We propose a short-lived extreme precipitation event, which is identified by the definition of 75th and 95th percentile using gauge observations across northeast China (NEC). Atmospheric variables from reanalysis dataset are then composited to examine the contribution of synoptic-scale circulations to variations in extreme events. Results show that the divergence aloft combined with lower pressures at surface lead to upward vertical motion of circulations, along with flow around low-pressure area and high pressure to east NEC derived from associated wavetrain conveying efficient moisture, providing favorable environment for occurrence of precipitation extremes. The northwestward shift of western Pacific subtropical high, together with northward shifted position of upper-level westerlies over NEC, results in the strengthened southwesterly, which transports more moisture into NEC and produces extreme rainfall. Moreover, the stronger anomalies of dynamical quantities present for 95th percentile cases. The roughly same percentage of summertime short-lived extreme events related to cut-off lows (COLs) is found for both percentile composites, 21.2% (79 out of 373) and 21.1% (77 out of 365) for 75th and 95th percentile events, respectively. Overall, the contribution of COLs to short-lived extreme precipitation is insignificant during 1960–2015 in NEC, although COLs have been documented to be more active in summer over NEC. The time series of COL-induced events exhibits inter-annual variability with not statistically significant linear trend, suggesting that COLs play a tiny role to the slightly decreasing trend of short-lived precipitation events over NEC.

KEYWORDS
atmospheric variables, cut-off lows, extreme precipitation event, northeast China

1 | INTRODUCTION

Northeast China (NEC) is a region of momentous significance for development of grain production and it is also the northeast industrial base of China. Rainfall is mainly concentrated in summer, and the summertime precipitation accounts for approximately 65.7% of annual total rainfall in NEC (Liang et al., 2011). The changes in floods derived from summertime extreme precipitation events are therefore the majority of severe natural hazards, resulting in substantial impacts on local crop safety, agriculture, economic society and the eco-environment (Shen et al., 2011; Du et al., 2013; Han et al., 2015). For example, extreme rainfall caused severe floods in August 2013 over NEC and led to 81 casualties and 97 unaccounted people, total economic loss was estimated to be approximately 2.6 billion USD (Gao et al., 2014). Understanding the atmospheric circulation anomalies dominating the variations in summertime precipitation extremes over NEC is still challenging.
Summertime rainfall experienced remarkable variability during last decades, even though the regional trend was insignificant owing to lack of homogeneous precipitation changes over different sub-regions across NEC (Zhai et al., 2005; Liang et al., 2011; Du et al., 2013; Fan and Chen, 2016; Yang et al., 2017). Zhai et al. (2005) pointed out that summertime rainfall had significantly decreased in southern NEC during 1951–2000. Liang et al. (2011) further suggested that 80 of the 98 weather stations exhibited negative trend of precipitation in summer over NEC. Du et al. (2013) investigated the characteristics of precipitation extremes and argued that extreme rainfall frequency and intensity showed insignificant decreasing and increasing trend, respectively, in NEC from 1961 to 2009. Yang et al. (2017) analyzed spatiotemporal features of precipitation extremes by utilizing multiple indices and demonstrated that extreme rainfall indices displayed declining trends with extremely wet stretch from south to north across NEC.

Physical mechanisms underlying the variations in summertime rainfall over NEC have been documented by many publications. Existing studies have reported that the summertime rainfall across NEC was influenced by multiple factors. Strong (weak) East Asian summer monsoon (EASM) may cause more (less) heavy precipitation in NEC (Sun et al., 2007; Gao et al., 2014; Luo and Lin, 2017). Also, preceding sea surface temperature (SST) anomalies over key regions, including equatorial and northern Atlantic Ocean as well as the southwest Indian Ocean, and dipole anomalies of Arctic atmospheric variability in summer, also play a significant role to the changes in summertime precipitation over NEC (Wu and Zhang, 2008; Han et al., 2015). In addition, cut-off low (COL) has substantial impacts on variability of summertime intense rainfall in NEC, since the occurrence frequency of COL events peaks during the summer (Hu et al., 2010). Zhao and Sun (2007) indicated that the severe floods during the summer of 1998 induced by precipitation extremes over the reaches of Songhuajiang and Nenjiang Rivers in NEC were closely linked with anomalous activities of COLs. Moreover, the inter-seasonal and inter-annual occurrence of COLs is largely unpredictable due to internal dynamical and nonlinear features. However, previous studies for physical causes mainly focused on mean and total rainfall at seasonal and annual scales, while the extreme precipitation events and associated anomalies of atmospheric circulations across NEC have been drawn limited attention, which are crucial to the occurrence of flooding disasters in summer and grain production and security.

In this study, we conduct systematic analyses of the major synoptic-scale circulation anomalies responsible for variations in precipitation extremes over NEC. The rest of paper is structured as follows. Data and methods are introduced in section 2, section 3 provides results, followed by the summary in section 4.

2 | DATA AND METHODS

2.1 | Data

We use daily precipitation at rain gauge stations from China Meteorological Administration (http://cdc.nmic.cn/home.do), without consecutive missing data of precipitation amount (Zhang et al., 2011). Effective precipitation days are defined when the daily total rainfall amount is greater than or equal to 1 mm, which is consistent with previous studies (e.g., Zhai et al., 2005; Sun et al., 2015). Selected criteria for the reserved stations over NEC (38°–55°N, 119°–135°E) during 1960–2015 are adopted from Ma et al. (2015) and Gao et al. (2017). As a result, 115 stations meet these criteria and are employed in this study. Daily reanalysis dataset, including specific humidity, geopotential height, temperature and sea level pressure (SLP), is obtained from the 55-year Japanese Reanalysis Project (JRA-55, http://jra.kishou.go.jp/JRA-55/index_en.html), with resolution of 1.25 × 1.25° in the period of 1960–2015 (Harada et al., 2016).

2.2 | Definition of extreme precipitation events

Expert Team on Climate Change Detection and Indices and the Climate Data Operators define precipitation extremes using 75th, 95th and 99th percentiles (Zhang et al., 2011). In this study, we employ 75th and 95th percentiles for the representation of intense and extreme rainfall events, which is also widely used in the extreme climate studies both at global and regional scales (e.g., Alexander et al., 2006; Ma and Zhou, 2015; Gao et al., 2017). By considering the meteorological conditions for occurrence of short-lived extreme rainfall events, which are more likely to induce flash flooding (Pathiraja et al., 2012), we adopt the methods developed by Frei et al. (2015) and Marquardt Collow et al. (2016), who investigated the variability of short-lived extreme precipitation over northeastern United States by computing percentile indices using this definition. To facilitate analyses of anomalous circulations associated with precipitation extremes, we expand this definition to make it more suitable for NEC. The ±5 percentile units of defined events are utilized for avoiding overlapping events for 75th percentile precipitation events falling in 95th percentile cases, and vice versa. That is, we identify the 75th and 95th percentile precipitation extremes with the events falling into category when these are within a range of ±5 percentile units of the selected 75th and 95th percentile threshold, respectively, which confirm that the events in the 75th (95th) percentile group exclude the precipitation events identified in the 95th (75th) percentile cases. And 75th (95th) percentile threshold value is the 75th (95th) percentile of precipitation based on all the days having at least 1 mm of rainfall ranging from small to large during 1960–2015. Additionally, a window of 2-week period is adopted through considering all the daily rainfall values for each selected percentile date of ±1 week,
which provides robust statistics maintaining any seasonal difference. For more detailed information of the defined events referred to Frei et al. (2015) and Marquardt Collow et al. (2016). To our knowledge, this kind of short-lived extreme precipitation events, compared with persistent extreme rainfall, have not been investigated in NEC.

3 | RESULTS

3.1 | Climatology of the NEC

The annual and summer rainfall over NEC characterizes a significantly spatial inhomogeneity with multiple time-scales derived from combined impacts of the complex topography and EASM (Liang et al., 2011), as well as COLs (Shen et al., 2011), and these features are different with the variability of precipitation over northern and southern China (Gao et al., 2014; Han et al., 2017; Sun et al., 2017). Summertime climate characteristics in NEC during 1960–2015 are illustrated in Figure 1. The temperature generally decreases along with increasing latitude (Figure 1a), and mountains associated with higher elevations also result in cooler temperature, particularly over northwest NEC affected by Da Hinggan Mountains. Moreover, variability of temperature could in part explain the summer mean precipitation changes based on Clausius–Clapeyron relation (Deng et al., 2014), which can be manifested by similar spatial distribution of summertime temperature and rainfall in NEC (Figure 1a,b). The mean daily rainfall is also influenced by mountains, as the stations with larger precipitation amount mainly concentrate southeast areas of NEC, which is impacted by Changbai Mountains (Figure 1b).

Summertime mean vertically integrated water vapor (VIWV) flux shows the major water vapor transports and sources over NEC (Figure 1c). Northeastward VIWV transports indicate that EASM and East Asian jet stream play a crucial role to changes in precipitation across NEC (Shen et al., 2011). Furthermore, southward bend of VIWV flux over northern NEC may suggest that the mid-high latitude circulations induced by Arctic sea ice cover also change VIWV transports (Han et al., 2015). The VIWV fluxes situated over southeast regions are stronger than other sub-regions across NEC, in accordance with larger mean rainfall in these areas (Figure 1b,c). This kind of southeast–northwest stretch of VIWV fluxes and summer precipitation can also be confirmed by spatial distribution of total precipitable water (TPW) vapor (Figure 1d).

Based on the least squares regression and Student’s t test, a time series is seen a decreasing trend for region-averaged mean rainfall within the area of interest during the 56-year time period, although it is not statistically significant (Figure 1e). The distinct shift occurs around the 1990s, indicating that negative trend of regional mean precipitation is superimposed on an oscillation. This may be caused by warming in the tropical Indian Ocean, which acts the bridge linking eastern El Niño–Southern Oscillation (ENSO) and summertime rainfall in NEC around the 1990s (Han et al., 2017; Sun et al., 2017), and it is also correlated to the synchronous Pacific Decadal Oscillation (PDO) shift from positive phase to negative phase before and after 1990s (Han et al., 2015). Figure 1e shows that median value of summer precipitation exhibits remarkable interannual variability with a slightly decreasing trend during the entire period. Similar changes are also found for the frequency of 95th percentile events over time, which has insignificant negative trend with larger shifts in the 1990s (Figure 1f). While the more slightly declining trend is found for 75th percentile case, not significant in the statistical test. It is noteworthy that the correlation coefficient between 95th (75th) percentile precipitation events and summer total rainfall is 0.829 (0.364), and both of them are significant at 95% level, combined with congruent variability of mean and 95th percentile events, indicating that extreme precipitation, rather than moderate rainfall, plays a significant role to the changes in summer total rainfall over NEC.

3.2 | Composited fields during the occurrence of precipitation extremes

We calculate summer mean value of the identified extreme precipitation events in NEC, as the base for composites in the 75th and 95th percentile cases, respectively (Figure S1). For both percentile events, a wide region, including eastern coastal areas and NEC, shows obvious rainfall on average during extreme events. This method generally pulls out larger-scale precipitation events covering a larger area than the defined NEC. Figure S1 illustrates daily average precipitation extremes in fact capture rainfall from the systems that travel through and affect a different area earlier on the day of extreme events. Especially for 95th percentile events, in the study domain the heaviest precipitation falls in the southeast NEC (Figure S1b).

The anomalous flow of VIWV during the extreme precipitation process based on two sets of composites is represented in Figure 2. To highlight larger anomalies responsible for the occurrence of precipitation extremes, values below 20 kg m$^{-1}$ s$^{-1}$ have been omitted. Two days prior to extreme events, the difference between 75th percentile events and climatological fields is insignificant (Figure 2a), while an anticyclone circulation begins to take shape over northwestern Pacific for 95th percentile cases (Figure 2b). On the day out extreme events, the magnitude and range of these anomalies are amplified both in the 75th and 95th percentile precipitation events, with the center shifting northward (Figure 2c,d). For 95th percentile cases, these VIWV flux anomalies are likely stronger to southern portion of NEC, forming a feeble convergence of moisture flux coming...
from northwestern Pacific and moisture from Mongolia. Whereas the anomalous flux convergence is somewhat deceptive over NEC for 75th percentile cases.

On the day of precipitation extremes, the circulation pattern of VIWV flux anomalies takes on a tilt from southwest to northeast with an elongated shape (Figure 2e,f). The
VIWV flux anomalies become strongest in the northwest portion of the anticyclone circulation, the majority of moisture fluxes are pulled in from northwestern Pacific through a warm conveyor belt of the strengthened southwesterly flow. For 95th percentile events, the enhanced convergences with largest moisture anomalies extend farther north, situating
over NEC, which provide suitable conditions for the formation of extreme precipitation events. A significant difference between 75th and 95th percentile rainfall events is seen in the location and magnitude of the convergence of VIWV anomalies, there is relatively weak and propagating in the southern NEC for 75th percentile events. And a cyclone of VIWV flux anomalies with moisture from southern China, originated from eastern tropical Pacific (Figure 2a), presents in NEC. The day after precipitation extremes, the pattern of converging circulations tends to disappear over NEC for 75th percentile events (Figure 2g). While the convergence of VIWV flux anomalies becomes weakened and moves southward for 95th percentile cases (Figure 2h). The favorable conditions of occurrence of intense rainfall events are not available for both sets of percentile events.

As a key component for the occurrence of extreme precipitation events, the availability of moisture water vapor is shown in Figure S2. The positive anomalies of the TPW develop in and surrounding areas of northern China, since the moisture fluxes are conveyed from northwestern Pacific by southwesterly flow (Figure S2a,b). TPW anomalies are feeble 2 days before of extreme events but become more remarkable the day prior to the events. Maximum TPW anomalies locate over southwest NEC for both of 75th and 95th percentile events, and the anomalies are much stronger in the 95th percentile cases (Figure S2c,d). On the day of precipitation events, TPW anomalies are stronger and stretch from southwest to northeast (Figure S2e,f), similar to what is seen with VIWV flux anomalies, which further manifest the availability of moisture responsible for the occurrence of precipitation extremes. The TPW anomalies propagate southeastward with decreasing magnitude in the following day (Figure S2g,h), as the systems decline or disappear after the day of precipitation events (Figure 2g,h).

The TPW flux anomalies provide some indications of overall water vapor flow in the troposphere for the occurrence of precipitation extremes (Zhou and Yu, 2005; Sun et al., 2017). Nevertheless, wind anomalies at 250 hPa, in the upper troposphere, can also further provide information in link with the dynamics responsible for extreme precipitation events (Shen et al., 2011; Fang et al., 2017). As illustrated in Figure 3, wind anomalies less than 1 m/s are masked out for drawing more attentions to significant anomalies. Compared with the climatology (figures not shown), the largest wind anomalies in jet stream are situated around the north of 40°N with a resembling westerly flow, covering the study region. 2 days before extreme precipitation events, a meridional component of 250 hPa wind anomalies is stronger over the western areas of the NEC, along the north China and Inner Mongolia as well Mongolia (Figure 3a,b). The day prior to the events, these anomalies become much stronger and form a pattern of cyclonic circulation centered over the border area between China and Mongolia (Figure 3c,d). The wind speed divergence is found in western portion of the NEC. This divergence appeared in the upper troposphere suggests a signal of upward vertical motion of atmospheric circulations, indicating a convergence at the surface responsible for a suitable component of precipitation extremes over NEC. The strongest wind anomalies at 250 hPa are available on the day during extreme events, with maximum values located over the northwestern quadrant of study area. NEC is situated over the right entrance area of the strengthened upper level wind anomalies (Figure 3e,f), where the upward vertical motion of atmospheric circulations occur. These maxima of the anomaly wind fields are more significant in the 95th percentile rainfall events compared with 75th cases. Furthermore, cyclonic anomalies located over Mongolia and Lake Baikal indicate atmospheric baroclinic instability (Holton, 1992) and also favor ascending anomalous flow, thereby the cold vortex is formed to the east NEC.

The composites of 500 hPa heights in both sets of 75th and 95th percentile precipitation events suggest that a trough forms upstream of the NEC before 2 days of an extreme event (Figure 4a,b). The positive height anomalies are generally stronger in the 95th percentile events and locate to the south. A trough is embedded with a wavetrain from west to east for both percentile cases, this trough tracks to southeastward, and moves slowly from the day of events to the day after extreme precipitation events. Note that magnitude of the low-high dipoles around rainfall events is larger for 95th percentile composites. The western Pacific subtropical high (WPSH) illustrated by blue solid lines in Figure 4 has a significant northwestward in comparison with climatological state for both 75th and 95th percentile cases, with far northwestern propagation in the 95th events. Moreover, the negative anomalies of 500 hPa height is generally accompanied by the similar pattern of SLP anomalies, even though low pressure system of SLP is not vertical stacked (Figure S3). In the both of 75th and 95th percentile composites, the positive height anomalies at 500 hPa to the east of negative anomalies develop coherently with the low of SLP. The distribution of SLP anomalies (Figure S3a) suggests that precipitation extremes in NEC are closely related to EASM, which is characterized by the pressure differences between mainland China and North Pacific (Fang et al., 2017).

During the extreme precipitation events, further northward propagation of the WPSH with enhanced intensity is found in the 95th percentile events (Figure 4e,f), but not appearing for 75th cases. Combined with the VIWV flux anomalies (Figure 2e,f), we further confirm the possible physical mechanism for the impacts of WPSH on summertime extreme precipitation over NEC documented in previous studies (Shen et al., 2011; Sun et al., 2017). With northward and westward advance of the strengthened WPSH, the southerly moisture flux transports are enhanced, which favor northern transport of VIWV flux anomalies in southwesterly directions to the
west WPSH and result in more precipitation extremes. Particularly, the WPSH locations affecting extreme rainfall in NEC are not consistent with that influence precipitation extremes over Yangtze River basin (Gao et al., 2016). The negative SLP anomalies become elongated on the day of the precipitation events and the day after the
events (Figure S3). Besides, the shape of negative SLP anomalies for the day of extreme events resembles a trailing cold front with a low pressure system. These indicate that the stronger EASM is conducive to VIWV flux convergence over NEC and advantageous to larger precipitation events.

FIGURE 4  Five-hundred hectopascal height anomalies composited from 2 days before to 1 day after (left) 75th and (right) 95th percentile rainfall events. Hatching indicates regions with a statistical significance of 95% level. Blue solid lines denote the 588-dagpm contours.
3.3 Contribution of COLs to precipitation extremes

COL is typically represented as closed geopotential lows with cold trough or core in the mid-upper troposphere, which is also known as cold vortex, low vortex and upper cold low (Hoskins et al., 1985; Sakamoto and Takahashi, 2005; Hu et al., 2010). NEC-Siberia is one of the most preferred areas of COL occurrence, and the COLs are prominently associated with convective activities and above-normal precipitation events over NEC (Zhang et al., 2008; Hu et al., 2010). Following the method of Nieto et al. (2005), an extreme precipitation event is defined to be caused by COLs when a closed contour at 500 hPa height, or a closed region of SLP below 1,008 hPa accompanied by a trough at 500 hPa develops, alongside negative anomalies at 1,000–500 hPa thickness of more than 20 m in comparison with climatology within the synoptic area. In keeping with the calculations of Nieto et al. (2005), we used the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset (Kistler et al., 2001) to compute COLs. The number of percentile extreme events related to COLs as a function of the year for both sets of percentile composites is illustrated in Figure 5, with the time series of total number of extreme events.

Given our definition of short-lived precipitation extremes when falling within ±5% units of the percentile events, the contribution of COLs to extreme precipitation events is not significant in NEC, since the percentages of summertime extreme rainfall events induced by COLs are roughly the same, 21.2% and 21.1% in the 75th and 95th percentile cases, respectively. For 95th percentile events, most of extreme precipitation events that we have related to COLs are mainly concentrated during 1960s and 2000s (Figure 5a). While no distinct variations are seen over time for 75th percentile cases caused by COLs, despite exhibiting year-to-year variability (Figure 5b). Particularly, we show that the severe floods occurred in summer of 1998 also have close linkage with COLs, and 2 COL-induced extreme events responsible for the floods are found in the 75th and 95th percentile composites, respectively. The second largest accumulation of extreme precipitation events occurred in 1964 for 95th percentile cases, which is consistent with the maximum number of COL-induced extreme events. There are also a number of years having many extreme events but without any COL-induced events for both percentile cases, for example, 1963, 1984 and 2002. Furthermore, there is no remarkable trend of the time series of the total number of COL-induced extreme events during 1960–2015 across NEC. On the other hand, no statistically significant indication shows that COLs are responsible for the decreasing summertime rainfall events that have been documented in previous studies. These also suggest that other forcing factors, excluding COLs, may dominate the variations in this kind of extreme precipitation events over NEC.

To confirm the robustness of these results, we also calculate the COLs using the same method of Nieto et al. (2005) based on 55-year Japanese Reanalysis dataset (Figure S4). And very similar conclusions are obtained, 20.6% (77 out of 374) and 23% (84 out of 366) for 75th and 95th percentile rainfall events, respectively. These suggest that the different reanalysis datasets play an insignificant role to the changes of COL-induced events. Since the COL has multiple definitions, we further compute the COLs by utilizing another method adopted from Hu et al. (2010) with NCEP/NCAR reanalysis dataset (Figure S5), 31.8% (119 out of 374) and 33.3% (122 out of 366) in the 75th and 95th percentile events are detected, respectively. This definition of COL encompasses geopotential height and temperature, excluding component of wind, which is inconsistent with definition of Nieto et al. (2005) considering effects of wind, the results therefore show subtle discrepancies between these two methods. In general, our results are robust although they partly depend on the defining methods of COL.

4 SUMMARY

In this study, we define the short-lived extreme precipitation events and in detail examine the features of meteorological anomalies associated with this kind of extreme events in NEC. The synoptic structure of circulations prior to, during and after the precipitation extremes are composited to analyze the key synoptic-scale components responsible for the occurrence of extreme events.

The atmospheric circulation composites provide evidence of the extratropical anticyclones (cyclones) that pass through the NEC and produce large amount of extreme
precipitation. The divergence aloft in conjunction with lower pressures at surface favors the upward vertical motion of atmospheric circulations, meanwhile, the flow around low pressure region and high pressure to the east derived from associated wavetrain convey moisture fluxes into the NEC. Both provide suitable and sufficient conditions for the formation of above-normal rainfall events. Furthermore, the northwestward shift of WPSH accompanied with northward-shifted position of upper-level westerlies across NEC is enhanced southwesterly, which transports more moisture fluxes into NEC from the Tropics and triggers more extreme rainfall. It is worth noting that the significantly stronger anomalies of dynamical quantities are found for 95th percentile rainfall events compared with 75th percentile cases, as larger magnitude of precipitation (extreme rainfall events) are often associated with intensified large-scale atmospheric circulations with abundant moisture in comparison with heavy rainfall events (e.g., Gimeno et al., 2016).

The percentage of contribution of COLs to extreme precipitation events is almost the same for both sets of composites over NEC, 21.2% (80 out of 374) and 21.1% (78 out of 366) in the 75th and 95th percentile precipitation events, respectively. These indicate that not many summertime short-lived extreme precipitation events across NEC are found to be related to COLs on the whole, although the existing studies reported that the majority of COLs concentrate in summer over NEC compared with other seasons (Hu et al., 2010; Shen et al., 2011). The possible causes may be that most of summertime COLs linked to convective events in NEC have a duration threshold of 3 days (Hu et al., 2010), which are generally associated with persistent above-normal rainfall, rather than the short-lived precipitation extremes defined in this study. We also calculate the variability of COL-induced precipitation events using different definition of COL and reanalysis datasets, and obtain the similar findings as aforementioned analyses. It suggests that the results are relatively robust and independent on reanalysis dataset, even though they partly rely on COL definition. Additionally, summer mean and extreme precipitation has a slightly decreasing trend over NEC from 1960 to 2015, with none of them being statistically significant. And the contribution of COLs plays a minor role to the linear trend of this decreasing summertime rainfall, while other key factors dominating temporal changes in precipitation extremes across NEC are worthy of further research. What should be noted that there is still much we can examine about the extreme precipitation events over NEC by utilizing model techniques, which will form our following studies.

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