Inter-annual variations of precipitation over the monsoon transitional zone in China during August–September: Role of sea surface temperature anomalies over the tropical Pacific and North Atlantic

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Funding information
the Chinese Academy of Sciences “The Belt and Road Initiatives” Program on International Cooperation: Climate Change Research and Observation Project, Grant/Award Number: 134111KYSB20160010; the National Natural Science Foundation of China, Grant/Award Number: 41461144001, 41721004, and 41605050

The present study investigates inter-annual variations of precipitation during transitional periods (August–September) of the rainy season over the monsoon transitional zone (MTZ) in China. More precipitation tends to occur over the MTZ during August–September when a significant anticyclonic anomaly simultaneously appears over the western North Pacific (WNP). Prominent southerly wind anomalies induced by the anticyclonic anomaly over the WNP contribute to more precipitation over the MTZ via transporting abundant water vapor northward. Sea surface temperature (SST) cooling in the tropical central-eastern Pacific and SST warming in the northern tropical Atlantic (NTA) are crucial to the formation of the anticyclonic anomaly over the WNP. In addition, it is showed that the significant impact of the SST warming in the NTA on the WNP anticyclonic anomaly is independent of the SST cooling in the tropical central-eastern Pacific. Atmospheric general circulation model experiments demonstrate that the SST warming over the NTA can produce an anticyclonic anomaly over the WNP via modulation of the Walker circulation with upward motion anomalies over the NTA and downward motion anomalies over the tropical central Pacific. The resultant negative precipitation anomalies over the tropical central Pacific further trigger an anticyclonic anomaly over the WNP via a Gill-type atmospheric response. The results suggest that SST anomalies in the tropical central-eastern Pacific and the NTA play a key driver for inter-annual variations of precipitation over the MTZ in China during August–September.

KEYWORDS
monsoon transitional zone, northern tropical Atlantic, precipitation, sea surface temperature, tropical central-eastern Pacific

1 INTRODUCTION

Monsoon transitional zone (MTZ) is the transitional belt between humid and arid regions (e.g., Qian et al., 2012; Wang et al., 2017). The MTZ in China is featured by a northeast–southwest-oriented pattern covering more than eight provinces, including Hebei, Gansu, Shanxi, Qinghai, etc. (Zhao et al., 2002). Studies have found that the MTZ in China has a fragile ecosystem, which is more sensitive to climate changes and vulnerable to natural disasters (e.g., Dai,
2011; Qian et al., 2012; Dai, 2013). Any deficiency or excess in precipitation during the rainy season has large impacts on the residential irrigation, animal husbandry, and social economics (e.g., Meng et al., 2010; Qian et al., 2012). For example, provinces in northern China, especially Shanxi and Gansu, experienced severe drought events in 1997 which brought about dry up of the Yellow River for 226 consequent days (Bai, 1999). In addition, an extreme precipitation event occurred in Zhouqu city of Gansu province in 2010, causing a serious debris flow and resulting in enormous property damages and human losses (Ren, 2014). Hence, it is important to improve our understanding of precipitation variations over the MTZ in China.

Previous studies have investigated inter-annual variations of the precipitation over China but mainly over the monsoon domain (e.g., Lu, 2005; Zhou and Yu, 2005; Ding et al., 2008; Han and Zhang, 2009; Ye and Lu, 2012). The leading mode of inter-annual variability of summer precipitation in east China is generally characterized by a meridional triple structure (e.g., Ye and Lu, 2012; Sun and Wang, 2015). This meridional triple mode is characterized by above-normal precipitation around the Yangtze River and below-normal precipitation over south China and north China, which has a close relationship with sea surface temperature (SST) anomalies in the tropical central-eastern Pacific (e.g., Hsu and Lin, 2007; Ding et al., 2009). Recent studies have validated that the leading mode of the summer precipitation over east China experienced a significant interdecadal change around the early 1990s, displaying a meridional dipole mode after the decadal change (e.g., Ding et al., 2008; 2009). The dipole precipitation mode after the 1990s has a close relationship with SST anomalies in the South China Sea and western North Pacific (WNP; e.g., Han and Zhang, 2009; Ye and Lu, 2012). Besides summer, precipitation variations during other seasons and regions are also closely associated with the tropical central-eastern Pacific SST anomalies. For example, Gu et al. (2018) reported that inter-annual variations of precipitation over south China during spring is closely connected to a zonal SST dipole in the tropical Pacific. In addition, Lu (2005) noted that inter-annual variations of precipitation anomalies over north China during its rainy season (i.e., July and August) are closely related to the SST anomaly in equatorial eastern Pacific.

The above studies primarily focused on the precipitation variations over the monsoon domain in China. However, inter-annual precipitation variations over the MTZ remain unresolved, especially during the transitional periods (i.e., August–September). Here, this study attempts to examine inter-annual variations of the precipitation during August–September over the MTZ in China and elucidates the related factors. The rest of this paper is organized as follows. Section 2 describes the data and methods. Section 3 examines inter-annual variations of precipitation anomalies over the MTZ in China and associated atmospheric circulation anomalies. Section 4 investigates key factors responsible for the formation of the anomalous anticyclone over the WNP, which plays important role in modulating inter-annual variations of precipitation anomalies over the MTZ. Section 5 provides a summary and discussion.

2 | DATA AND METHODS

The monthly precipitation data used in this study are provided by the National Meteorological Information Center of the Chinese Meteorology Academy (CMA) (Zhao et al., 2014; Zhao and Zhu, 2015) covering the period from 1961 to 2013. This precipitation dataset has a horizontal resolution of 0.5 × 0.5°, which is constructed based on more than 2,400 observational stations. The atmospheric circulation data are obtained from the ERA-Interim reanalysis from 1979 to the present, which is provided by the European Centre for Medium-Range Weather Forecast (ECMWF; Dee et al., 2011). The ERA-Interim reanalysis has a horizontal resolution of 0.5 × 0.5°. We also employ the monthly mean SST data from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST version 3b (Smith et al., 2008). This SST dataset has a horizontal resolution of 2 × 2°.

As this study focuses on investigating the variations on the inter-annual timescales, all the variables are subjected to a 2–9-year band-pass Lanczos filter to extract their interannual components (source code of the band-pass Lanczos filter is available at http://www.ncl.ucar.edu/Document/Functions/Built-in/filwgts_lanczos.shtml) (Duchon, 1979). Using the 2–7 or 2–11-year band pass Lanczos filter can obtain similar results (not shown). Statistical significance of correlation coefficient and anomalies based on linear regression is estimated according to a two-tailed Student’s t test. Here, the geographic location of MTZ in China in this study is defined as the overlaid region of decadal boundaries of land monsoon domain in China (Figure S1, Supporting Information), following the definition of the global monsoon domain proposed by Liu et al. (2009).

We have also performed a suite of numerical experiments to investigate the impact of SST anomalies in the tropical North Atlantic on the atmospheric circulation anomaly over the WNP by using the Community Atmosphere Model (CAM5.3) from the National Center for Atmospheric Research. The CAM5.3 has a horizontal resolution of 1.9 × 2.5° and 30 vertical levels with hybrid pressure-sigma vertical coordinate (Simmons and Burridge, 1981). More details for CAM5.3 can be found at http://www.cesm.ucar.edu/models/cesm1.0/cam/docs/description/. We will further introduce details of experiments in section 4.
To investigate inter-annual variations of precipitation over the MTZ in China during August–September, a precipitation index (MTZI) is first defined as regionally averaged precipitation anomalies over the MTZ. The MTZI in Figure 1a shows an obvious inter-annual variation during 1979–2013. We further examine spatial distributions of precipitation anomalies in China related to the MTZI. Figure 1b shows August–September averaged precipitation anomalies obtained by linear regression on the simultaneous MTZI during 1979–2013. Significant positive precipitation anomalies appear in the MTZ and surrounding regions during positive phase of the MTZI (Figure 1b).

Atmospheric circulation anomalies during August–September are further examined to reveal the changes in precipitation anomalies in China related to the MTZI. Figure 2 displays anomalies of winds and streamfunction at 850 hPa, water vapor flux integrated from 1,000 to 300 hPa, 500 hPa omega, and 200-hPa divergence during August–September obtained by regression upon the simultaneous MTZI. A pair of anomalous anticyclonic circulations are observed over the tropical north and south western Pacific, accompanied by significant southerly anomalies over east China (Figure 2a). In addition, an anomalous cyclone is found over the northern tropical Atlantic (NTA), albeit with weaker amplitude (Figure 2a). It should be noted that abundant water vapor is transported from the South China Sea and WNP northward to the MTZ due to the low-level southerly anomalies (Figure 2a,b). Significant upward motion and related high-level (i.e., 200 hPa) divergence anomalies are found over the MTZ (Figure 2c,d). Correspondingly, more precipitation occurs over the MTZ.

4 PHYSICAL PROCESSES FOR THE GENERATION OF THE ATMOSPHERIC CIRCULATION ANOMALY RESPONSIBLE FOR THE INTER-ANNUAL VARIATION OF PRECIPITATION OVER THE MTZ

The results shown above suggest that the anticyclonic or cyclonic anomaly over the WNP plays an important role in affecting inter-annual variations of precipitation over the MTZ in China during August–September. In the following, the possible factors responsible for the formation of the anticyclonic anomaly over the WNP are explored, particularly the tropical SST anomalies related to the MTZI, as reported in previous studies (e.g., Wang et al., 2000; Xie et al., 2009; Chang et al., 2016).

Figure 3a exhibits August–September SST anomalies obtained by regression upon the simultaneous MTZI. SST anomalies in the Indian Ocean are relatively weak and statistically insignificant, implying weak contribution of Indian Ocean SST anomalies to the WNP anticyclonic anomaly (Figures 2a and 3a). By contrast, a La Niña-like SST pattern is observed in the tropical central-eastern Pacific, with significant SST cooling in the tropical central-eastern Pacific and SST warming in the tropical western Pacific. The correlation coefficient between the Niño3.4 index and MTZI during simultaneous August–September reaches −0.40, which is statistically significant at the 95% confidence level (Figure 1a). Here, Niño3.4 index is defined as regionally averaged SST anomalies over 5°S–5°N and 120°–170°W, which is generally used to represent El Niño–Southern Oscillation (ENSO) variability (e.g., Anderson, 2007; Deser et al., 2012). Significant correlations can also be observed when Niño3.4 index leads the MTZI by 2 months (Figure 3c). In addition, most extreme values of the MTZI
are corresponding to extreme values in the Niño3.4 index (Figure 1a). This indicates that the significant correlation between the Niño3.4 index and the MTZI is not attributed to a few extreme events. Hence, the La Niña-like SST cooling may have a significant contribution to the formation of the anticyclonic anomaly over the WNP. In particular, the downward motion (Figure 3b) and related negative precipitation anomalies (not shown) over the tropical central Pacific triggered by the SST cooling (Figure 3a) could directly contribute to generation of the anomalous anticyclone over the WNP (Figure 4a) via a Gill-type atmospheric response (Gill, 1980).

Moreover, significant SST warming is also observed in the NTA (Figure 3a). Recent studies have shown that SST anomalies in the NTA can exert an impact on inter-annual variations of WNP subtropical high during boreal summer (e.g., Hong et al., 2014; Chen et al., 2015a; 2015b; Chang et al., 2016; Chen and Wu, 2017; Chen et al., 2018). This implies that formation of the anticyclonic anomaly over the WNP during August–September related to the MTZI may also be partly attributed to NTA SST anomalies. In the following, we further examine contributions of the SST warming in the NTA to the formation of the anticyclonic anomaly over the WNP in association with the MTZI. We first define a NTA SST index to represent inter-annual variation of the SST anomalies in the NTA. Based on the significant SST anomalies in the NTA shown in Figure 3a, the NTA SST index is defined as regionally averaged SST anomalies over 0°–20°N and 40°–60°W. This NTA SST index has a significant positive correlation with the MTZI during simultaneous August–September, with correlation coefficient being 0.50 significant at the 95% confidence level. In addition, significant correlations between the NTA SST index and the MTZI can also be found when the former leads the later by 2 months (Figure 3c, red solid line). Results obtained in this study are similar for the reasonable change of regions employed to define the NTA SST index (not shown). Our results suggest that the SST warming in the NTA may also have a contribution to the formation of the anticyclonic anomaly over the WNP related to the MTZI.
Previous studies have demonstrated that ENSO-related SST anomalies over the tropical central-eastern Pacific can exert an impact on the NTA SST anomalies via modulating the tropical Walker circulation or inducing atmospheric teleconnection pattern (e.g., Zuo et al., 2013; Chen et al., 2015a; 2015b; Chang et al., 2016). Hence, a question exists whether the significant connection between the MTZI and the NTA SST stems from ENSO? To verify that the NTA SST warming can lead to an anticyclonic anomaly over the WNP without ENSO-related impact, an ENSO-unrelated NTA SST index (NTA_res for short) is defined as follows:

\[ \text{NTA}_{\text{res}} = \text{NTA} - R \times \text{Niño3.4}, \]

where Niño3.4 and NTA represent Niño3.4 index and NTA SST index, respectively. \( R \) denotes the correlation coefficient between the Niño3.4 index and NTA SST index. NTA_res indicates the part of NTA SST index that is linearly unrelated to the Niño3.4 index. This method has been used in previous studies (e.g., Chen et al., 2013; Chen et al., 2015a; 2015b). We further examine evolutions of the correlation between the MTZI and the NTA_res SST index (Figure 3c). The NTA_res SST index still has a significant correlation with the MTZI during simultaneous August–September \((R = 0.40)\), which is statistically significant at the 95% confidence level (Figure 1a). In particular, most extreme values of the NTA_res SST index corresponds well with those of the MTZI (Figure 1a). Above evidences suggest that SST warming in the NTA has a significant connection with the anticyclonic anomaly over the WNP, which is critical to inter-annual variations of precipitation over the MTZ in China.

![Figure 3](image1.png)

**FIGURE 3** (a) SST (unit: °C), and (b) 500 hPa omega (unit: \(10^{-3} \text{ Pa/s}\)) anomalies during August–September obtained by regression upon the simultaneous August–September MTZI. Values of 500 hPa omega over the land in (b) are omitted. Stippling regions in (a, b) indicate SST and omega anomalies significant at the 95% confidence level, respectively. Positive (negative) value of omega indicates downward (upward) motion anomalies. (c) Correlation coefficients of the August–September MTZI with the 2-monthly mean Niño3.4 index (blue solid line), NTA SST index (red solid line), and NTA_res SST index (red dashed line) from preceding February–March to following October–November. Definitions of the Niño3.4 index, NTA SST index, and NTA_res SST index are provided in the text. Horizontal dashed lines in (c) indicate correlation coefficients significant at the 95% confidence level.

![Figure 4](image2.png)

**FIGURE 4** Anomalies of 850 hPa winds (vectors, unit: m/s) and streamfunction (shadings, unit: \(10^5 \text{ m}^2/\text{s}\)) during August–September obtained by regression upon the (a) minus one Niño3.4 index and (b) the NTA_res SST index during simultaneous August–September. Stippling regions in (a, b) indicate streamfunction anomalies significant at the 95% confidence level.
Figure 4b displays 850 hPa wind and streamfunction anomalies during August–September obtained by regression upon the NTA_res SST index during simultaneous August–September. Figure 5a,b exhibits the August–September divergent wind and velocity potential anomalies at 850 and 200 hPa, respectively, obtained by regression upon the NTA_res SST index. A significant cyclonic anomaly is found over the subtropical North Atlantic and a significant anticyclonic anomaly is seen over the WNP related to positive phase of the NTA_res SST index (Figure 4b). In addition, a pronounced anomalous Walker circulation is induced over the tropics with significant upward motion anomalies around the NTA and downward motion anomalies around the tropical central Pacific (Figure 5). The significant downward motion and related negative precipitation anomalies (figure not shown) over the tropical central Pacific induced by the positive NTA SST anomalies further contribute to formation of the anticyclonic anomaly over the WNP (Figures 4b and 5).

In the following, an atmospheric general circulation model (AGCM) is employed to elucidate the impact of the NTA SST anomalies on inter-annual variations of the precipitation over the MTZ in China during August–September. Three experiments are conducted by using CAM5.3. Details of experiments are listed in Table 1. The control experiment forced by observed monthly climatological SST is referred to as EXP_CLIM. The sensitive experiment is referred to as EXP_NTAPOS (EXP_NTANEG), which is forced by the observed SST anomalies over the NTA region obtained by regression upon the (minus one) NTA SST index during August–September plus the climatological SST. Each simulation lasts for 30 model years. The first 2 years of all simulations are considered as spin-up and the remaining 28 years are used for analysis. Here, the difference between a sensitivity run (i.e., EXP_NTAPOS or EXP_NTANEG) and a control run (i.e., EXP_CLIM) is computed to represent the model response to observed NTA SST anomalies.

Figure 6 shows the differences in winds and streamfunction at 850 hPa, precipitation, vertical velocity at 500 hPa, velocity potential and divergent winds at 850 and 200 hPa during August–September between experiment EXP_NTAPOS and EXP_NTANEG. As a response to the SST warming in the NTA, a significant cyclonic anomaly appears over the subtropical western North Atlantic as a Rossby wave type atmospheric response, accompanied by strong westerly winds over the tropical eastern Pacific and Atlantic (Figure 6a). In addition, a pronounced anticyclonic anomaly is found over the WNP, accompanied by significant southerly wind anomalies over eastern China, consistent with the observed (Figure 4b). Additionally, the AGCM experiment captures positive precipitation and upward motion anomalies over the MTZ strikingly well, as well as negative precipitation and downward motion anomalies over south China as a response to the NTA SST warming, albeit with statistically insignificant correlations (Figure 6b,c). Anomalous low-level convergence (high-level divergence) are also seen over the NTA and pronounced low-level divergence (high-level convergence) anomalies are found over the tropical central Pacific (Figure 6d–e). This is in good agreement with the observation (Figure 5). Hence, AGCM experiments demonstrate the contribution of NTA SST warming to the formation of the anticyclonic anomaly over the WNP related to inter-annual variations of the precipitation during August–September over the MTZ. Our results highlight that NTA

**TABLE 1** Details of numerical experiments

| Number | Name       | SST boundary conditions                                                                 | Integrated period |
|--------|------------|-----------------------------------------------------------------------------------------|-------------------|
| 1      | EXP_CLIM   | Climatological global SST during 1981–2010 with seasonal cycle                           | 2001–2030         |
| 2      | EXP_NTAPOS | Similar to EXP_CLIM, but for regressed SST anomalies over the region (0°–20°N, 20°–60°W) with respect to NTA SST index imposed on climatological SST | 2001–2030         |
| 3      | EXP_NTANEG | Similar to EXP_NTAPOS, but for regressed SST anomalies over the region (0°–20°N, 20°–60°W) with respect to (−1)^*NTA SST index imposed on climatological SST | 2001–2030         |
SST anomalies can exert impacts on the anticyclonic anomaly without the influence of ENSO.

5 | CONCLUSION AND DISCUSSIONS

This study investigates inter-annual variations of precipitation over the MTZ in China during August–September for the period 1979–2013. A precipitation index (MTZI) is first defined as the regional-averaged precipitation anomaly over the MTZ. During the positive phase of the MTZI, a significant anticyclonic anomaly is seen over the WNP, which induces pronounced southerly wind anomalies over East Asia. The anomalous southerly winds contribute to more precipitation over the MTZ via transporting abundant water vapor northward from the South China Sea and WNP to the MTZ. The formation of the anomalous anticyclone over the WNP associated with MTZ precipitation is attributed to the La Niña-like SST cooling in the tropical central-eastern Pacific and SST warming in the NTA. The pronounced negative precipitation anomalies over the tropical central Pacific induced by the La Niña-like SST cooling could directly induce an anticyclonic anomaly over the WNP via a Rossby wave type atmospheric response. Furthermore, the SST warming in the NTA can trigger an anomalous Walker circulation, with upward motion over the tropical Atlantic, and downward motion over the tropical central Pacific. The negative precipitation anomalies related to the downward motion
anomalies over the tropical central Pacific further contribute to the anticyclonic anomaly over the WNP. It is found that the significant impact of the NTA SST warming on the WNP anticyclonic anomaly and inter-annual variations of precipitation over the MTZ is independent of SST anomalies over the tropical central-eastern Pacific. AGCM experiments shed light on the contribution of the NTA SST warming to the formation of the anomalous anticyclone over the WNP via inducing anomalous Walker circulation over the tropics. Hence, SST anomalies in both the tropical central-eastern Pacific and NTA region are important for inter-annual variations of precipitation over the MTZ in China during August–September.

This study focuses on examining precipitation anomalies over the MTZ on the inter-annual timescale. Precipitation anomalies over the MTZ on other timescales, such as intra-seasonal, seasonal, and inter-decadal decadal timescales, remain to be explored. For example, previous studies have found that intra-seasonal atmospheric variability (such as the Madden and Julian Oscillation [MJO]) may play a significant role in modulating the precipitation anomaly over many parts of China (e.g., Lau et al., 1988; Madden and Julian, 1994; Lawrence and Webster, 2002; Shao et al., 2018). In particular, the convection activity related to MJO around the South China Sea can excite a northeastward Rossby wave train into north China, which further leads to precipitation anomalies there (Shao et al., 2018). Impacts of the atmospheric variations on the precipitation anomalies on the seasonal, intra-seasonal, and other timescales over the MTZ require further investigations.

ACKNOWLEDGEMENTS
We thank two anonymous reviewers for their constructive suggestions and comments, which led to a significant improvement in the paper. This study is supported jointly by the National Natural Science Foundation of China (Grant Nos. 41461144001, 41605050, 41721004, and 41661144016), the Young Elite Scientists Sponsorship Program by the China Association for Science and Technology (Grant No. 2016QNRC001), and the Chinese Academy of Sciences “The Belt and Road Initiatives” Program on International Cooperation: Climate Change Research and Observation Project (134111KYSB20160010).

Conflict of interests
The authors declare no potential conflict of interests.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**How to cite this article:** Zhao W, Chen W, Chen S, Yao S-L, Nath D. Inter-annual variations of precipitation over the monsoon transitional zone in China during August–September: Role of sea surface temperature anomalies over the tropical Pacific and North Atlantic. *Atmos Sci Lett*. 2019;20:e872. [https://doi.org/10.1002/asl.872](https://doi.org/10.1002/asl.872)