Linkage between the Arctic Oscillation and summer climate extreme events over the middle reaches of Yangtze River Valley

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ABSTRACT: The Arctic Oscillation (AO) is commonly recognized as a dominant large-scale mode influencing climate over the Northern Hemisphere. Here, the influences of May AO on summer (JJA) extreme precipitation events and summer extreme warm days over the middle reaches of Yangtze River Valley for the period 1961−2014 are investigated. Following a positive May AO, there are usually fewer summer extreme precipitation events but more summer extreme warm days over the middle reaches of Yangtze River Valley. Composite analyses show that positive May AO induces the northward displacement of the East Asian jet stream and northeastward displacement of the western Pacific subtropical high (WPSH), and causes a stronger, more northerly subtropical northwestern Pacific cyclone/anticyclone anomaly, as well as an anticyclonic circulation anomaly on the north side of the South China Sea, resulting in a northward shift of the rainfall belt and an enhancement of the East Asia summer monsoon. Therefore, the cumulative distribution probability of daily precipitation values shift significantly to a lower precipitation value, indicating lower probabilities of summer extreme precipitation events following positive May AO. A weakening of WPSH induces an anomalous sinking motion over the middle reaches of the Yangtze River Valley. The 850 hPa wind field shows southerly wind anomalies over the Jiang-Huai River Basin, which cause a decrease in total cloud cover, resulting in an increase in solar radiation flux. A significant shift of the daily maximum temperature probability distribution towards to higher values indicates higher probabilities of summer extreme warm day occurrences following positive May AO. This study will provide useful insights to help improve the understanding of the dynamics and projections of future regional extreme precipitation changes over the middle reaches of Yangtze River Valley.

KEY WORDS: AO · Summer extreme precipitation events · Summer extreme warm days
1. INTRODUCTION

In recent decades, the reduction of sea ice in the Arctic has caused amplified climate responses (Zhao et al. 2015), making the Arctic a focal area of climate change research (Tanaka & Tamura 2016). As a dominant large-scale mode of climate variability, characterized by winds circulating counter-clockwise around the Arctic region (Thompson & Wallace 1998), the Arctic Oscillation (AO) has attracted attention because of its important role in regional climate variability over the Northern Hemisphere (Wang 2004). Many studies have pointed out that the continued trend of the AO towards higher index values in recent decades is one of the important reasons leading to winter warming in the Northern Hemisphere (Thompson & Wallace 2001). Over East Asia, the AO influences aspects of regional climate variability on multiple temporal scales (Shen et al. 2012, Park & Ahn 2016, He et al. 2017). For example, a positive (negative) phase of winter AO usually causes a weaker (stronger) East Asian winter monsoon (EAWM) and corresponding warmer (colder) winters; this significant influence results from the AO’s impact on the Siberian high (Gong et al. 2001, Wu & Wang 2002). Park et al. (2011) indicate that the AO also has a significant relationship with cold surges over East Asia, finding that during a negative AO phase, cold surges are stronger in amplitude and duration. Furthermore, the state of the spring AO is also found to have significant influences on the East Asian summer monsoon (EASM) through shifts of the Asian summer jet stream (Gong et al. 2002), and on changes in north Pacific sea surface temperatures (SST) and the western North Pacific subtropical high (WNPSH) (Gong et al. 2011).

Besides the inter-annual variations, the inter-decadal variations of winter and summer climate over Asia are also profoundly influenced by the AO (Ding et al. 2014, He et al. 2017). For example, the transition of the AO from its negative phase to its positive phase after the mid-1980s might have contributed to weakening of the EAWM and inter-decadal warming over Eurasia (He 2015). Liu et al. (2017) summarized that the relationship of AO and EAWM is statistically significant during the 1928–1948 and 1975–1995 periods, with a robust positive phase of AO and upper-level convergence anomalies. Meanwhile, the relationship between spring AO and EASM on inter-annual timescale also shows a remarkable decadal variation in the late 1990s (Gao et al. 2014). Chen et al. (2015) found that the relationship between spring AO and EASM underwent a significant inter-decadal change in the early 1970s, with a weak relationship during the 1950s and 1960s and a strong and significant relationship from the mid-1970s through the mid-1990s. These influences on the inter-decadal scale are confirmed through Meiyu precipitation with annual time resolution, which was reconstructed based on the length of the monsoon rainy season over this region from 1736 to 2000 (Hao et al. 2015).

Eastern China, which is undergoing rapid economic and societal development, faces many challenges in understanding and adapting to the impacts of climate change. As a major part of the Asian monsoon region, many studies have confirmed that regional climate over eastern China is strongly influenced by the AO (Gong & Wang 2003, Shen et al. 2012, Qu et al. 2015). During a negative phase of AO, the concurrent deeper East Asian trough and stronger Siberian high usually cause anomalously lower temperatures over eastern China (Gong et al. 2001). This relationship between winter AO and southeastern China air temperature shows intra-seasonal variation, due to the migrations of the Azores center of the AO (Zuo et al. 2015). Moreover, positive winter AO usually causes negative precipitation anomalies over northeastern China (He et al. 2017). However, a positive phase of the AO usually leads to above-average summer temperatures over eastern China (Huang et al. 2007). Previous studies (Gong et al. 2002, Gong & Ho 2003) also revealed that summer precipitation over the Yangtze River Valley is strongly influenced by the spring AO through the EASM, with reduced precipitation during a positive phase of the AO. These relationships also show inter-decadal variation due to the inter-decadal changes in the relationship between the spring AO and the EASM (Chen et al. 2015).

Since 1951, with a background of global warming, the frequency and magnitude of extreme weather and climate events in China has notably increased (Gong et al. 2009, Ning & Qian 2009, Wang & Qian 2009, Ren et al. 2010, Ning et al. 2017), causing massive loss of life and property, especially across eastern China (Guo et al. 2013), leading to increasing societal attention. Ding et al. (2010) found that the number of winter extreme warm days and warm nights in most areas of northern China were larger during positive AO phases than during negative AO phases. Chen et al. (2013) also indicated that AO has a strong impact on the number of winter extreme warm and cold days over eastern China through variations of EAWM, both on inter-annual and inter-decadal scales.

Most previous studies (Gong et al. 2011, Lu et al. 2011, Mao et al. 2011, Chen et al. 2013, He 2015) mainly focused on the influence of AO on mean summer and winter climate, or on winter climate extreme conditions.
events in China; however, relationships between AO and summer extreme climate events and corresponding physical mechanism have rarely been investigated. In this study, the influence of May AO on summer extreme precipitation events and summer extreme warm days over the middle reaches of Yangtze River Valley is examined. Detailed physical mechanisms connecting the negative AO phase and daily scale extreme events (Ning & Bradley 2015a,b) are investigated. These analyses may help improve the understanding of mechanisms causing summer extreme climate events over the middle reaches of Yangtze River Valley and the future predictions on different scales, and may also help decision-makers better manage the mitigation of the impacts of increasingly frequent extreme climate events.

2. DATA AND METHODOLOGY

2.1. Datasets

The observational data of daily precipitation and maximum temperature were derived from the CN05.1 dataset provided by the China National Climate Center (CNCC, also known as Beijing Climate Center, BCC). As in the work by Xu et al. (2009), the CN05.1 dataset was modified using by the 'anomaly approach' during the interpolation, but with more station observations (~2400) in China (Wu & Gao 2013). The data cover an area from 14.75° to 55.25° N and 69.75° to 140.25° E, with a resolution of 0.25° × 0.25°, from 1961 to 2014.

The monthly AO index values were acquired from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA/CPC, www.esrl.noaa.gov/) in May for the same time period. The daily 200 and 850 hPa horizontal and vertical wind speed components (u- and v-wind), 500 hPa geopotential height, and 1000–500 hPa omega field data with a resolution of 2.5° × 2.5° for the period 1961–2014, derived from National Centers for Environmental Prediction (NCEP) Reanalysis I, were used for the composite analysis.

2.2. Definition of summer extreme precipitation events and summer extreme warm days

A summer extreme precipitation event was defined as a day with a daily precipitation above than the 90th percentile of daily precipitation in summer (JJA) during the whole 1961–2014 period. A summer extreme warm day was defined as a day with a daily maximum temperature above than the 90th percentile of daily maximum temperature in the same month during the 1961–2014 period. Finally, the total number of each extreme event in the entire season was calculated.

The definitions of these extreme indices have been commonly used in previous studies of climate extremes (Ning & Bradley 2015a,b). These two indices help inform a wide range of regional inter-disciplinary research topics, which are also of increasing concerns due the potential impacts of future climate change on society and economy (Easterling et al. 2000, Meehl et al. 2000, Ning et al. 2015).

3. RESULTS

3.1. Correlation between May AO and summer extreme climate events

To examine the lag-relationships between AO and summer extreme precipitation events and summer extreme warm days, linear correlation coefficients between AO and the number of summer extreme precipitation events and warm days were calculated. This showed that the correlation between May AO and number of summer extreme precipitation events and summer extreme warm days was the most significant one. The spatial patterns of the correlations are shown in Fig. 1. It can be seen that the May AO has significant negative correlations with number of summer extreme precipitation events over the middle reaches of Yangtze River Valley (27°–31° N, 110°–119° E) (Fig. 1a), which is similar to rainfall correlation (He et al. 2017). The correlation between the May AO and number of summer extreme warm days over the middle reaches of Yangtze River Valley are positive, and most of them are significant (Fig. 1b), as proposed by He et al. (2017). This indicates that when May AO is in positive status, there are usually fewer summer extreme precipitation events but more summer extreme warm days over the middle reaches of Yangtze River Valley.

Fig. 2 shows the standardized time series of the May AO and the number of summer extreme precipitation events and summer extreme warm days. The area average is calculated for the middle reaches of Yangtze River Valley with the most significant correlations with May AO. Considering the impact of global warming on the data, the detrended time series of the number of summer extreme warm days is presented in Fig. 2b. May AO has a significant
negative correlation with the number of summer extreme precipitation events ($r = -0.40$, $p < 0.01$), and a significant positive correlation with the number of summer extreme warm days ($r = 0.35$, $p < 0.01$). This indicates that May AO can possibly modulate the inter-annual variability of summer extreme precipitation events and summer extreme warm days over the middle reaches of Yangtze River Valley. When May AO is in the positive phase, there are usually fewer summer extreme precipitation events and more summer extreme warm days over the middle reaches of the Yangtze River Valley. These correlations are consistent with previous studies on the influences of preceding spring AO on the average summer precipitation (Gong et al. 2002) and temperature (Huang et al. 2007) over the eastern China.

To investigate the physical mechanisms behind the correlations between May AO and summer extreme climate events over the middle reaches of Yangtze River Valley, the differences of the circulation fields between years with positive and negative May AO phases relative to precipitation anomalies or extreme warm events are examined in the following composite analysis.

### 3.2. Mechanisms

Dekyi-Pedron et al. (2017) found that the AO directly influences the surface temperature, sea-level pressure (SLP), 500 hPa geopotential height and the
In this section, the differences of the averaged summer extreme precipitation events and summer extreme warm days daily 200 hPa zonal wind, 850 hPa u-winds and v-winds, 500 hPa geopotential height, low-level omega field (1000−500 hPa) and downward solar radiation flux data between the high-AO (>1 SD) and low-AO (< 1 SD) years are first calculated. Then, the responses of daily precipitation and warm days are investigated through the changes in the probability distributions.

Table 1 shows the years with high and low AO. High-AO years are defined as a May with AO >1 SD. Low-AO years are defined as a May with AO <1 SD. For this analysis, 10 high-AO and 10 low-AO years were selected.

In order to analyze the physical mechanism of AO impact on summer climate extreme events, we calculate the difference of the daily average summer climate extreme events between the high-AO and low-AO years, according to the formula: variable | (daily average summer climate extreme events during high-AO years) − variable | (daily average summer climate extreme events during low-AO years).

### 3.2.1. May AO influence on summer extreme precipitation events

Previous studies have revealed that 2 large-scale circulation systems in summer, i.e. the East Asian jet stream (EAJS) and western Pacific subtropical high (WPSH), dominate the EASM that directly influence the summer precipitation over eastern China, especially over the lower and middle reaches of Yangtze River Valley (Gong & Ho 2003). The variabilities of these 2 large-scale circulation systems are both significantly correlated with the preceding spring AO (He et al. 2017). A positive phase of May AO usually leads to a northward shift of summer EAJS, with a simultaneous northward shift of the rain belt, resulting in drier conditions over the middle reaches of the Yangtze River Valley (Gong et al. 2002). This northward shift of summer EAJS is also reflected in zonal wind anomalies at 200 hPa (Fig. 3a), namely the significant negative anomalies locating over 30° N and significant positive anomalies locating over ~45° N, indicating that the EAJS core shifts northward by ~15°. The northward shift of the EAJS plays an important role in the tropical convective anomalies that affect the tropical outer circulation: after the EAJS shifts northward, the tropical western Pacific atmospheric convection anomalies can ignite a stronger, northwest-shifted subtropical northwest Pacific cyclone/anticyclone anomaly, which leads to a northward shift of precipitation anomalies in East Asia (Ye & Lu 2011).

Table 1. Years with high and low AO anomalies

|--------|----------------------------------------------------------|

The 500 hPa geopotential height anomalies (Fig. 3b) shows that a weaker WPSH usually follows a positive phase of May AO, similar to the pattern found in monthly data (Gong et al. 2011). Meanwhile, we find that the WPSH moved to the northeast during the high-AO years. When the WPSH shifts to the northeast, anomalous cyclonic circulation occurs near the South China Sea, and the north side of the South China Sea shows an anticyclonic circulation anomaly, strengthening the East Asian summer monsoon (Yu et al. 2014). This northeastward shift of the WPSH results in an enhanced EASM, correspondingly less convergence over the middle reaches of the Yangtze River Valley, and more convergence over the northern part of eastern China due to moist warm advection and cold dry advection, respectively (Ning et al. 2017).

Both the northward shift of the EAJS and the northeastward shift of the WPSH induce anomalous water sinking motion (Fig. 3c) over the middle reaches of the Yangtze River Valley, resulting in a decrease in the number of summer extreme precipitation events over the middle reaches of the Yangtze River.

### 3.2.2. May AO’s influences on the summer extreme warm days

When the May AO is in the positive phase, the WPSH is anomalously weaker (Fig. 4a). This geopotential height pattern induces the significant downward movement (Fig. 4b). Moreover, there are southerly wind anomalies over the Jiang-Huai River Basin (Fig. 4c), which reduces the total cloud cover (Fig. 4d), and finally brings more solar radiation to the surface with anomalies >5 W m⁻² (Fig. 4e). These significant increases in solar radiation flux also cause positive temperature anomalies, and leads to higher temperatures over central South China, a finding also reported by Ye et al. (2013).

The detailed mechanisms behind the May AO influence on EASM variability through the summer EAJS and WPSH are still an open scientific question. Some potential mechanisms have been hypothe-
sized; for example, He et al. (2017) summarize in their review that changes in soil moisture, as well as SST changes over the North Atlantic, Indian Ocean and North Pacific, are the pathways through which spring AO affects the EASM. Investigating how the AO influences the EAJS, Gong et al. (2002) suggested that possible mechanisms include jet stream–tropical SST interaction, the AO signal’s downward propagation from the stratosphere, wave-mean flow interaction, and land surface process–atmosphere interaction. Using both observational data and model simulations, Gong et al. (2011) found that the AO-associated atmospheric circulation change over the north Pacific produces positive SST anomalies, which intensify the cyclone-like circulation over the western North Pacific through a Gill-type response, and finally influence the monsoon trough and the WPSH. Moreover, the upper troposphere wave-train pattern associated with the AO may also contribute to regional climate variability over eastern Asia (Ha et al. 2012).

### 3.3. Responses of daily variables

To examine the responses of daily precipitation and maximum temperature to the seasonal-scale synoptic circulation anomalies due to the May AO variability, changes in the probability distributions of daily precipitation and maximum temperature due to differences of seasonal mean synoptic circulation patterns are investigated in this section.

Fig. 5 compares the cumulative distributions (Fig. 5a) and the probability distributions (Fig. 5b)
Fig. 4. Anomalies of (a) 500 hPa geopotential height anomaly; (b) low-level (1000 hPa to 500 hPa) vertical velocity; (c) 850 hPa wind field; (d) total cloud cover; and (e) surface downward solar radiation flux of summer extreme warms days between high and low May AO.
of daily average precipitation during the years with high- and low-AO indices over the area (the middle reaches of the Yangtze River Valley: $27^\circ$–$31^\circ$ N, $110^\circ$–$119^\circ$ E) which are significantly correlated. During high-AO years, the probability of daily precipitation shifts leftward compared with low-AO years, indicating a lower probability of extreme precipitation events. At the same time, we compared the average, standard deviation, skewness and kurtosis of summer daily precipitation under high-AO and low-AO (Table 2). We find that the average (5.93 mm) and SD (2.44 mm) during the low-AO years are higher than the average (4.25 mm) and SD (2.06 mm) during the high-AO years. When a Student’s $t$-test is applied, the average of the daily precipitation during high-AO years is significantly smaller than the average during the low-AO years ($p < 0.01$). Similarly, we found that the skewness (2.99) and kurtosis (9.74) during the low-AO years are greater than the skewness (2.65) and kurtosis (7.93) during the high-AO years, indicating that there are more summer extreme precipitation events during the low-AO years.

The cumulative distributions (Fig. 6a) and probability distributions (Fig. 6b) of daily maximum temperature during the years with high-AO and low-AO indices over the area are shown in Fig. 6. The probability distribution of daily maximum temperature during high-AO years shifts to the right compared with low-AO years, indicating a lower probability of days with higher maximum temperature, while mean temperature of high-AO is prominently higher than that of low-AO in summer. The average, SD, skewness and kurtosis of daily maximum temperature distributions are calculated in Table 3. During high-AO years, the average (32.50°C) and SD (5.70°C) are higher than the average (31.13°C) and SD (5.57°C) during low-AO years. Moreover, when Student’s $t$-test is applied, the average of daily maximum temperature during the high-AO years is significantly larger than the average during the low-AO years ($p < 0.01$). The higher skewness ($-3.22$) and kurtosis ($19.45$) compared to the skewness ($-3.26$) and kurtosis ($19.37$) during the low-AO years indicate more summer extreme warm days.

Based on the analysis of the mean, standard deviation, skewness and kurtosis of the daily precipitation

**Table 2.** Average, SD, skewness and kurtosis of summer daily precipitation under high-AO and low-AO anomalies

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<th>Average</th>
<th>SD</th>
<th>Skewness</th>
<th>Kurtosis</th>
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<tr>
<td>High-AO</td>
<td>4.25</td>
<td>2.06</td>
<td>2.65</td>
<td>7.93</td>
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<tr>
<td>Low-AO</td>
<td>5.93</td>
<td>2.44</td>
<td>2.99</td>
<td>9.74</td>
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</tbody>
</table>

**Table 3.** Average, SD, skewness and kurtosis of summer daily maximum temperature under high-AO and low-AO anomalies

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<tbody>
<tr>
<td>High-AO</td>
<td>32.50</td>
<td>5.70</td>
<td>$-3.22$</td>
<td>19.45</td>
</tr>
<tr>
<td>Low-AO</td>
<td>31.13</td>
<td>5.57</td>
<td>$-3.26$</td>
<td>19.37</td>
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and the daily maximum temperature during high-AO and low-AO years, we found that the influence of May AO on summer extreme precipitation events and summer warm days is dominated by change, which cause the daily precipitation (daily maximum temperature) to move to lower (higher) values.

4. DISCUSSION AND CONCLUSIONS

In this study, the correlations between May AO, summer extreme precipitation events, and summer extreme warm days over the middle reaches of Yangtze River Valley, and the corresponding physical mechanisms, were investigated. The results show that May AO has significant negative correlations with summer extreme precipitation events, but significant positive correlations with summer extreme warm days over the middle reaches of Yangtze River Valley, similar to results of previous studies focusing on summer mean precipitation and temperature (Gong et al. 2002, Huang et al. 2007, He et al. 2017).

Composite analyses show that during summers that follow a positive phase of May AO, the EAJS shifts to the north and the WPSH shifts to the northeast, resulting in an enhancement of the EASM and a northward displacements of the rain belt. These changes of synoptic circulation fields induce the cumulative distribution probability of daily precipitation to shift significantly to smaller values, indicating a lower probability of extreme precipitation occurrences following a positive phase of May AO.

Meanwhile, the weakening of the WPSH and the southerly wind anomalies over the Jiang-Huai River Basin result in positive solar radiation flux anomalies. The enhanced solar radiation induces the daily maximum temperature to increase significantly, indicating a higher probability of warm day occurrences following a positive phase of May AO.

The findings in this study can help to improve the understanding of variability and mechanisms of summer extreme climate events over the middle reaches of Yangtze River Valley. Our findings can also contribute to more accurate short-term predictions and long-term projections of summer extreme events, and help decision-makers to prepare corresponding adaptations and the mitigation of the socio-economic impacts of future climate change.

The mechanism behind May AO and summer extreme precipitation events and summer extreme warm days are investigated in this study; however, the detailed mechanisms linking the May AO and summer EAJS and WPSH are not well understood, e.g. the AO signal’s downward propagation from the stratosphere and the wave–mean flow interaction (Gong et al. 2002), which should be investigated in future work.
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