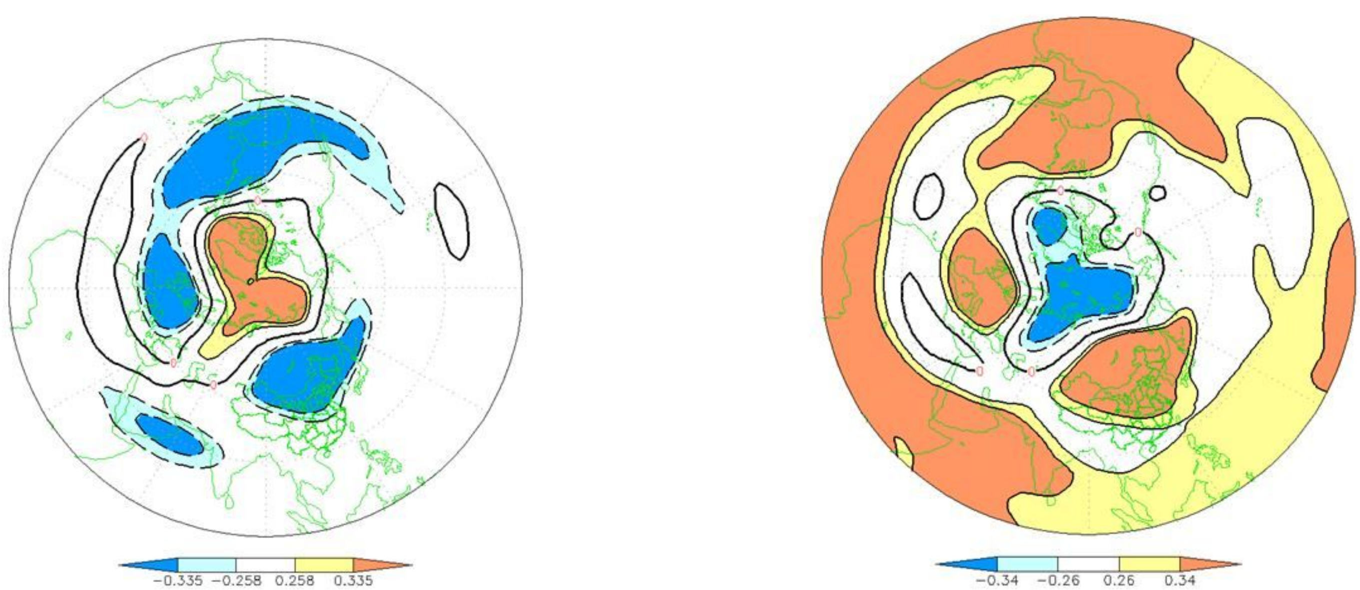


Figure 4

Correlation distribution between 500 hPa height field and WACCI (a), temperature (b) in Heilongjiang Province during 1961–2018

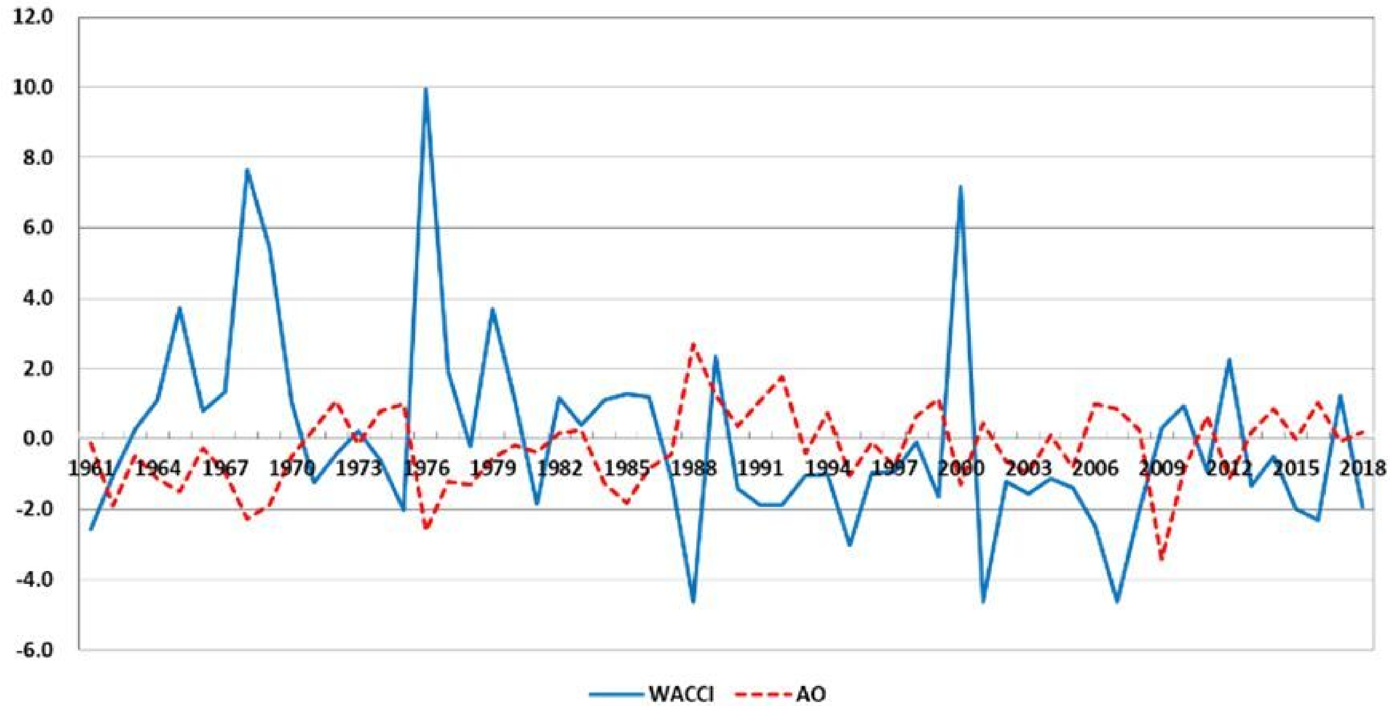


Figure 5

Annual change curve of AO and WACCI in Heilongjiang Province from 1961 to 2018

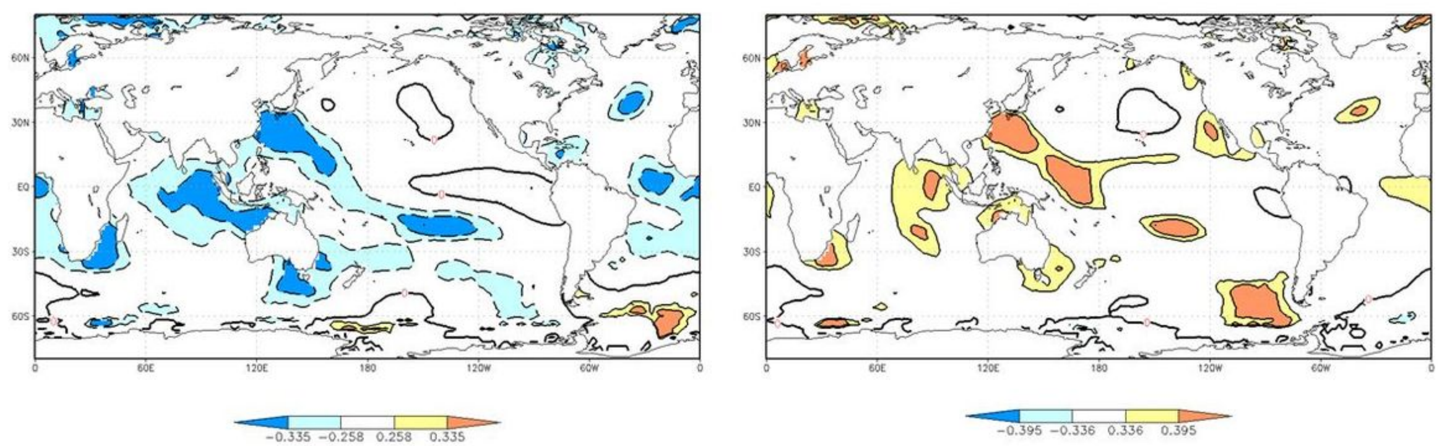


Figure 6

Correlation distribution between summer sea surface temperature and WACCI (a), temperature (b) in Heilongjiang Province from 1961 to 2018