Influence of North Pacific SST on heavy precipitation events in autumn over North China

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ABSTRACT

The characteristics of heavy precipitation occurrence in autumn (the month of September) over North China are investigated using daily observational data. Results indicate that heavy precipitation events experienced a significant decadal increase in 2000/2001. Further investigation reveals a close connection between heavy precipitation occurrence and simultaneous North Pacific SST. The SST anomaly over the North Pacific can result in intensification of the western North Pacific subtropical high and increased water vapor transport from the tropical ocean, which benefits the occurrence of heavy precipitation over North China. However, the key region of North Pacific SST influencing heavy precipitation events over North China was different in the periods 1960–2000 and 2001–2014, being located over the eastern Ocean to China in the first period but more eastward in the second period. This drift in the key region of SST is partly responsible for the decadal increase in heavy precipitation events over North China since 2000/2001. Additionally, the changes in SST variability (a decrease in the eastern Ocean to China and an increase to its east) may have been the main reason for the eastward movement of the key region in the latter period. Certainly, more work is needed in the future to verify the findings of this study.

1. Introduction

A worldwide increase in the probability of occurrence of extreme meteorological events has become apparent under global warming (Michel-Kerjan and Morlaye 2008; Stefan and Dim 2011; Chen and Sun 2015). Extreme precipitation can cause disasters such as landslides and floods, which can then lead to substantial economic, ecological, and societal damage. For example, in summer 2012, Beijing experienced an extreme precipitation event with subsequent economic losses reaching 11.6 billion Yuan, and 1.6 million people affected. Thus, it is of great importance to understand the mechanisms behind the occurrence of extreme precipitation events, to improve our ability to predict them and develop early warning systems.

Numerous studies have investigated the characteristics of extreme precipitation in China, as well as the related changes in atmospheric circulation and the possible mechanisms involved (e.g. Yang, Jiang, and Wang 2008; Wang and Qian 2009; Dong, Chen, and Chen 2011; Chen, Sun, and Fan 2012; Wang et al. 2012; Fu et al. 2013; Sun and Ao 2013; Liu et al. 2015). For example, Sun et al. (2010) explored changes in intense snowfall in China; Mao et al. (2011) indicated that extreme precipitation in winter over central-southern China shows a close link with variation in
the Arctic Oscillation. Li, Chen, and Wang (2016) demonstrated different moisture sources for clustered extreme precipitation events in summer over southern China; and Uotila, Karpechko, and Vihma (2014) showed that the variability of Arctic sea-ice concentration plays an important role in extreme precipitation in summer over China. In addition, SST also has a strong relationship with extreme precipitation over China, in both summer and winter (Zhang and Ding 2004; Wang et al. 2014; Zhang et al. 2015).

In China, precipitation in autumn is much weaker, in amount and intensity, when compared to summer. Nonetheless, the consequences can still be serious and its influence should thus not be neglected (Gu et al. 2012). The variation in mean precipitation in autumn over China and its associated mechanisms have been successfully investigated (Zhang, Gao, and Zhao 2003; Niu and Li 2008; Gemmer et al. 2011). For example, Gu et al. (2014) indicated that the tropical Pacific east–west SST gradient has a considerable impact on autumn precipitation over South China; Zhang and Sumi (2002) pointed out that the mature phase of El Niño is conducive to more autumn precipitation over South China; and Han, Zhang, and Su (2013) proposed a close relationship between the cooling of tropical Pacific SST and autumn precipitation over North China. Clearly, the impact of tropical Pacific SST on changes in autumn mean precipitation in China is important. Furthermore, some studies (e.g. Han 2014) have documented that changes in extra-tropical Pacific SST also play an important role in regulating autumn precipitation in China.

Despite the considerable body of work as summarized above, few studies have focused on the variation in autumn extreme precipitation, which forms the topic of interest in the present work. Following this introduction, Section 2 describes the datasets used, Section 3 presents the results, and Section 4 summarizes the study’s key findings.

2. Data

The target region in this study is North China; specifically, the region (35°–45°N, 110°–120°E). Daily precipitation data from 67 meteorological stations in North China are used, as collected and provided by the National Meteorological Information Center of China. Heavy precipitation events are defined as daily precipitation exceeding 5 mm d⁻¹, corresponding to the 90th percentile threshold from daily precipitation. According to this definition, almost no occurrences of heavy precipitation can be observed in October and November over this region; thus, the heavy precipitation events in this study are focused mainly on the month of September. NCEP–NCAR monthly reanalysis data at a horizontal resolution of 2.5° × 2.5° (longitude × latitude) are also employed. Variables given by NCEP–NCAR include geopotential height, meridional and zonal winds, surface pressure, and specific humidity. The monthly SST data are from the Hadley Centre, with a horizontal resolution of 1.0° × 1.0°.

3. Results

Figure 1(a) shows the time series of the occurrence of heavy precipitation events in September over North China and its corresponding 9-yr low-pass-filtering result. The interannual variation is obvious, as well as its interdecadal change. Both a Lepage test (Figure 1(b)) and moving t-test (MTT) (figure not shown) indicated that heavy precipitation occurrence in September over this region experienced a significant (both exceeding the 95% confidence level) interdecadal increase around 2000/2001. Thus, the following analyses focus on two sub-periods: 1960–2000 and 2001–2014. Additionally, the variability of extreme precipitation occurrence also increased, from 0.99 in 1960–2000 to 1.08 in 2001–2014.

To understand the possible reason for the interdecadal increase in heavy precipitation events over North China, we regressed it with the simultaneous SST over the western North Pacific for the two sub-periods, as shown in Figure 1(c) and (d), respectively. Clearly, there are different spatial patterns for the two periods. The significant signal can be observed near the East Asian continent (eastern Ocean to China) during the first period, as labeled by the ‘A’ within (25°–45°N, 120°–140°E). However, the significant signal near the East Asian continent disappeared during the latter period, moving eastward to within (15°–35°N, 140°–160°E), labelled by the ‘B’. Thus, the variation in SST over the western North Pacific may be responsible for interdecadal change in heavy precipitation events over North China in recent decades. Furthermore, a weaker signal of the SST anomaly can be observed over the western North Pacific in August (figures not shown), which then persists and enhances in September. This could provide valuable information for the early prediction of extreme precipitation events in North China.

Two indices (I_{SSTA} and I_{SSTB}) are defined and employed for further research. I_{SSTA} is defined as the standardized time series of average SST in region A during 1960–2014, and I_{SSTB} is the same but for region B. Additionally, another index regarding the frequency of heavy precipitation (FHP) events (I_{FHP}) is also employed, defined as the standardized time series of regional averaged FHP over North China. Figure 1(e) displays the time series of these indices. Obviously, I_{SSTA} demonstrates consistent variation with I_{FHP} before the early 1990s, whereas I_{SSTB} becomes closer in agreement with I_{FHP} after the early 2000s. The 21-yr sliding correlation coefficients between I_{FHP} and I_{SSTA} (I_{SSTB}) validate this change of relationship (figure not shown). Results
Figure 1. Temporal variation of heavy precipitation events in the month of September over North China: (a) time series of heavy precipitation occurrence (blue) and its corresponding 9-yr low-pass-filtered result (red) (units: day); (b) Lepage test result with an 11-yr window; (c, d) regression maps of SST anomalies with frequency of heavy precipitation events (detrended) during the periods (c) 1960–2000 and (d) 2001–2014 (shading indicates statistical significance at the 90% (light) and 95% (median), and 99% (dark) confidence level, based on the Student’s t-test); (e) standardized variation of $I_{fhp}$ (index of frequency of heavy precipitation, black), $I_{sstA}$ (index of average SST in region A, blue), and $I_{sstB}$ (index of average SST in region B, red).
Figure 2. Regression maps of heavy precipitation events against (a) zonal wind velocity at 200 hPa, (c) geopotential height at 500 hPa, (e) wind at 850 hPa, and (g) integrated WVT (water vapor transport), during 1960–2000 after removing their linear trends. The right-hand panels ((b), (d), (f), and (h)) are the same as the left ((a), (c), (e), and (g)), except that they show the regression of circulation against $I_{\text{SSTA}}$ (index of average SST in region A).

Note: Shading from light to dark indicates statistical significance at the 90%, 95%, and 99% confidence level based on the Student’s t-test; red, positive regression; blue, negative regression; blue box, North China.
Figure 3. Regression maps of heavy precipitation events against (a) zonal wind velocity at 200 hPa, (c) geopotential height at 500 hPa, (e) wind at 850 hPa, and (g) integrated WVt (water vapor transport), during 2001–2014 after removing their linear trends. The right-hand panels ((b), (d), (f), and (h)) are the same as the left ((a), (c), (e), and (g)), except that they show the regression of circulation against $I_{sstB}$ (index of average SST in region B).

Note: Shading from light to dark indicates statistical significance at the 90%, 95%, and 99% confidence level based on the Student’s t-test; red, positive regression; blue, negative regression; blue box, North China.
show that the relationship between $I_{fhp}$ and $I_{sst}$ became weaker after 1987/1988; while for $I_{fhp}$ and $I_{sstb}$ the relationship became stronger after 2000/2001. These relationship changes are consistent with the interdecadal change of $I_{fhp}$, particularly for the correlation between $I_{fhp}$ and $I_{sstb}$.

Figure 2 presents regression maps of $I_{fhp}$ with atmospheric circulation after removing their linear trends (left), as well as those of $I_{sst}$ (right), during 1960–2000. Although the relationship between $I_{sst}$ and $I_{fhp}$ became weaker after 1987, the regression patterns for the period 1960–1987 (figures not shown) are quite similar to the results for the period 1960–2000. Thus, we only show the results for the period 1960–2000 here. As shown in Figure 2(a), the regression map of 200-hPa zonal wind exhibits a negative–positive–negative pattern over the East Asian region. Earlier studies documented that the right-hand side of the East Asian westerly subtropical jet (EAWJ) entrance benefits horizontal divergence in the upper levels (e.g. Barry and Carleton 2001). Additionally, large-scale and unanimous upward motion prevails over the location of the EAWJ entrance (figures not shown), which is also the region of North China. Thus, both the upward movement and the upper-level divergence are conducive to the occurrence of heavy precipitation over North China. The regression pattern of 500-hPa geopotential height (Figure 2(c)) shows a significant anomalous anticyclone center over the northwestern Pacific, suggesting a stronger western North Pacific subtropical high (WNPSH) when heavy precipitation events happen over North China. Because of the intensification of the WNPSH, a significant anomalous anticyclone prevails in the 850-hPa wind velocity field (Figure 2(e)), leading to increased water vapor transport (WVT) into the North China region (Figure 2(g)). The anomalous southerly wind in the lower levels and the integrated WVT can produce favorable conditions for the occurrence of heavy precipitation over North China.

We further regressed the atmospheric circulation with the simultaneous $I_{sst}$, and similar results were obtained (right-hand panels in Figure 2). A similar negative–positive–negative pattern prevails over the East Asian continent in the 200-hPa zonal wind field. The increased SST near the East Asian region can intensify the WNPSH and strengthen the southerly wind anomalies, which leads to increased WVT into North China. Thus, the increased SST provided a favorable background for the occurrence of heavy precipitation over North China during 1960–2000.

For the latter period (2001–2014), the significant SST region moved southeastward from A to B (Figure 1). Meanwhile, the pattern of 200-hPa zonal wind (Figure 2(a), during 1960–2000) moved eastward with a significant tripole pattern located over the central North Pacific (Figure 3(a), during 2001–2014). The position of the EAWJ in this pattern also favored unanimous upward motion over North China (figures not shown). In terms of 500-hPa geopotential height (Figure 3(c)), the significant positive anomaly center moves southeastward, also with a significant tripole pattern formed over the central North Pacific. Moreover, this pattern also favors the WVT from the tropical ocean to the North China region (Figure 3(g)), which provided sufficient water content for the occurrence of heavy precipitation during the latter period. Similar patterns were obtained when regressions were implemented with $I_{sstb}$ (right-hand panels in Figure 3).

The above analysis shows that SST in the northwestern Pacific can influence heavy precipitation occurrence over North China by regulating the corresponding circulation.
and WVT. However, during the period studied here, the key region for SST differed in two sub-periods. Thus, the question arises as to why such a change can take place. To answer this, we computed the SST difference between the two periods (Figure 4). Clearly, SST increased uniformly over the North Pacific in the period 2001–2014 against 1960–2000. Meanwhile, the variability (standard deviation) of SST in region A became much weaker, but increased in region B, in the latter period. This increase in variability have been partly responsible for the shift in the key SST region from A to B. Further work is required in the future to verify this suggestion.

4. Conclusion

This study characterizes the occurrence of heavy precipitation in September over North China in several recent decades, revealing a decadal shift around 2000/2001. The possible reason for this change is investigated. Results showed the atmospheric circulation from the upper to the lower levels to be consistent, providing a beneficial environment for the occurrence of heavy precipitation over North China. The atmospheric pattern involves the position of the EAWJ relative to North China, and its intensity; consistent upward vertical circulation over North China; enhancement of the WNPSh; southerly anomalies in the lower levels; and increased integrated WVT from the tropical ocean. All of these factors are conducive to the occurrence of heavy precipitation events in North China. Furthermore, the simultaneous SST over the North Pacific was found to significantly influence heavy precipitation occurrence. However, in the study period, the key SST region influencing heavy precipitation differed between the sub-periods of 1960–2000 and 2001–2014. Additional work indicated that the change in SST variability over the North Pacific might have been partly responsible for this decadal shift in heavy precipitation occurrence over North China. The SST variability over region A decreased, while it increased over region B. This led to an unstable relationship between SST and heavy precipitation occurrence, ultimately resulting in the key SST region drifting from A to B over the North Pacific.

Disclosure statement

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