Inter-decadal change of the middle-upper tropospheric land–sea thermal contrast in the late 1990s and the associated Northern Hemisphere hydroclimate

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Although the middle-upper tropospheric land–sea thermal contrasts play very important roles in modifying global monsoon, the inter-decadal influences of the middle-upper tropospheric land–sea thermal contrasts in the Northern Hemisphere on the global monsoon have not investigated specifically. In this study, it is found that the summer middle-upper tropospheric zonal land–sea thermal contrast in the Eurasia–Pacific region changed from weak during the late 1980s and earlier middle 1990s to strong after the late 1990s. This feature indicates a strengthened zonal land–sea thermal contrast during summer, which drives a stronger than normal Northern Hemisphere summer monsoon, with a hypothermal and wet climate over most of the subtropical East Asian and tropical African monsoon regions. In addition, the extensive anticyclonic circulation anomalies together with the less precipitation results in a warm and dry climate over the arid and semiarid regions to the west and north of the monsoon region, such as central Asia, Mongolia, and Northeast Asia. The inter-decadal change of the middle-upper tropospheric zonal thermal contrast is also closely associated with the warming trends of the extratropical North Pacific and North Atlantic during summer. However, this link possibly reflects a response of the warming oceans to the local atmospheric variability.

KEYWORDS
inter-decadal change, the Northern hemispheric hydroclimate, tropospheric land–sea thermal contrast

1 | INTRODUCTION

As an important component of the global large-scale atmospheric circulation system, the global monsoon system greatly influences regional climates and plays a significant role in global climate change. The inter-decadal change of the global monsoon remains a critical topic of climate research. The thermal contrast between a continent and its adjacent oceans is associated with a different response to solar forcing and represents a major driver of the global monsoon change (Webster, 1987).

Many studies have been performed to determine influences of land–sea thermal contrasts on the global monsoon using different definitions of thermal contrasts, such as land–sea temperature differences at surface (Kamae et al., 2014a), the lower troposphere (Fu and Fletcher, 1985; Zhang et al., 2008), and the middle-upper troposphere (Li and Yanai, 1996; Dai et al., 2013). Kamae et al. (2014a) found that the surface land–sea thermal contrast between the Far East and its adjacent ocean is an essential factor affecting the inter-annual variability of the Northeast Asian monsoon. Li et al. (2010) and Zhu et al. (2012) suggested that under the...
global warming the meridional asymmetric warming with the prominent warming at the mid-high latitude of East Asia may generate a weakened meridional thermal contrast over East Asia, which may lead to a weakened trend of the East Asian summer monsoon during the 1950s–2010s. While, according to the thermal wind equation (Holton, 2004), the variations of winds are directly related to the atmospheric thermal contrasts instead of surface ones. Thus, surface land–sea thermal contrasts first affect the local atmospheric thermal contrasts and then modify winds. It is physically better to use the atmospheric thermal contrasts than to use surface land–sea thermal contrasts.

Moreover, we know that the Tibetan Plateau has a mean elevation above 5,000 m and most of the East Asian monsoon region also has a mean topographic elevation above 1,500 m. Clearly, it is unsuitable to calculate a large-scale atmospheric thermal contrast using the lower tropospheric temperatures in East Asia. Additionally, an observational research by Dai et al. (2013) investigates specifically the relative roles of upper and lower tropospheric thermal contrasts in driving Asian summer monsoons. It is found that the mean and variations of upper tropospheric thermal contrasts over the Asian monsoon sector are about three times larger and thus three times more important than lower tropospheric thermal contrasts in driving the mean Asian monsoon circulations and explaining their variations. Zhang and Zhou (2012; 2015) investigated the inter-annual and inter-decadal variations of the tropospheric meridional temperature gradient between the Yangtze River valley and northwestern China–Mongolia during summer and their relationships with El Niño–Southern Oscillation (ENSO). Recently, Zhao et al. (2015) found that the middle-upper tropospheric temperature over East Asia has significantly increased at the beginning of the 21st century, which connects closely to a significant intensified East Asian summer monsoon. It is evident that these studies focused on the local meridional thermal contrasts and their influences on the East Asian monsoon. However, there are fewer studies on the influences of the middle-upper tropospheric zonal thermal land–sea contrasts in the Northern Hemisphere on the global monsoon on the inter-decadal scales.

The global monsoon circulation is a complex system and can be affected by ocean–atmosphere interactions. Some studies documented the contributions of the Atlantic warming to the recent enhanced monsoon trends through tropical ocean–atmosphere interactions (Wang et al., 2013; Kamae et al., 2017) or mid-latitude atmospheric teleconnections (Lin et al., 2016; Wu et al., 2016; Zhou and Wu, 2016). The Sahel and northern African droughts during the 1970s–1990s are associated with the cooling of the Atlantic Ocean (Zhang and Delworth, 2006). The cooling of the Pacific also influences the Asian summer monsoon through the atmospheric teleconnections, resulting in an increase/a decrease of rainfall over the mid-low/high latitudes of East Asia since the late 1990s (Ueda et al., 2015; Zhou and Wu, 2016). A few studies also discovered that the Indian Ocean warming may lead to the enhanced monsoon over America, North Africa, and East Asia since the late 1970s (Ueda et al., 2015; Kamae et al., 2017). But this effect of the Indian Ocean is likely weaker compared to that of the Atlantic warming (Kamae et al., 2017) and the Pacific cooling (Ueda et al., 2015).

Moreover, Zhao et al. (2007) defined a middle-upper tropospheric zonal thermal contrast between the Eurasian–African region and the extratropics of the North Pacific and North Atlantic, and it is referred to as the Asian–Pacific Oscillation (APO) phenomenon. A positive phase of the APO is characterized by a warm troposphere over the Eurasian continent and a cold troposphere over the North Pacific and the North Atlantic. This anomalous pattern may be an important factor affecting the monthly-scale prediction skill of East Asian precipitation (Chen et al., 2016) and is also closely linked to the atmospheric circulation in the Northern Hemisphere. Corresponding to the amplifying of the land–sea thermal contrast between Eurasia and its adjacent oceans, the Northern Hemisphere summer monsoon intensifies. Meanwhile, summer precipitation enhances over the major monsoon regions in the Northern Hemisphere and summer precipitation reduces over the arid and semiarid regions of northern Africa, the Middle East, West Asia and middle and high latitudes of East Asia (Zhao et al., 2012a). This link between the APO and the atmospheric circulation and rainfall can be also captured by some climate models under the RCP8.5 scenario (Zhou et al., 2017).

Since the 1980s, significant global warming associated with anthropogenic forcing has been observed. This warming trend is higher over land than over ocean, with the strongest trend observed at the high latitudes of the Northern Hemisphere, such as Eurasia (Hansen et al., 2006). Furthermore, many studies have also suggested that the Pacific Decadal Oscillation (PDO) has shifted to a new cold phase since the late 1990s (Peterson and Schwing, 2003; Deser et al., 2004; Zhu et al., 2015), which may have contributed to the slowdown of global warming (hiatus) in the past decadal and half (Meehl et al., 2011; Kosaka and Xie, 2013; England et al., 2014; Dai et al., 2015). This shift leads to a warm SST over the extratropical North Pacific and a cold SST over the tropical central and eastern Pacific.

However, whether the warming over Eurasia and the changing of the SST over North Pacific cause a shift of a zonal thermal contrast between the land and ocean during recent warming decades remains to be determined. In this study, we utilize the APO to identify this zonal thermal contrast during summer and examine the inter-decadal variations of the APO and the associated summer monsoon circulation and hydroclimate (including precipitation, air temperature, and drought) over the Northern Hemisphere since the late 1970s.

## 2 | DATA AND METHOD

In the present study, the atmospheric circulation data come from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim reanalysis (Dee et al., 2011) with a horizontal resolution of 2.5° during 1979–2013. The
observed global precipitation and air temperature data are obtained from the University of Delaware (Willmott and Matsuura, 2001), and they have a horizontal resolution of 0.5°. The monthly Palmer drought severity index (PDSI) on a 2.5 × 2.5° grid (Dai et al., 2004) and the extended reconstruction of the sea surface temperature (SST) data (ERSST V3) on 2 × 2° grids from 1981 to 2010 (Smith et al., 2008) are used. The global land-based Hadley Centre climate extremes indices 2 (HadEX2) data sets employed in this study include the monthly maximum 1-day precipitation amount (R × 1 day) and percentile-based temperature indices of warm days (TX90P) from 1901 to 2010 (Donat, 2013) are available on 2.5 × 3.75° grids. Some missing data possibly appear over certain areas, such as Africa, central Asia, and Mongolia. Moreover, the composite and correlation analyses are utilized in this study, which the significance is examined by the Student’s t test.

3 | RESULTS

3.1 | Inter-decadal change of APO

Referring to the definitions of Zhou and Zhao (2010) and Huang et al. (2016), the zonal difference in summer (JJA) middle-upper tropospheric (500–200 hPa) temperature departure between East Asia (14°–45°N, 75°–120°E) and North Pacific (15°–46°N, 160°E–145°W) was used to represent the APO index. These two regions are shown in Figure 1a. Figure 1a shows the correlation pattern between the time series of the APO index (shown in Figure 1b) and the middle-upper (500–200 hPa) troposphere temperature during summer. This pattern is mainly characterized by an out-of-phase relationship between most of Eurasia and the North Pacific, with coherent variations over Eurasia, northern subtropical Africa, and Northeast Asia and an opposite variation over the extratropical North Pacific, also indicating a leading pattern of stationary waves over the Northern Hemisphere. The pattern is similar to the APO phenomenon obtained by Zhao et al. (2007), Zhou and Zhao (2010), and Liu et al. (2015). Thus, the APO may indicate the variability of the zonal thermal contrast between the European–central Asian region and the North Pacific. Corresponding to a positive (negative) APO index, an anomalous warm (cold) middle-upper troposphere is observed over most of Eurasia and an anomalous cold (warm) middle-upper troposphere is observed over the North Pacific, and these anomalies generally intensify (weaken) the zonal contrast between Eurasia and the North Pacific.

Figure 1b shows the temporal variation of the APO index from 1979 to 2013. This index exhibits a remarkable inter-decadal change. Its negative phase mainly occurs during 1986–1997 and the positive phase mainly appears since 1998. The moving t test (MTT) and Mann–Kendall test are applied to detect the abrupt change point of the inter-decadal shift of the APO phase. The result shows that the change point occurred in 1997/1998, significant at the 95% confidence level. This inter-decadal shift indicates a change of the zonal thermal contrast between Eurasia and the North Pacific from weak during the late 1980s and the earlier and middle
1990s to strong after the late 1990s. These changes correspond to a inter-decadal change in the summer rainfall in East Asia, with the main rainbelt shifting from the Yangtze River valley to the north of the Yangtze River in the late 1990s (Si et al., 2009; Si and Ding, 2013). In Europe, there is also a substantial shift in summer climate towards a pattern that was characterized by anomalously wet in northern Europe and hot/dry in southern Europe in the late 1990s (Sutton and Dong, 2012). Moreover, atmospheric and oceanic conditions in the North Pacific clearly exhibited a negative PDO pattern in the late 1998. A strong North Pacific High developed, leading to vigorous anticyclonic winds and anomalously strong coastal upwelling-favourable winds in the California Current (Peterson and Schwing, 2003). Referring to the persistence of the positive or negative APO values in Figure 1b, we select the periods 1986–1997 and 1998–2013 as the negative and positive APO decades, respectively, and analyse the inter-decadal changes of atmospheric circulation and climate associated with the APO via a composite analysis.

3.2 Inter-decadal change of atmospheric circulation and hydroclimate associated with APO

Figure 2a shows the zonal departure of tropospheric temperature ($T'$) changes associated with phase shift of APO. Corresponding to the enhancement of positive phase of APO since the late 1990s, significant positive anomalies of tropospheric $T'$ occur over Eurasia, and significant negative anomalies occur over Pacific Ocean. Their central values appear in the middle-upper troposphere. However, an opposite anomalies are found above 150 hPa. According to static equilibrium, a cold/warm air column is accompanied by shrinking/expanding and sinking/ascending, with variations of horizontal convergence and divergence and pressure systems in the troposphere (Zuo et al., 2011). Thus corresponding to the inter-decadal change of the tropospheric temperature anomalies indicated by the APO, significant changes also occur in zonal departure geopotential height ($H$). As seen from the changes in the vertical tropospheric $H$ pattern (Figure 2b), positive and negative $H$ anomalies occur over Asia at the upper and lower troposphere, respectively. An opposite feature is found over the central Pacific Ocean, where negative and positive $H$ anomalies are observed at the upper level and lower level, respectively. In the upper troposphere, the South Asian High with the contour 122,500 gpm at 200 hPa expands in space, which indicates an intensified and expanded South Asian High since the late 1990s (Figure 3a). Previous studies have shown that the enhanced South Asian High may contribute to an intensified East and South Asian monsoons (Krishnamurti et al., 1973; Zhang et al., 2002; Bansod et al., 2003) and an increased summer rainfall over East China and India, respectively (Wei et al., 2015). At 850 hPa, an anomalous anticyclonic circulation covers most of the North Pacific, while an anomalous cyclonic circulation appears over extratropical West Africa and the West Asia (Figure 3b). Associated with the anomalous cyclonic circulation over West Africa and West Asia, the anomalous southwesterly or southerly wind dominates tropical Africa, with the anomalous moisture convergence over western and central Africa. The anomalous southerly wind over Somali indicates a strengthened cross-equatorial flow, which may transport more water vapour into the South Asian monsoon region and strengthen the local moisture convergence. Over East Asia, the anomalous southerly wind to the west of the anomalous anticyclonic centre over the North Pacific prevails from the coasts of southern China to southern Japan and enhances the convergence of moisture over southern China as well as the Huanghe–Huaihe River valley of China (31°–38°N, 108°–118°E) and the Korean Peninsula.

Moreover, significant changes also occur in the tropospheric convergence and vertical motion. Figure 4 shows the evidence of these changes. In the lower troposphere (Figure 4a), we note the convergence and divergence anomalies of air masses over the Eurasian–northern African
continent and the North Pacific, respectively. These anomalies are accompanied by the upper-tropospheric divergence and convergence over the Eurasian–northern African continent and the North Pacific, respectively (Figure 4b). This coupling feature between the upper and lower levels may dynamically generate a large-scale zonal cell, with the ascending and descending branches over the Eastern Hemisphere (especially subtropical Asia and western North Pacific) and the central-eastern North Pacific, respectively (Figure 4c). As a consequence, summer precipitation generally increases over the subtropical East Asian (to the south of 35°N) and tropical African monsoon regions, except some scattered decreased precipitation in the Yangtze River valley of China (28°–31°N, 110°–120°E) (Figure 5a). The decreases/increases of summer precipitation over the Yangtze River valley/the Huanghe–Huaihe River valley indicate the enhancements in the local monsoon circulation and rainfall (Si and Ding, 2012; 2013), also providing more evidence for supporting an intensified East Asian summer monsoon since the late 1990s (Liu et al., 2012; Wu et al., 2016a).

The enhanced monsoon circulation and rainfall could generate anticyclonic anomalies over the adjacent arid regions that are often located to the west and north of the monsoon regions, which may be caused by the intensified descending motion in the arid region through the interaction between the Rossby wave and the mean state flow (Hoskins and Rodwell, 1995). Therefore, the extensive southerly wind associated with the anomalous anticyclonic centre over eastern Europe–central Asia (Figure 3b) may transport substantial warm and wet airflow into western Europe, thus resulting in a warm and wet climate in these regions (Sousa et al., 2016; Wu et al., 2016b). In addition, the large-scale anomalous anticyclonic circulation over the North Pacific stretches eastwards into western North America (Figure 3b), not favouring the transport of water vapour into western North America. Under the influence of these atmospheric circulation anomalies, summer precipitation decreases over eastern Europe, central Asia, Mongolia, northeast Asia, and western North America (Figure 5a). Meanwhile, the extreme 1-day precipitation also changes accordingly. It increases over western Europe and southern China but decreases over North China, northeast Asia, and western North America (Figure 5b).

The previous studies addressed that the “heat wave” phenomenon frequently attacked East Asia and Europe over the past 10 years (Ding and Qian, 2011; Sun et al., 2014; Chris tidis et al., 2015; Chen and Sun, 2017), which may be often attributed to the recent Arctic warming, the Pacific cooling, the Atlantic warming, anthropogenic activity, and other atmospheric circulation (e.g., Coumou et al., 2014; Kamae et al., 2014b; Zhou and Wu, 2016). Here we further exhibit a close inter-decadal link between the APO and extreme warm days. Figure 6a shows the inter-decadal change in surface air temperature over the Northern Hemisphere. Over the Asian–African monsoon regions, although the intensified southerly wind transports more warm and wet air masses northwards (Figure 3b), the increased rainfall may also reduce the local warming. Thus a hypothermal (Figure 6a) and wet climate (Figure 5a) occurs over most of the East Asian and African monsoon regions. Over Europe, northern Africa, West Asia, the middle and high latitudes of East Asia, and western North America, a warm and dry climate (Figure 6a) is possibly due to the decreased rainfall (Figure 5a) associated with the anticyclonic anomalies (Figure 3b). Meanwhile, an increase in extreme warm days is observed in Europe, the middle and high latitudes of East Asia, and western North America (Figure 6b).

The occurrence of regional droughts is associated with local precipitation and temperature. Figure 7 shows the inter-decadal change in the PDSI in the Northern Hemisphere. It is seen that the PDSI significantly decreases over the West Asia, northeastern Asia, and western North America because of low levels of local rainfall and high temperature. The PDSI significantly increases over western and central Africa near 10°–20°N, western Europe, Siberia, and the Far East region of Russia because of increased levels of local rainfall.

### 4 DISCUSSION ON FACTORS RESPONSIBLE FOR THE SUMMER APO VARIABILITY

In this section, we discuss a possible cause of the inter-decadal APO shift from two aspects: continental and oceanic thermal conditions. Although the equatorial central-eastern Pacific forcing is often considered as an important factor of
affecting global monsoon changes (e.g., Wang et al., 2013; Ueda et al., 2015; Zhou and Wu, 2016), there are no significant anomalies of SST over the tropical central-eastern Pacific in Figure 8. This result implies a weak effect of the tropical central-eastern Pacific SST on the APO and associated climatic anomalies on the present inter-decadal timescale. Meanwhile, it is noted that there are locally significant positive anomalies of SST in Figure 8. The increased SST over the extratropical North Pacific, similar to the PDO pattern, corresponds to the low-level anomalous anticyclonic circulation (Figure 3b), and the increased SST over the central-western Atlantic, similar to the Atlantic Multidecadal Oscillation (AMO) pattern, also corresponds to the local low-level anomalous anticyclonic circulation. This relationship between SST and low-level atmospheric circulation over the extratropical North Atlantic is different from that of Sutton (2005). Their study exhibited a positive SST–low-level cyclonic relationship over the Atlantic, which indicates an atmospheric response to the oceanic forcing. Some studies have documented that a positive SST–low-level anticyclonic relationship may reflect a response of SST to atmospheric anomalies through shortwave radiation and cloud–SST feedback processes during boreal summer (e.g., Battisti et al., 1995; Foltz and McPhaden, 2006a; 2006b; Wu and Kinter, 2010; Wu et al., 2012a; Zhao et al., 2012b). Moreover, the low-level anticyclone over the

**FIGURE 4** Atmospheric circulation change associated with the upper-tropospheric thermal contrast enhancement. (a) Inter-decadal changes (1998–2013 minus 1986–1997) of the 850-hPa velocity potential (unit: $10^6$ m$^2$/s) and divergent wind (unit: m/s) in summer. (b) Same as (a), except for 200 hPa. (c) Same as (a), except for longitude-height cross section of vertical circulation (zonal wind, unit: m/s, vertical velocity, unit: Pa/s) along the latitudes 15°–35° N. Values exceeding the 95% confidence level are stippled.
extratropical North Pacific and the extratropical central-western Atlantic associated with the APO (Figure 3b) may enhance positive advection of temperature to the extratropical North Pacific (Figure 9), and then lead to the local warm SST anomalies. Therefore, this SST–low-level anticyclonic relationship over the extratropics of the North Pacific and Atlantic shown in Figures 3b and 8 might reflect a response of SST to the local low-level anomalous anticyclones. Of course, this result is not to say that the SST anomalies in the North Pacific and Atlantic (PDO and AMO) cannot affect the climate over the extratropical Northern Hemisphere in other cases. For example, many previous studies have revealed that variations in the PDO and AMO can exert significant climate impacts in many regions, including North Africa, North and South America, South and East Asia, and Europe.

The Tibetan Plateau has experienced a pronounced warming since the late 1990s (Guo and Wang, 2011; Wu et al., 2012b; Si and Ding, 2013; You et al., 2017), and the warming over the Eurasian continent has not ceased, even with the occurrence of a global warming hiatus since the late 1990s (mainly associated with the cooling of the tropical central and eastern Pacific Ocean). This warming over Eurasia is also observed in Figure 6a. Some studies have shown that the warming Asian continent may heat the tropospheric air and enhance the local ascending motion (Wang et al., 2008; Zhao et al., 2011), which may result in middle-upper tropospheric warming and divergence over the Asian continent and an APO pattern (Zhao et al., 2011; Liu et al., 2017). Thus, the warming Asian land may cause a phase shift of the APO pattern and associated climate occurring since the late 1990s.

5 | SUMMARY

The APO reflects the leading mode of the Northern Hemisphere stationary wave, measuring the middle-upper tropospheric land–sea thermal contrast between the Eurasian continent and the North Pacific, as well as a regional meridional thermal contrast over East Asia. Previous studies (Zhao et al., 2007; 2012a) have noted that the APO is significantly associated with the summer monsoon and hydroclimate over the Northern Hemisphere at the inter-annual timescale. In this study, it is found that the APO also exhibits a remarkable inter-decadal variability during the recent decades, experiencing an inter-decadal shift in the late 1990s. From 1986 to 1997, the APO primarily occurred in a negative phase, whereas after that, it primarily occurred in a positive phase. Accompanying this phase transit, the atmospheric
land–sea thermal contrast between the Eurasian continent and the North Pacific generally intensifies, which further strengthens the subtropical East Asian and African summer monsoon. Summer precipitation is generally increased over the Huanghe–Huaihe River valley and the African monsoon region, but decreased over the arid and semiarid regions. Moreover, air temperature does not change significantly over the East Asian and African monsoon regions, whereas it increases significantly over the arid and semiarid regions. These changes have contributed to a hypothermal wet climate and moist soil over most of the East Asian and African monsoon regions, but a warm, dry climate and dry soil over...
parts of the arid and semiarid regions since the late 1990s. Recently, some studies documented that the upper-tropospheric teleconnection pattern in the Eurasia sector (Silk Road pattern) also experienced a notable inter-decadal change at 1996/1997 (Hong et al., 2017; Wang et al., 2017). Furthermore, this change is significantly associated with the inter-decadal climate change in Eurasia.

The phase shift of the thermal contrast indicated by the APO is closely associated with the warming trends of the extratropical North Pacific and Atlantic during summer. However, this link does not possibly reflect a forcing of oceans to the local atmospheric variability. Relative to the link between the APO and these oceanic anomalies, the tropical central-eastern Pacific SST has a weak relationship with the APO. On the other hand, warming of the Eurasian continent possibly exerts influences on the phase shift of the APO (Zhao et al., 2011; Liu et al., 2017).

This work demonstrates a close inter-decadal relationship between the middle-upper tropospheric land–sea thermal contrast and climate (rainfall and surface air temperature). However, it does not mean that the climate anomaly pattern in the Northern Hemisphere could not be affected by other external large-scale forcings from the inter-decadal variation of SST and polar sea ice. In the future work, it should be needed to further compare inter-decadal influences of ocean, land, and sea ice on the stationary wave and thermal contrast indicated by the APO from observations and numerical models.
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