Contribution of the tropical western Atlantic thermal conditions during the preceding winter to summer temperature anomalies over the lower reaches of the Yangtze River basin–Jiangnan region

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ABSTRACT: Using the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis and National Oceanic and Atmospheric Administration extended reconstructed sea surface temperature (SST) data sets, we examine the preceding factors in the Atlantic Ocean contributing to summer high temperature anomalies over the lower reaches of the Yangtze River basin–Jiangnan (LRYB–JN) region. We find that summer LRYB–JN surface air temperature (SAT) anomalies are highly correlated with, and physically connected to, the preceding winter SST and SAT anomalies in the tropical western Atlantic (TWA) region ([10°–30°N, 60°–35°W] and [0°–10°N, 50°–35°W]). The effect of preceding winter thermal conditions in the TWA region can be explained by the following two mechanisms. Coupled with SST, positive TWA SAT anomalies can persist from the preceding winter to summer and excite a zonal wave train at middle latitudes extending from the Atlantic to Eurasia, with a deep and stable high pressure anomaly centred over the LRYB–JN region. As a result, high temperature anomalies occur over the LRYB–JN region. In addition to the above mechanism, the TWA SAT anomalies also exert an impact on summer LRYB–JN SAT by modulating the tropical Indian Ocean (TIO) SAT and SST variation, which causes summer LRYB–JN SAT anomalies. Given the contributions of TWA SAT anomalies, independent of and in concert with the TIO SAT variation, we define a preceding winter TWA–TIO SAT index, which measures the concurrent variation of TWA and TIO SATs. The preceding winter TWA–TIO index is more significantly correlated with the summer LRYB–JN SAT and therefore can reflect the latter better than the individual TWA or TIO SAT index.

KEY WORDS: winter sea surface temperature; summer surface air temperature; preceding factor; Atlantic Ocean; Yangtze River valley

Received 31 October 2016; Revised 18 March 2017; Accepted 30 March 2017

1. Introduction

The Yangtze River valley is one of the most economically developed areas in China. The agriculture, ecosystems, economy, and lives of inhabitants in this region are strongly related to summer climate anomalies, such as floods, droughts, and high temperature anomalies. As more long-duration (over eight consecutive days) high temperature events occur in this location relative to surrounding regions (Liu et al., 2015), high temperature anomalies over the Yangtze River valley should not be ignored. Therefore, understanding the factors and physical mechanisms associated with the occurrence of high temperature anomalies over the Yangtze River valley region will be of great benefit to socio-economic activities.

The western Pacific subtropical high (WPSH) and the South Asian high (SAH) are the most important systems influencing the Yangtze River valley region, and their anomalous states can cause summer high temperature anomalies in this region (Peng et al., 2007; Shi et al., 2009; Chen et al., 2013; Peng, 2014; Liu et al., 2017). Generally, both a stronger and westward-extended WPSH and a stronger and eastward-extended SAH can contribute to high temperature anomalies over the Yangtze River valley region. Furthermore, the superposed pattern of WPSH and SAH anomalies has been shown to contribute to most cases of high temperature anomalies (Liu et al., 2017).

The East Asian monsoon circulation and related climate anomalies can be modulated by sea surface temperature anomalies (SSTAs) in several key oceans. For instance, the El Niño–Southern Oscillation (ENSO) affects the climate over China through its influence on the WPSH and the SAH (Zhang et al., 1996; Wang et al., 2000; Yang et al., 2007; Xie et al., 2009; Huang et al., 2011). The SSTAs of the Indian Ocean (IO) can also adjust the Asian monsoon circulation and related climate anomalies (Yuan et al., 2008; Zhu et al., 2014; He and Zhu, 2015). In particular, many studies have indicated the contribution of the IO SST...
Figure 1. Distribution of the correlation coefficients between the summer LRYB–JNSAT index and the preceding winter (a) SAT and (b) SST during 1980–2015. Blue boxes indicate the tropical western Atlantic (TWA) region ([10°–30°N, 60°–35°W] and [0°–10°N, 50°–35°W]). The correlation coefficients over land are removed in (a). Yellow (red) shading denotes positive correlation significant at the 95% (99%) confidence level, and blue (purple) shading indicates negative correlation significant at the 95% (99%) confidence level.

state to the summer WPSH and SAH anomalies (Li et al., 2008a, 2008b; Xie et al., 2009; Chowdary et al., 2010; Wu et al., 2010a, 2010b, 2012, 2014; Wang et al., 2013) and associated high temperature anomalies over the Yangtze River valley (Hu et al., 2013). Liu et al. (2017) recently revealed that summer high temperature anomalies over the southern Yangtze River valley are closely related to preceding winter SAT and surface air temperature (SAT) anomalies over the tropical IO (TIO; Figure 1). Coupled with SST, positive SAT anomalies over the TIO region may persist from the preceding winter to summer, regulating the strength and location of the WPSH and SAH and eventually leading to summer high temperature anomalies over the southern Yangtze River valley (Liu et al., 2017).

The SSTAs in a few specific regions of the Atlantic Ocean and patterns of SST variability in these locations (e.g. the North Atlantic SST tripole and the Atlantic Multidecadal Oscillation), as well as the related patterns of atmospheric circulation anomalies, such as the North Atlantic Oscillation (NAO) and Arctic Oscillation, are closely linked to climate anomalies in adjacent Europe, North and South America, and Africa, on different timescales (Uvo et al., 1998; McHugh and Rogers, 2001; Sutton and Hodson, 2005, 2007; Kushnir et al., 2010; Nnamchi and Li, 2011; Sutton and Dong, 2012; Amorim et al., 2014; Myoung et al., 2015). Moreover, the SST and atmospheric circulation anomalies in the Atlantic Ocean can remotely affect Asian circulations and associated precipitation and temperature anomalies (Goswami et al., 2006; Lu et al., 2006; Sung et al., 2006; Li and Bates, 2007; Li et al., 2008a, 2008b, 2015; Wu et al., 2009c, 2010a, 2010b, Sun, 2012, 2014; Zuo et al., 2013; Chen et al., 2015). Wu et al. (2009c) suggested that an anomalous NAO in boreal spring can induce a tripole SST anomaly pattern in the North Atlantic, persisting into the ensuing summer and stimulating atmospheric teleconnection affecting the East Asian summer monsoon. Through forcing anomalous circulations extending from the North Atlantic to Northeast China via Eurasia, the tripole North Atlantic SST anomaly pattern in boreal spring can modulate summer temperature anomalies over Northeast China (Wu et al., 2010b). The above two studies indicated that the Atlantic sea–air anomaly in boreal spring can be regarded as a precursor for East Asian summer climate anomalies. However, the specific impact of the Atlantic sea–air anomaly on high temperature anomalies over the Yangtze River basin and adjacent region remains unclear. Is the tripole North Atlantic SST pattern or the SST anomaly in a specific region responsible for high temperature anomalies over this region? Is there a precursor in the Atlantic Ocean for the high temperature anomalies? Can this precursor be traced to boreal winter? How does the precursor affect the ensuing summer high temperature anomalies over the Yangtze River basin and adjacent region? © 2017 The Authors. International Journal of Climatology published by John Wiley & Sons Ltd Int. J. Climatol. 37: 4631–4642 (2017) on behalf of the Royal Meteorological Society.
With the above issues in mind, in this study we explore the preceding factors for summer temperature anomalies over the Yangtze River basin and adjacent region, primarily from the Atlantic Ocean, and investigate the associated physical mechanisms. The rest of the article is organized as follows. In Section 2, we describe the data and methods. The preceding factors of summer temperature anomalies are presented in Section 3. The associated physical processes are examined in Section 4. Finally, a summary is provided in Section 5.

2. Data and methods

In this study, we focus on the lower reaches of the Yangtze River basin–Jiangnan (LRYB–JN) region, because more long-duration (over eight consecutive days) high-temperature events occur in this region relative to the surrounding areas (Liu et al., 2015). The LRYB–JN region is also called the southern Yangtze River valley region in the work of Liu et al. (2017).

Li et al. (2016) revealed that both the temperature mean and extremely high temperature days increase consistently in nearly the whole of China throughout the four seasons. Liu et al. (2015) found that the variation of summer mean SAT is highly correlated with that of the number of long-duration high temperature events over the LRYB–JN region, even after removing their increasing linear trends. Thus, studying the causes for the variation of summer mean temperature over the LRYB–JN region is helpful for predictions of both summer mean SAT and high temperature event frequency. In this article, the summer (June, July, and August) LRYB–JN SAT index is defined as the area-mean summer SAT over the LRYB–JN region [(26°–32°N, 110°–122°E); black box in Figure 2(a)]. The monthly mean air temperature at 2 m during 1979–2015, obtained from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis data set (Kalnay et al., 1996), is used in this study. The detailed calculation of the wave-activity flux can be obtained from the literature (Takaya and Nakamura, 1997, 2001; Bueh and Kirtman, 1997, 2001), is used in this study. The detailed calculation of the wave-activity flux can be obtained from the literature (Takaya and Nakamura, 1997, 2001; Bueh and Nakamura, 2007; Liu et al., 2012b).

The statistical significance of the correlation coefficient is assessed using the Student’s t-test. Following Liu et al. (2017), we remove the linear trends of the summer LRYB–JN SAT index and all the other variables, because the summer LRYB–JN SAT experiences a linear increase (Liu et al., 2015), and we focus on the inter-annual variations in this study.

3. Precursory signals in the Atlantic Ocean for the summer LRYB–JN SAT

The correlations of the summer LRYB–JN SAT index with the previous winter (December, January, and February) SAT and SST (Figure 1) show that significant correlations mainly occur in the TIO and the tropical Atlantic Ocean. In a previous study (Liu et al., 2017), the effect of previous winter TIO SAT and SST anomalies on the summer
4. Potential mechanisms

4.1. Summer LRYB–JN SAT-related circulation anomalies

Figure 3 presents the correlation of the summer LRYB–JN SAT index with simultaneous 500- and 200-hPa geopotential height during 1980–2015, in which significant positive correlation is shown over the LRYB–JN region and adjacent East China Sea at both levels. By comparing to the climatological mean strength and location of the WPSH (blue contour in Figure 3(a)) and SAH (blue contour in Figure 3(b)), the anomalies of the WPSH and SAH, which correspond to the anomalous summer LRYB–JN SAT, can be clearly detected in Figure 3. The significant positive correlation at 500 hPa indicates a stronger (weaker) and westward-extended (eastward-shrunk) WPSH related to higher (lower) summer LRYB–JN SAT. Similarly, the positive correlation at 200 hPa reflects a stronger (weaker) and eastward-extended (westward-shrunk) SAH related to higher (lower) summer LRYB–JN SAT. A stronger and eastward-extended SAH, coupled with a stronger and westward-extended WPSH, constitutes a deep and stable high pressure anomaly throughout the troposphere over the LRYB–JN region. This high pressure anomaly governs the LRYB–JN region and accordingly results in decreased precipitation and cloudiness and increased downward solar radiation reaching the surface, eventually causing and maintaining summer high temperature anomalies in the region through a feedback process of land surface heat fluxes (Liu et al., 2017). This mechanism resembles the one contributing to high temperature over Hawaii, that is anomalous high pressure (descending motion) suppresses convection and cloud and thus increases downward solar radiation, which warms the Hawaiian Islands (Zhu and Li, 2017).

4.2. The persistence of TWA SAT from winter to summer

The delayed effect of preceding winter TWA SAT on summer SAT over the LRYB–JN region should be attributable to the persistence of SAT over the TWA. The correlation of the preceding winter TWA SAT index with winter, subsequent spring and summer SAT fields shows significant positive correlation covering the TWA, signifying the persistence of SAT anomalies over the TWA region (Figures 4(a)–(c)). As a result of this persistence, the winter TWA SAT index can indicate well a summer SAT anomaly over the TWA region. The winter
TWA SAT index also shows a significant positive correlation with winter, spring, and summer SSTs in the TWA region (Figures 4(d)–(f)), similar to Figures 4(a)–(c). This implies that the SST and SAT anomalies over the TWA are tightly coupled and that the ‘memory’ effect of the ocean seems to be responsible for the persistence of TWA SAT anomalies from winter to summer.

4.3. The effect of previous winter TWA SAT

Corresponding to a higher winter TWA SAT index, positive SST and related SAT anomalies govern the TWA region and persist from winter to summer. Figure 5 illustrates summer geopotential height anomalies at different levels obtained by regression on the preceding winter TWA SAT index. In response to positive SST and SAT anomalies over the TWA region persisting into summer, significant negative and positive geopotential height anomalies appear at the lower (Figure 5(a)) and upper (Figure 5(d)) tropospheric levels, respectively. Furthermore, corresponding to positive SST and SAT anomalies over the TWA region, significant positive geopotential height anomalies throughout the troposphere appear over the mid-latitude North Atlantic (MNA), centred around \(40^\circ N, 30^\circ W\), forming a barotropic high pressure anomaly over this position (Figures 5(a)–(d)).

In the climatological mean wind field in the upper troposphere, there are southwesterly winds from the TWA region to the MNA region during summer (figure not shown), which may induce a southwest–northeast-oriented anomalous vertical circulation linking the TWA...
heating to the geopotential height anomaly over the MNA region. Along a vertical cross section from the TWA to the MNA (i.e. along the pink diagonal lines in Figure 5), anomalous geopotential heights and vertical circulations obtained by regression on the preceding winter TWA SAT index are presented in Figure 6. Corresponding to positive SST and SAT anomalies over the TWA region, local upward motion strengthens and results in negative height anomalies at lower levels and positive height anomalies at higher levels in situ. This anomalous upward flow over the TWA region turns and moves northeastwards along the upper-tropospheric southwesterly winds, and ultimately descends over the MNA region, leading to a high pressure anomaly throughout the troposphere in situ. This further supports that higher TWA SAT and SST anomalies, which persist from winter to summer, can excite a deep high pressure anomaly over the MNA region by modulating anomalous vertical circulations between the TWA and MNA regions.

The correlation between the previous winter TWA SAT index and summer 500-hPa geopotential height (Figure 7(a)) also shows that there is a significant positive correlation over the MNA region, with a correlation coefficient of over 0.60 centred near (40°N, 30°W). This significant correlation should be due to the impact of the TWA SAT–SST coupled variation on the MNA geopotential height anomalies. Moreover, the MNA height index, which is defined as the area-mean summer 500-hPa geopotential height over the MNA region ([32°–48°N, 45°–23°W]; blue box in Figure 7(a)), is significantly correlated with the previous winter TWA SAT index during 1980–2015, with a correlation coefficient of 0.60.

As shown in Figure 7(a), in the downstream of the MNA region, we can also detect two negative correlations over Western Europe and to the east of the Caspian Sea, and two significant positive correlations over the East European Plain and East Asia. The height anomalies associated with the variation of TWA SAT display a positive–negative–positive–negative–positive teleconnection pattern extending from the MNA region to East Asia, implying that higher TWA SAT and SST anomalies persisting from winter to summer can stimulate a downstream development of an Atlantic–Eurasian wave train and induce atmospheric circulation anomalies over East Asia, in particular contributing to a positive height anomaly over the LRYB–JN region during summer. A similar wave train pattern related to the TWA SAT can also be identified at the 200-hPa level (Figure 7(b)), indicating that higher TWA SAT and SST anomalies can also cause a positive 200-hPa height anomaly over the

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*Int. J. Climatol.* 37: 4631–4642 (2017) on behalf of the Royal Meteorological Society.
Figure 6. Summer anomalous geopotential height (contours and shading; units: gpm) and vertical circulation (red streamline arrows) along a vertical cross section from the TWA region to the MNA region (pink diagonal line in Figure 5). Yellow (orange) shading denotes that positive anomalies are significant at the 95% (99%) confidence level, and blue (purple) shading indicates negative anomalies significant at the 95% (99%) confidence level.

Figure 7. Correlation between the previous winter TWA SAT index and summer (a) 500- and (b) 200-hPa geopotential height during 1980–2015. Yellow (red) shading denotes positive anomalies significant at the 95% (99%) confidence level. The blue dashed arrow lines indicate the path of the zonal wave train, which is determined by the propagation of the wave-activity fluxes shown in Figure 8. The blue box in (a) denotes the MNA region (32°–48°N, 45°–23°W), which was selected to define the MNA height index associated with the TWA SAT variation.

The LRYB–JN region by inducing such a wave train pattern. As a part of the wave train pattern, the positive 500- and 200-hPa height anomalies over the LRYB–JN region (Figure 7), which are highly consistent with the summer LRYB–JN SAT-related height anomalies (Figure 3), reflect a stronger and eastward-extended SAH and a stronger and westward-extended WPSH, respectively. The vertically superposed SAH and WPSH anomalies constitute a deep and stable high pressure anomaly and eventually result in summer high temperature anomalies over the LRYB–JN region.

To further reveal the effect of the previous winter SAT anomalies on the summer Atlantic–Eurasian wave train pattern, we present the composite difference of the summer wave-activity fluxes between the years with the high- and low-TWA SAT indices (high minus low), in which 7 years (1980, 1981, 1988, 1998, 2005, 2007, and 2010) with the previous winter TWA SAT index greater than 1.0 standard deviation (σ), and 5 years (1989, 1992, 1993, 1994, and 2001) with the index smaller than −1.0σ, are chosen to make the composite difference (Figure 8). Corresponding to the higher TWA SAT, a strong convergence of wave-activity fluxes (dark shading) can be seen to the west of Western Europe, indicating that Rossby wave energy has accumulated and formed a source of wave energy over this region. The anomalous wave-activity fluxes (purple arrows) clearly show the propagation of Rossby waves from the MNA region to East Asia. Along the propagation path of Rossby waves (red line with an arrow), anomalous wave-energy divergences and convergences appear in turn.
over downstream areas, which implies that the TWA SAT anomaly can remotely affect East Asian climate anomalies through the propagation of Rossby waves. Note that the teleconnection in the geopotential height field related to the previous winter TWA SAT anomalies (Figure 7) is along the propagation path of Rossby waves (blue line with an arrow in Figure 7), consistent with the path in Figure 8. This further verifies that the teleconnection pattern across the Atlantic–Eurasian region should be considered as a Rossby wave train induced by the previous winter TWA SST and SAT anomalies.

In Figure 6, it is also noteworthy that the positive SST anomaly in the TWA excites the upward-motion anomalies during summer. The upward-motion anomalies can lead to stronger convection activities and hence less downward solar radiation reaching the Earth’s surface, which is, in turn, conducive to lowering the SSTs in the TWA region during summer. This is a negative-feedback process, which to some extent disarranges the statistical relationship of the TWA SST/SAT with the anomalous upward motion in situ and related geopotential height anomalies over the MNA region. Therefore, the correlation coefficient between the summer TWA SAT index and the simultaneous MNA height index is only 0.27, which is statistically insignificant. Correspondingly, the downstream circulation anomalies from the MNA to East Asia during summer is also different from the summer LRYB–JN SAT-related circulation anomalies. As a result, the summer LRYB–JN SAT has no close statistical relationship with the simultaneous TWA SAT index. However, the Rossby wave pattern contributing to summer SAT anomalies over the LRYB–JN region has been formed during the process of negative feedback. Therefore, the background of warmer SST/SAT persisting into summer in the TWA tends to cause warmer SAT over the LRYB–JN region, albeit there is the process of negative feedback involved during summer.

A series of physical processes that explain the delayed effect of the preceding winter TWA SAT and SST anomalies on summer SAT anomalies over the LRYB–JN region can be summarized as follows. First, higher TWA SAT coupled with higher SST can be maintained into summer from the preceding winter due to the ‘memory’ effect of the oceans. Second, higher TWA SAT and SST anomalies during summer trigger a deep high pressure anomaly over the MNA region during summer by regulating anomalous vertical circulations between the TWA and MNA regions. Meanwhile, originating from the MNA high pressure anomaly, a zonal wave train appears across downstream Eurasia, with a deep and stable high pressure anomaly over the LRYB–JN region. Finally, summer positive SAT anomalies occur over the LRYB–JN region under the control of this high pressure anomaly.

4.4. The contribution of previous winter TWA SAT independent of and in concert with the TIO SAT

The variation of SSTs in the Atlantic Ocean can remotely stimulate circulation anomalies over the IO and accordingly give rise to SSTAs in the IO (Rong et al., 2010). Moreover, the IO has a relay effect, through which the SST anomaly in the tropical Atlantic can exert a remote impact on the circulation in the western North Pacific and related climate anomalies in situ (Yu et al., 2016). The correlation between the winter TWA SAT index and simultaneous SAT field (Figure 9(a)) also shows that there are significant positive correlations over the TIO, verifying that the variation of TWA SAT/SST is not independent from that of TIO SAT/SST. Coupled SST and SAT anomalies in the TWA can result in SST and SAT anomalies in the TIO. The TIO SST and SAT anomalies cause increased Indian summer monsoon precipitation and associated condensational heating, which regulate the strength and location of the WPSH and SAH and eventually result in summer high temperature anomalies over the LRYB–JN region. The effect of the TIO SST and SAT anomalies has recently been demonstrated in detail by Liu et al. (2017). The above physical processes indicate that, in addition to forcing an Atlantic–Eurasian wave train, the TWA SAT may also affect the summer LRYB–JN SAT by adjusting the variation of the TIO SST and SAT.

To further demonstrate the individual effect of the Atlantic Ocean, the partial correlation between winter SAT and the simultaneous TWA SAT index after removing the variability of the TIO SAT index is shown in Figure 9(b). Here, the TIO index is defined as the winter SAT averaged over the TIO region [20°S–15°N, 40°–100°E]; black box in Figure 9].
that there are significant positive correlations over the TWA region and no significant positive correlations over the TIO, which confirms that the TIO-independent TWA SAT index retains the variation of TWA SAT and eliminates the response of SAT in the TIO to the TWA SAT and SST anomalies.

Figure 10(a) presents the partial correlation between summer SAT and the previous winter TWA SAT index after removing the variability of the TIO SAT index, in which we can clearly identify significant positive correlation over the LYRB–JN region, with a center of the positive correlation located in the east of the LRYB–JN region, albeit the significance is lower than that between the previous winter original TIO-related TWA SAT index and summer SAT. The partial correlation coefficient between the previous winter TIO-independent TWA SAT index and the summer LRYB–JN SAT index during 1980–2015 is 0.39, still significant at the 95% confidence level. This result suggests that the individual effect of previous winter TWA SAT and SST anomalies contributes to summer SAT anomalies over the LRYB–JN region. That is, the preceding winter TWA SAT can affect summer SAT over the LYRB–JN region by exciting an Atlantic–Eurasian wave train pattern, even though the response of the TIO SST and SAT anomalies is absent.

Liu et al. (2017) indicated that the preceding winter SAT anomalies over the TIO region can affect summer LYRB–JN SAT. As such, the preceding winter TIO SAT index, which is defined as the preceding winter SAT averaged over (5°–15°N, 55°–75°E) and (0°–15°S, 40°E–55°E), is considered as an important predictor for summer SAT temperature anomalies over the LYRB–JN region (Liu et al., 2017). Moreover, the partial correlation between summer SAT and the preceding winter TTO SAT index after removing the variation of the TWA SAT index (Figure 10(b)) also shows significant positive correlation over the LRYB–JN region, centred in the west of the LRYB–JN region. The partial correlation coefficient between the previous winter TWA-independent TIO SAT and summer LRYB–JN SAT indices is 0.34 during 1980–2015, also significant at the 95% confidence level.
The results indicate that the individual effects of the previous winter SAT and SST anomalies over both the TWA and TIO regions contribute to the variation of the summer LRYB–JN SAT, and the areas affected by the two individual indices seem to compensate each other over the LRYB–JN region.

Considering the effect of previous winter TWA SAT independent of and in conjunction with the TIO SAT, we speculate that the synthesized effect of the preceding winter TIO and TWA SAT anomalies may modulate the summer LRYB–JN SAT more effectively. The arithmetic mean of the normalized TWA and TIO SAT indices is denoted as a TWA–TIO SAT index to measure the synthesized variation of TWA and TIO SATs. The correlation between the previous winter TWA–TIO SAT index and summer SAT (Figure 10(c)) shows that significant positive correlation appears over the LRYB–JN region, with a correlation center of over 0.60. The correlation coefficient of the summer LRYB–JN SAT index with the preceding winter TWAO–TIO SAT index during 1980–2015 reaches 0.60, significant at the 99.9% confidence level, and higher than that with the preceding winter TIO-independent (0.39), original TIO-related TWA (0.53), TWA-independent TIO (0.34), and original TWA-related TIO (0.53) SAT indices.

In addition, the 20-year running correlation coefficient between the previous winter TWA–TIO SAT index and the summer LRYB–JN SAT index (Figure 11(a)) always exceeds the 95% confidence level, which is higher than the 20-year running correlation coefficient between the previous winter TWA SAT index and the summer LRYB–JN SAT index throughout the whole period (Figure 11(b)). The latter shows a decrease in the correlation coefficient from the 95% to approximately the 90% confidence level since 1991 (Figure 11(b)). The results imply that the preceding winter TWA–TIO SAT index can be considered as a more stable and better predictor for the summer LRYB–JN SAT than the TWA SAT index. That is, the new TWA–TIO SAT index effectively improves the ability in forecasting summer SAT anomalies over the LRYB–JN region.

5. Summary

This paper explores the preceding factors in the Atlantic Ocean contributing to summer SAT anomalies over the LRYB–JN region. We find that summer LRYB–JN SAT anomalies are closely associated with anomalous previous winter SAT over the TWA region ([(10°–30°N, 60°–35°W) and (0°–10°N, 50°–35°W)], and therefore should be considered as an important precursor.

Coupled with SST in the TWA, positive TWA SAT anomalies can be maintained into summer from the preceding winter. Through modulating anomalous vertical circulations between the TWA and MNA regions, the TWA SST and SAT anomalies induce anomalous high pressure over the MNA region during summer. Originating from this high pressure anomaly over the MNA region, a series of anomalous circulations extend downstream through Eurasia to East Asia, forming a zonal wave train in the middle latitudes. As a part of the wave train, a deep and stable high pressure anomaly appears over the
LRYB–JN region and consequently results in summer SAT anomalies in situ. That is, the TWA SAT anomalies persisting from the preceding winter to summer can cause the summer LRYB–JN SAT anomalies by inducing a Rossby wave train across the Atlantic–Eurasian region. However, the detailed mechanisms of the formation of the Rossby wave train remain unclear, which should be further investigated in the future. Especially, we should further examine whether the perturbation heating over subtropical Asia, which triggers an Asia–North America teleconnection along the subtropical westerly jet stream during boreal summer (Zhu and Li, 2016), can also, together with TWA SST and SAT anomalies, modulate the Rossby wave train contributing to the summer LRYB–JN SAT anomalies.

In addition, the TWA SAT and SST anomalies can affect the variation of SAT and SST in the TIO. The positive TIO SAT and SST anomalies result in increased Indian monsoon precipitation over the northwestern India and Arabian SAT and SST anomalies result in increased Indian monsoon precipitation. Consequently, these teleconnections modulate the teleconnection along the subtropical westerly jet stream. In brief, the TWA SAT anomalies can also exert an impact on the summer LRYB–JN SAT by adjusting the TIO SAT and SST variation.

Although the TWA SAT and SST anomalies are closely related to the TIO SAT and SST anomalies, the individual effects of the TWA SAT and SST anomalies should not be ignored, because they can modulate the summer LRYB–JN SAT by inducing an Atlantic–Eurasian wave train, which is to some extent independent from the contribution of the TIO SAT and SST anomalies. To measure the synchronized variation of TWA and TIO SAT, we define a preceding winter TWA–TIO SAT index, which is highly correlated with the summer LRYB–JN SAT during 1980–2015. Moreover, the 20-year running correlations further reveal that, relative to the TIO SAT index, the preceding winter TWA–TIO SAT index has a more stable relationship with the summer LRYB–JN SAT. Therefore, the preceding winter TWA–TIO SAT index is a better predictor for the summer LRYB–JN SAT.

This study focuses on the effects of preceding factors in the Atlantic Ocean. Clearly, the summer LRYB–JN SAT is also influenced by other external forcings, such as soil moisture, snow cover, sea ice, and the land–sea thermal contrast between East Asia and the western Pacific, which play important roles in regulating Asian climate (Douville and Royer, 1996; Yang and Lau, 1998; He et al., 2007; Wu and Kirtman, 2007; Wu et al., 2009a, 2009b; Zhang and Zuo, 2011; Liu et al., 2012a; Zhu et al., 2012b). These boundary conditions may also be used as predictors and therefore merit further study. In addition, the synergized effects of SAT–SST coupled anomalies in conjunction with the above land boundary conditions remain unclear and should be further investigated in the future.

Acknowledgements

We acknowledge the support of the National Natural Science Foundation of China (41375090, 91437218, and 41221064), the National Basic Research Program of China (grant no. 2014CB953904), the Special Project of the China Meteorological Administration (grant no. GYHY201406001), and the Basic Research Fund of the Chinese Academy of Meteorological Sciences (grant no. 20152001).

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