Interannual Variations in Summer Precipitation in Southwest China: Anomalies in Moisture Transport and the Role of the Tropical Atlantic

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ABSTRACT

Using a Lagrangian trajectory model, contributions of moisture from the Indian Ocean (IO), the South China Sea (SCS), the adjacent land region (LD), and the Pacific Ocean (PO) to interannual summer precipitation variations in southwestern China (SWC) are investigated. Results show that, on average, the IO, SCS, LD, and PO contribute 48.8%, 21.1%, 23.6%, and 3.7% of the total moisture release in SWC, respectively. In summers with the above-normal precipitation, moisture release from the IO and SCS increases significantly by 41.4% and 15.1%, respectively. In summers with below-normal precipitation, moisture release from the IO and SCS decreases significantly by 44.2% and 24.6%, respectively. In addition, the moisture anomalies from the four source regions together explain 86.5% of the total interannual variances of SWC summer precipitation, and the IO and SCS only can explain 75.7%. Variations in moisture transport from the IO, SCS, and LD to SWC are not independent of one another and are commonly influenced by the anomalous anticyclone in the western North Pacific Ocean, which enhances the moisture transport from the IO and SCS by the anomalous southwesterlies over its northwestern quadrant but reduces that from the LD east of SWC by the anomalous westerlies along its northern edge. Anomalous warming in the tropical Atlantic Ocean can modify the Walker circulation, induce anomalous descending motion over the central tropical Pacific, and excite the anomalous anticyclone in the western North Pacific as the classic Matsuno–Gill response. The observed impacts of the tropical Atlantic warming on the anomalous anticyclone and summer precipitation in SWC can be well reproduced in an atmospheric general circulation model.

1. Introduction

Southwestern China (SWC) has distinct wet and dry seasons (Fig. 1). The wet season in boreal summer receives over 50% of the annual precipitation but experiences substantial year-to-year variations. This often increases local environmental stress and brings considerable losses in the agricultural and economic sectors. For example, the precipitation deficit in the summer of 2011 affected 98.4 million people and caused a direct economic loss of approximately 4.8 billion U.S. dollars (Song et al. 2012). Hence, it is important to reveal underlying mechanisms responsible for the summer precipitation variations for better prediction and mitigation.

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Summer precipitation in SWC is substantially impacted by the East Asian summer monsoon (EASM), which comprises complex dynamical, thermal, and hydrological processes (e.g., Wang and Ho 2002; Ding and Chan 2005). In a broad sense, the EASM can be regarded as a large-scale atmospheric circulation system, redistributing air moisture from adjacent regions to East Asia and introducing precipitation there. In this regard, air moisture transport is an essential component of the EASM. As revealed by Huang et al. (1998), meridional moisture transport is dominant in the EASM. Summer precipitation in southern China is mainly fueled by moisture supply from the Bay of Bengal (BOB) and South China Sea (SCS) (Simmonds et al. 1999). Eastern SWC is greatly impacted by the moisture transport from the BOB (Li et al. 2010). The tropical Indian Ocean (IO), BOB, SCS, and Pacific Ocean (PO) are the major moisture sources for summer monsoon precipitation over the Yangtze-Huaihe River valley (Jiang et al. 2013). In addition, the leading patterns of large-scale

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FIG. 1. (a) The geographical location of SWC (thin dark border lines) and the distribution of observation stations (dark dots). (b) The monthly climatology (gray bars) and standard deviation (dark line) of SWC precipitation (mm month⁻¹) for the period of 1979–2015.

summer precipitation anomalies in China are mainly caused by anomalies in the large-scale moisture transport that can be driven by the anomalous anticyclone in the western North Pacific (Zhou and Yu 2005).

Formation of the anomalous anticyclone in the western North Pacific has been investigated extensively due to its significant impacts on the Asian climate and its close relation with El Niño–Southern Oscillation (ENSO) (e.g., Wang et al. 2000; Wang and Li 2004; Xie et al. 2009; Wu et al. 2017a,b; Yuan et al. 2019). Remote forcing of the positive SST anomalies in the central-eastern tropical Pacific related to El Niño can induce the anomalous anticyclone from the mature winter of El Niño to the decaying spring by generating negative SST anomalies in the western North Pacific via anomalous northerlies and local air–sea interaction (e.g., Wang et al. 2000; Wu et al. 2017a,b). Also, El Niño can trigger the IO basin warming in its mature winter (Klein et al. 1999). This anomalous warming can persist until the subsequent spring and early summer and maintain the anomalous anticyclone in the western North Pacific by exciting the westward-propagating warm Kelvin waves and the resultant low-level convergence in the western tropical Pacific and divergence in the western North Pacific (e.g., Xie et al. 2009, 2016). A recent study by Yuan et al. (2019) showed that the zonal SST gradient in the western-central tropical Pacific, similar to La Niña Modoki, can directly excite the anomalous anticyclone in late summer. The tropical Atlantic Ocean also plays a role in the anomalous anticyclone (e.g., Rodríguez-Fonseca et al. 2009; Losada et al. 2010; Ding et al. 2012; Martín-Rey et al. 2015; Polo et al. 2015; Yu et al. 2016). At the interannual time scale, anomalous warming of the tropical Atlantic in summer can modulate the Walker circulation and cause anomalous descending motion and low-level divergence over the central tropical Pacific. This not only can trigger the occurrence of El Niño in the subsequent winter through the local

Bjerknes feedback (Bjerknes 1969) but also can induce the anomalous anticyclone in the western North Pacific via the classic Matsuno–Gill response (Matsuno 1966; Gill 1980), influencing moisture transport to China (e.g., Hong et al. 2014; Jin and Huo 2018).

Many studies on moisture transport use the Eulerian method to diagnose sources of moisture (e.g., Simmonds et al. 1999; Zhou and Yu 2005; Zhu et al. 2014). This method describes the air velocity and moisture at different grids in space at a given moment or over an averaged period. Hence, it does not reflect the real trajectories of air parcels carrying moisture from the source to the target regions, hindering establishment of the source–receptor relationship of air moisture (Sun and Wang 2014a,b). To this end, the Lagrangian method is a better alternative. It can trace the backward trajectories of air parcels from a user-specified grid to different source regions (e.g., Draxler and Hess 1997, 1998). By this method, Brimelow and Reuter (2005) found the Gulf of Mexico to be an important water vapor source for extreme precipitation in the Mackenzie River basin. Perry et al. (2007) revealed the importance of water vapor transport in the lower troposphere from the Great Lakes in North America in forming snowfall over the southern foothills of the Appalachian Mountains. Gustafsson et al. (2010) discovered the unique trajectories of water vapor crossing Europe and the Baltic Sea to southern Sweden during extreme precipitation events. Sodemann et al. (2008) considered the variations in moisture contained in an air parcel when being transported to a target grid due to precipitation and evaporation and developed a moisture source–receptor attribution method by taking into account the loss and uptake of moisture during the transport. Sun and Wang (2014a,b) further extended this method from a target grid to a target region as “the areal source–receptor attribution method” (see the appendix for the details). They found that approximately 60% of the total moisture released in

the semiarid grasslands in northern China during the warm season and 50% of the total released during the cold season can be attributed to moisture fluxes originating from the Eurasian continent.

To better quantify the contributions of different moisture sources to summer precipitation in SWC, in this study we adopt a Lagrangian trajectory model and apply the areal source–receptor attribution method following [Sun and Wang \(2014a,b\)](#). We mean to address the roles of moisture source changes in the interannual variations of SWC summer precipitation. Only the interannual variations are considered here because summer precipitation in East Asia has significant interdecadal components that can be caused by different factors (e.g., [Chang et al. 2000](#); [Zeng et al. 2007](#)). The underlying mechanisms responsible for the moisture source changes are also examined. In particular, impacts of the tropical Atlantic SSTs in summer on modifying the large-scale moisture transport to SWC are investigated through analyzing both the observed and reanalysis data and the numerical simulation. Hence, this study helps improve our understanding of the SWC summer precipitation variations and may also provide a possible source of seasonal predictability.

The rest of the content is organized as follows. [Section 2](#) briefly introduces data, methods, the Lagrangian trajectory model, and the atmospheric general circulation model adopted in this study. [Section 3](#) presents the long-term mean contributions of different moisture sources to SWC summer precipitation. Changes in the contributions in summers with above- and below-normal precipitation are also given. The impacts of tropical Atlantic SSTs on the contribution changes are examined in [section 4](#). [Section 5](#) presents the conclusions and discussion.

2. Data and methods

The monthly NCEP–DOE Reanalysis 2 ([Kanamitsu et al. 2002](#)) and NOAA Extended Reconstructed SST ([Huang et al. 2015](#)) for the period from January 1979 to December 2015 are used. The monthly station precipitation provided by the Chinese Meteorological Administration is also adopted. A total of 91 stations in SWC (98°–110°E, 22°–34°N) with no missing data in our interested period are selected (dark dots in [Fig. 1a](#)). The region-mean precipitation anomaly in June–August is thus defined as the SWC summer precipitation index. To focus on the interannual variations, an 11-yr high-pass Fourier harmonic filter is applied to extract the interannual components of all datasets. The linear correlation and regression and composite analyses are the major statistical methods and significance is examined by the two-tailed *t* test.

The Lagrangian model used is the Hybrid Single-Particle Lagrangian Integrated Trajectory model, version 4.9 (HYSPLIT4.9), developed by the NOAA Air Resource Laboratory ([Draxler and Hess 1997](#)). It is one of the most extensively used Lagrangian trajectory models in the climate research community and has been successfully applied to many different research fields, such as radionuclides, wildfire smoke, wind-blown dust, air pollutants, and moisture transport (e.g., [Rannik et al. 2000](#); [Sakamoto 2011](#); [Wernli 1997](#); [Cohen et al. 2002](#); [Draxler and Rolph 2012](#); [Escudero et al. 2011](#); [Chu et al. 2017](#)). The model is used to backtrack the air parcels released at 24 horizontal grids over SWC (the dark stars in the interpolated plot in [Fig. 2a](#)) and three vertical levels (200, 500 and 1000 m above ground level) four times per day with a 6-h interval in each summer day from 1979 to 2015. These air parcels are backtracked for 12 days by the 6-hourly NCEP–NCAR reanalysis data. It has been shown that the average residence time of water vapor in the atmosphere is around 10 days (e.g., [Trenberth 1998](#); [Numaguti 1999](#)); thus, the 12-day backtracking period for analyzing the moisture transport is reasonable (e.g., [Stohl and James 2005](#); [Sodemann and Stohl 2009](#); [Sun and Wang 2014a,b](#); [Chu et al. 2017](#)). The hourly outputs of HYSPLIT4.9 include the air parcel geographical location (longitude, latitude, and height), precipitation, specific humidity, temperature, etc. These outputs are used to diagnose the variations in moisture contained in the air parcels on their ways to SWC. We note that not all of the moisture contained in the air parcels and transported to SWC is released as precipitation. When calculating the contributions of different moisture sources to the SWC summer precipitation, only the portion of moisture absorbed from a specific source region and finally released in SWC is counted. Some studies show that the major moisture source regions of summer monsoon precipitation in China can be roughly categorized into the IO, SCS, PO, and the nearby land region (LD) (e.g., [Jiang et al. 2013](#); [Chu et al. 2017](#)). Here, the IO represents the tropical IO, Arabian Sea, and BOB together for simplicity. We adopt the similar categories to divide the source regions. The IO ranges from 20°S to 22.5°N with the eastern boundary at 40°E and the western boundary changing from 104° to 123°E at 7°S and southward. The SCS covers 104°–123°E, 7°S–20°N; the PO covers 123°E–170°W, 7°S–40°N. The scope of LD is irregular; it takes over the rest of the region of 40°–123°E, 20°S–60°N after excluding the IO, SCS, and SWC. Each source region is depicted by dark lines in [Fig. 2](#).

To verify possible impacts of the tropical Atlantic SST anomalies on the large-scale atmospheric circulation and thus moisture transport to SWC, the Community

FIG. 2. (a) Spatial distribution of trajectory frequency of air parcels in the last 12 days before their final arrival at SWC in summer averaged over 1979–2015, and the anomalies in summers of (b) above- and (c) below-normal precipitation in SWC, along with anomalous (d) warming and (e) cooling over the tropical Atlantic. Stars in the upper-right corner in (a) show horizontal grids within SWC where the air parcels are released for the back trajectories in HYSPLIT4.9. Outlined boxes in (a)–(e) denote the four moisture source regions.

Atmosphere Model version 5.3 (CAM5.3; Neale et al. 2012) is used to conduct numerical experiments. The model has a horizontal resolution of $1.9^\circ \times 2.5^\circ$ and 30 vertical levels under the hybrid pressure-sigma vertical coordinate (Simmons and Burridge 1981). The physical parameterization in CAM5.3 includes a two-moment cloud microphysics scheme (Zhang and McFarlane 1995; Richter and Rasch 2008), a shallow convection scheme (Bretherton and Park 2008), and a moist turbulence scheme (Bretherton and Park 2009). The detailed setup of the numerical experiments is given in section 4.

3. Contributions of different moisture sources to the SWC summer precipitation and their interannual variations

Figure 2a shows spatial distribution of trajectory frequency of the air parcels within last 12 days before their final arrival at SWC in summer averaged over 1979–2015. It is clear that many air parcels arriving at SWC come from the IO and SCS. Also, many come from the adjacent LD east of SWC, but few from the west probably due to blocking effect of the Tibetan Plateau that is located just to the west of SWC. However, still, a path of air parcels along the northern edge of the plateau from central Eurasia can be clearly seen (Fig. 2a). Due to

uneven distribution of humidity, the spatial distribution of accumulated moisture carried by the air parcels is also prepared, which is calculated at each grid by adding specific humidity of all the passing air parcels (Fig. 3a). Hence, when divided by the trajectory frequency shown in Fig. 2a, it reflects the averaged specific humidity of the air parcels when passing through these grids. It is apparent that the long-term mean accumulated moisture has an almost identical spatial pattern as the trajectory frequency (Figs. 2a and 3a), which is not surprising since moisture transported to SWC must be carried by air parcels. Nonetheless, the moisture over the IO and SCS is greatly enhanced compared to the trajectory frequency due to high humidity above the tropical oceans. It can be seen that abundant moisture from the IO is carried northeastward by the air parcels, passing through the Indo-China peninsula and arriving at SWC. Apparent moisture supply can also be detected from the SCS and adjacent LD, whereas relatively less moisture comes from the PO. This is generally consistent with Chu et al. (2017) when they diagnosed the moisture sources for summer precipitation in southern China. To quantify the percentages of summer precipitation in SWC contributed by these different moisture sources, the areal source–receptor attribution method is further applied. Results show that, on average, the IO explains 48.8% of the total moisture release

FIG. 3. As in Fig. 2, but for the accumulated moisture (g kg^{-1}) calculated at each grid by adding specific humidity of all of the passing air parcels in the last 12 days before their arrival at SWC in summer averaged over 1979–2015.

in SWC (Fig. 4a). The SCS and LD have similar proportions of 21.1% and 23.6%, respectively. The PO provides only 3.7%. The remaining 2.8% can be mainly attributed to the local evaporation in SWC.

The SWC summer precipitation experiences significant interannual variations that can be largely attributed to changes in the moisture supply from the different source regions (Fig. 5). In the past 37 years, the linear correlation coefficient between the SWC summer precipitation and the moisture release originating from the IO has been as high as 0.73, explaining 53.3% of the total variances and significant at the 99.9% confidence level. That between the precipitation and the moisture release originating from the SCS is 0.58, explaining 33.6% of the total variances and significant at the 99.9% confidence level. The moisture release originating from the PO plays a much less important role; the correlation coefficient with the precipitation is only 0.21. In contrast to the IO, SCS, and PO, the moisture release originating from the LD negatively impacts the summer precipitation; their correlation coefficient is -0.31 . If changes in the moisture release from all of the four source regions are considered as predictors in a multiple linear regression equation to predict the summer precipitation variations in SWC, the predicted precipitation anomalies have a correlation coefficient as high as 0.93 with the observed, and contribute 86.5% of the total interannual variances. In particular, the IO and SCS together

contribute 75.7% of the total interannual variances. This indicates the overwhelming impacts of moisture transport from the IO and SCS on the summer precipitation variations in SWC.

To further quantify the percentage anomalies of the moisture release from the different moisture sources in the above- and below-normal precipitation summers, composite analyses are conducted. Six above-normal (1991, 1993, 1998, 2007, 2008, and 2014) and eight below-normal (1981, 1982, 1989, 1992, 1997, 2004, 2006, and 2011) precipitation summers are chosen based on the summer precipitation indices above 0.8 or below -0.8 standard deviations, respectively (Fig. 5, gray solid lines). In the above-normal precipitation summers, compared to the climatological amounts, the moisture release in SWC originating from the IO, SCS, and PO increases by 41.4%, 15.1%, and 5.4%, respectively, while that from the LD decreases by 12.2% (Figs. 3b and 4b). In contrast, in the below-normal precipitation summers, the moisture release originating from the IO, SCS, and PO decreases by 42%, 24.6%, and 22.4%, respectively, whereas that from the LD increases slightly by 3.2% (Figs. 3c and 4c).

Anomalies in the moisture release from the four source regions can be raised by changes in the trajectory frequency of and/or moisture amount in the air parcels. In the above/below-normal precipitation summers, there are apparent anomalies in both of the trajectory

FIG. 4. (a) Percentage (%) of the total moisture release averaged in summers of 1979–2015 in SWC contributed by the different source regions. Also shown are changes (%) in the moisture release from the different source regions in the summers with (b) above- and (c) below-normal precipitation in SWC or anomalous (d) warming and (e) cooling over the tropical Atlantic, when compared with their own climatologies. Asterisks at the ends of the bars in (b)–(e) indicate statistical significance at the 95% confidence level.

frequency and accumulated moisture, and their anomalous patterns are very similar (Figs. 2b,c and 3b,c). This suggests that the large-scale atmospheric circulation anomalies are responsible for the anomalous patterns; they not only modify the numbers of air parcels from

different source regions to SWC but also alter the amount of moisture therein by changing the evaporation and precipitation through anomalous wind speed and the related convergence along the routes. We note that changes in the air parcel numbers can only explain

FIG. 5. Standardized time series (black solid lines) of anomalies in moisture release in SWC originating from (a) IO, (b) SCS, (c) LD, and (d) PO in 1979–2015. The superimposed gray solid lines represent the normalized time series of the SWC summer precipitation. The correlation coefficients between anomalies in the moisture release and SWC summer precipitation are shown in the upper-right corner of (a)–(d).

FIG. 6. Anomalies in (a) SST (color shading; $^{\circ}\text{C}$) and horizontal wind (vectors; m s^{-1}) and streamfunction (contour interval: $0.4 \times 10^6 \text{ m}^2 \text{ s}^{-1}$; red and blue contours indicate anticyclonic and cyclonic anomalies, respectively) at 850 hPa, and (b) precipitation and (c) zonal-vertical streamfunction averaged between 10°S and 10°N regressed upon the SWC summer precipitation index. Only anomalies significant at the 95% confidence level in SST, wind, and precipitation are shown in (a) and (b), and those in streamfunction at 850 hPa are stippled in (a).

28.1%, 37.2%, 16.8%, and 10.9% of the interannual variances of moisture release in SWC from the IO, SCS, LD and PO, respectively. Hence, the moisture anomalies contained in the air parcels caused by the atmospheric circulation anomalies contribute more to the moisture release variations from the four source regions.

The moisture release variations from the four source regions may not be independent of one another, especially those from the IO, SCS, and LD. They could be caused by the same large-scale atmospheric circulation anomalies that increase the moisture supply from the IO

and SCS but suppress that from the LD in summers with the above-normal precipitation, and vice versa in summers with the below-normal precipitation. Indeed, the anomalies in moisture release originating from the IO, SCS, and LD are closely related; the linear correlation coefficients between those from the IO and SCS or LD are 0.52 and -0.41 , respectively, significant at the 99.9% and 99% confidence levels, respectively. Hence, it is interesting to discover the large-scale atmospheric circulation anomalies and the underlying forcing responsible for the changes in moisture transport.

FIG. 7. Normalized time series of March–May ATL (gray dashed line), June–August ATL (gray solid line), and June–August SWC precipitation (dark solid line) indices. The linear correlation coefficients of the precipitation index with the March–May and June–August ATL indices, respectively, are also shown.

4. Large-scale atmospheric circulation anomalies responsible for changes in the moisture transport to SWC and impacts of the tropical Atlantic SSTs

In summers with the above-normal precipitation, a pair of anomalous anticyclones can be seen straddling the western tropical Pacific in the lower troposphere (Fig. 6a). The anomalous anticyclone centered over the western North Pacific extends westward to the Arabian Sea. By the circulation anomalies, more moisture from both the IO and SCS is transported to SWC by anomalous southwesterlies over the northwestern quadrant of the anomalous anticyclone. Also, the anomalous westerlies along the northern edge of the anomalous anticyclone hinder the climatological westward moisture transport from eastern China to SWC (Fig. 3a), resulting in the negative correlation between the SWC summer precipitation and the moisture originating from the LD (Fig. 5c). Some moisture from the southern part of PO could be directed westward and then northeastward to SWC by the anomalous winds along the southern and western edges of the anomalous anticyclone. However, it is a long route and the moisture could be precipitated halfway; there are positive precipitation anomalies around the Maritime Continent and eastern tropical IO (Fig. 6b). This may partly explain the positive but insignificant linear relation between the SWC summer precipitation and the moisture originating from the PO (Fig. 5d). Nevertheless, the anomalous anticyclone helps enhance the moisture transport from the IO and SCS to SWC, but reduce that from the LD. If an index is defined to reflect the anomalous anticyclone as the region-mean vortex anomalies at 850 hPa over 85° – 145° E, 10° – 25° N, it has the linear correlation coefficient of 0.73, 0.54, or -0.58 with the moisture release from the IO, SCS, and LD, respectively, significant at the 99.9% confidence level.

The anomalous anticyclone in the western North Pacific can be induced by the anomalous descending motion over the central tropical Pacific (180° – 150° W) as the direct Matsuno–Gill response (Fig. 6c). Furthermore, the anomalous descending motion may be closely related to the anomalous warming in the tropical Atlantic (Fig. 6a). As discussed in the introduction section, the anomalous warming there in boreal summer can enhance the local convection (Fig. 6b), modulate the zonal Walker circulation and lead to the anomalous descending motion over the central tropical Pacific (Fig. 6c) (e.g., Hong et al. 2014; Jin and Huo 2018). The anomalous warming in the tropical Atlantic is analogous to the Atlantic Niño (e.g., Richter and Doi 2019). If the region-mean SST anomalies in the cold tongue of the tropical Atlantic (10° W– 15° E, 5° S– 5° N) are chosen to represent the anomalous warming, say the ATL index, the linear correlation coefficient between the summer ATL and SWC precipitation indices is 0.52, significant at the 99.9% confidence level (Fig. 7). In addition, the large-scale atmospheric circulation anomalies related to the anomalous warming in the tropical Atlantic are very similar to those in the summers with the above-normal precipitation in SWC; the anomalous ascending motion over the tropical Atlantic induces the anomalous descending motion over the central tropical Pacific and leads to the anomalous anticyclone in the western North Pacific (Figs. 6 and 8). We note that there are also significant positive SST anomalies in the western North Pacific in summers with the above-normal precipitation or anomalous warming in the tropical Atlantic. These positive SST anomalies are located right below the anomalous anticyclone with the suppressed precipitation (Figs. 6a,b and 8a,b). Hence, they can be passively caused by the enhanced shortwave radiation due to less cloud and would not actively influence the atmospheric circulation, in stark contrast to the positive SST anomalies in the tropical Atlantic.

To reveal impacts of the tropical Atlantic SSTs on moisture transport to SWC, the areal source–reception attribution method is applied to the summers with anomalous warming or cooling in the tropical Atlantic. Here, 10 summers with anomalous warming (1979, 1984, 1987, 1988, 1991, 1995, 1998, 2003, 2007, and 2008) and 10 summers with anomalous cooling (1982, 1983, 1986, 1990, 1992, 1997, 2000, 2001, 2005, and 2011) are selected based on the summer ATL index above 0.8 or below -0.8 standard deviations, respectively. It is clear that, by the atmospheric circulation anomalies related to the anomalously warm tropical Atlantic, the moisture release in SWC originating from the IO, SCS, and PO increases respectively by 36.3%, 14.1%, and 6.1% while that from the LD decreases by 13.5%, when compared with the

FIG. 8. As in Fig. 6, but for the anomalies regressed upon the summer ATL index.

climatological amounts (Figs. 3d and 4d). In contrast, in summers with the anomalously cold tropical Atlantic, the moisture release in SWC originating from the IO, SCS, and PO decreases respectively by 20.9%, 12.2%, and 19.4%, whereas that from the LD increases by 2.4% (Figs. 3e and 4e). This is, in a broad sense, consistent with the changes in different moisture sources in summers with above- and below-normal precipitation in SWC (Figs. 3b–e and 4b–e). We note that although the net moisture transport from the LD is decreased in summers with both anomalous warming in the tropical Atlantic and above-normal precipitation in SWC, the anomalous patterns of accumulated moisture over eastern China are quite different (Figs. 3b,d). This is probably because the northern boundary of the anomalous anticyclone and the related westerly anomalies at sea level

and 1000 hPa in summers with the anomalous warming in the tropical Atlantic extend more northward compared to those with the above-normal precipitation (figures not shown). Nevertheless, the results confirm that the thermal condition of the tropical Atlantic can influence the summer precipitation in SWC by modifying the large-scale atmospheric circulation and the resultant moisture transport to SWC.

The impacts of the tropical Atlantic on the SWC summer precipitation can be further verified by the numerical experiments in CAM5.3. Two experiments are conducted. In the control experiment (CTL), the monthly SST climatology is prescribed as the boundary forcing and the model is integrated continuously for 35 years. Outputs of the last 25 years are used as the model

FIG. 9. Summer climatologies of (a),(b) the horizontal wind (vectors; m s^{-1}) and streamfunction (contour interval: $0.5 \times 10^7 \text{ m}^2 \text{ s}^{-1}$; red and blue contours indicate anticyclonic and cyclonic anomalies, respectively) at 850 hPa, (c),(d) the precipitation (mm day^{-1}), and (e),(f) the zonal-vertical section of streamfunction averaged over 10°S – 10°N based on (left) the observed and reanalysis data and (right) the CTL in CAM5.3.

climatology. It seems that the CTL reproduces well the observed climatologies in summer including the southwesterly monsoon airflows over the IO and Asian continent, the subtropical highs, and the equatorial Walker circulation (Figs. 9a,b,e,f). The CTL also simulates the observed precipitation to a large extent (Figs. 9c,d), even though bias is evident especially over the Asian monsoon regions as suffered by most of the current up-to-date models (Song and Zhou 2014). In the sensitivity experiment (SEN), the model is initialized by the atmospheric condition on 1 June of each year of the CTL. It is then forced by the monthly SST climatology plus additional positive SST anomalies in the tropical Atlantic (12.5°S – 12.5°N) and integrated for 3 months from 1 June to 31 August. The positive SST anomalies have the same pattern and magnitude as those regressed on the summer ATL index (Figs. 8a and 10a). Hence, the SEN has 25 ensembles that differ only in the initial atmospheric conditions. Differences between the SEN and CTL are regarded as the simulated responses to the anomalous warming in the tropical Atlantic in boreal summer. Statistical significance is examined by the two-tailed t test.

As shown in Fig. 10, with the anomalous heating in the tropical Atlantic, the SEN simulates the enhanced local convection and precipitation. This modifies the zonal

Walker circulation and leads to the anomalous descending motion over the central tropical Pacific. The anomalous descending motion perturbs the equatorial atmosphere and induces a pair of anomalous anticyclones in the off-equatorial regions northwest and southwest to the vertical perturbation (Matsuno 1966; Gill 1980). The thus-formed anomalous anticyclone in the western North Pacific enhances the summer precipitation in SWC by increasing the moisture transport especially from the IO and SCS (Figs. 10a,b). Hence, the model can reproduce well the observed impacts of the anomalous warming of the tropical Atlantic in summer on the large-scale atmospheric circulation and the resultant moisture transport to and precipitation in SWC.

5. Conclusions and discussion

This study quantitatively estimates contributions of different moisture source regions, the IO, SCS, LD, and PO, to summer precipitation in SWC by using the HYSPLIT Lagrangian trajectory model and the areal source–receptor attribution method. Results show that, on average, the IO contributes 48.8% of summer moisture release in SWC, the SCS contributes 21.1%, the LD contributes 23.6%, and the PO contributes 3.7%. The

FIG. 10. As in Fig. 6 except that the SST anomalies in (a) are the prescribed boundary forcing in summer and other anomalies are the simulated response to the SST forcing in CAM5.3.

interannual variations in SWC summer precipitation are largely caused by changes in the moisture transport from these source regions. In summers with the above-normal precipitation, the moisture release in SWC originating from the IO (SCS) significantly increases by 41.4% (15.1%), when compared to their climatological amounts. In contrast, in summers with the below-normal precipitation, the moisture release originating from the IO, SCS, and PO significantly decreases by, respectively, 44.0%, 24.6%, and 22.4%. Changes in the moisture release from the four source regions together explain 86.5% of the total interannual variances of the SWC summer precipitation. Particularly, the IO and SCS can explain up to 75.7%, indicating their enormous impacts on the SWC summer precipitation.

Changes in the moisture release from the IO, SCS, and LD are not independent of one another; they can be induced by the same large-scale circulation anomalies. In summers with above-normal precipitation in SWC, an anomalous anticyclone appears in the western North Pacific with the western edge extending westward to the Arabian Sea. By the anomalous circulation configuration, moisture from the IO and SCS is largely increased by the anomalous southwesterlies over the northwestern quadrant of the anomalous anticyclone. Also, the anomalous westerlies along the northern edge of the anomalous anticyclone weaken the eastward moisture transport from the LD.

The large-scale atmospheric circulation anomalies responsible for the surplus summer precipitation in

SWC are closely related to the anomalous warming in the tropical Atlantic; the correlation coefficient between the summer ATL and SWC precipitation indices is 0.52, significant at the 99.9% confidence level. The anomalous warming in the tropical Atlantic can modify the Walker circulation by inducing the anomalous ascending motion over the tropical Atlantic and descending motion over the central tropical Pacific. The anomalous descending motion perturbs the atmosphere and leads to the anomalous anticyclone in the western North Pacific as the classic Matsuno–Gill response. Hence, the tropical Atlantic SST anomalies can impact summer precipitation in SWC by modifying the atmospheric circulation and thus moisture transport to SWC via the atmospheric teleconnection.

The impacts of anomalous warming in the tropical Atlantic can be verified through the numerical experiments in CAM5.3 by prescribing the positive SST anomalies in the tropical Atlantic in summer. The model can successfully simulate the anomalous ascending motion over the tropical Atlantic and the anomalous descending motion over the central tropical Pacific. It also simulates the anomalous anticyclone in the western North Pacific, the enhanced moisture transport from the IO and SCS and the increased precipitation in SWC. We note that probably due to weaker dissipation in the model compared to the observed, the anomalous warming in the tropical Atlantic triggers stronger warm atmospheric Kelvin waves propagating eastward to the IO and introduces an additional anomalous anticyclone from the Arabian Sea to northern Africa (Fig. 10b). This is analogous to the response of anomalous anticyclone in the western North Pacific to the IO basin warming as suggested by Xie et al. (2009) and discussed in the introduction section. Kucharski et al. (2007, 2008, 2009) suggested that the anomalous warming of the tropical Atlantic can excite the quadrupole response in the lower troposphere with an anomalous anticyclone over India, which can weaken the Indian summer monsoon and lead to less precipitation in India. Our model results are complementary to theirs, showing a significant precipitation deficit in India (Fig. 10b).

SWC produces approximately 15% of the annual rice yield in China and thus plays an important role in national food security. Summer precipitation in SWC is crucial to the local agriculture but experiences substantial interannual variations. In this study, we have presented impacts of the anomalous warming in the tropical Atlantic analogous to the Atlantic Niño on the large-scale atmospheric circulation, moisture transport, and summer precipitation in SWC. In general, the anomalous warming develops in boreal spring and peaks in boreal summer. If a spring index is defined by the

same method as the summer ATL index in section 4, it has a correlation coefficient of 0.53 with the SWC summer precipitation, significant at the 99.9% confidence level (Fig. 7). This suggests that the tropical Atlantic could be a source of predictability of the summer precipitation in SWC and the spring ATL index can be used to predict the summer precipitation anomalies with one-season lead time. Hence, this study illustrates the importance of the tropical Atlantic on the SWC summer climate. Realistic representation of the tropical Atlantic in coupled models is thus beneficial to simulate and even predict the SWC summer precipitation variations. So far, most up-to-date coupled models suffer from biases in simulating the mean state of the tropical Atlantic. The simulated zonal SST gradient is often opposite to the observed (e.g., Richter and Xie 2008). This hinders the skillful prediction of tropical Atlantic variations (e.g., Stockdale et al. 2006). Further efforts are needed to improve our model representation of the tropical Atlantic to better reproduce and predict its impacts on the global climate including the SWC summer precipitation.

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APPENDIX

The Areal Source–Receptor Attribution Method

The areal source–receptor attribution method proposed by Sun and Wang (2014a,b) was developed from the source–receptor attribution method by Sodemann et al. (2008). It can quantify the contribution of different moisture sources to precipitation in a target region. The detailed calculation is summarized as follows.

- 1) Select the target region and categorize the different moisture source regions.
- 2) When an air parcel enters the i th source region on its way to the target region, analyze the changes in moisture taken from the source region (Δq_i) by the

air parcel at each time step whenever it remains in the i th source region. If evaporation occurs at the location of the air parcel, it indicates uptake of moisture, $\Delta q_i = \Delta q_i + \Delta e_i$, where Δe_i represents evaporation. If precipitation occurs, it releases some moisture back to the i th source region, $\Delta q_i = \Delta q_i - \Delta q_i(\Delta p_i/pw_i)$, where Δp_i is precipitation and pw_i is precipitable water at the air parcel location.

- 3) When the air parcel moves out of the i th source region and enters the j th region that is not the target region, analyze the changes in Δq_i at each time step whenever it remains in the j th region. If evaporation occurs at the air parcel location, Δq_i remains unchanged. If precipitation occurs, $\Delta q_i = \Delta q_i - \Delta q_i(\Delta p_j/pw_j)$, where Δp_j is precipitation and pw_j is precipitable water at the air parcel location within the j th region. For all of the regions after the i th source region where the air parcel has to pass through before its final arrival at the target region, repeat the above processes to record the changes in Δq_i .
- 4) When the air parcel finally enters the target region, if precipitation occurs at any time step when the air parcel remains in the target region, $\Delta q_i = \Delta q_i - \Delta q_i(\Delta p_{tar}/pw_{tar})$, where Δp_{tar} is precipitation and pw_{tar} is precipitable water at the air parcel location within the target region. Define the moisture originating from the i th moisture source and released as precipitation in the target region as $r_i = r_i + \Delta q_i(\Delta p_{tar}/pw_{tar})$.

Consider all of the air parcels that pass through the i th source region and finally arrive at SWC and then sum up r_i . Calculate the percentage of precipitation in the target region that originates from the i th source regions as $CP_i = (r_i/P) \times 100\%$, where P is the total precipitation in the target region considered and CP_i is the percentage of P originating from the i th source region.

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