Research Article

Connection between Two Leading Modes of Autumn Rainfall Interannual Variability in Southeast China and Two Types of ENSO-Like SSTA

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1. Introduction

Southeast China is economically prosperous and Chinese important tropical and subtropical crop production base, mainly including Fujian, Guangdong, East Guangxi, Jiangxi, Hunan, South Hubei, and South Zhejiang. Agricultural production is closely related to the local precipitation situation, so the variation characteristics of precipitation in SEC and associated impacts have attracted wide attention [1–6].

The interannual variation of autumn rainfall in Southeast China (SEC) is significant, with two major modes, namely, monopole and dipole modes. It is found that the monopole mode is closely related to EP ENSO-like sea surface temperature anomaly (SSTA), and the dipole mode is related to CP ENSO-like SSTA. During the warm phase of EP ENSO-like SSTA, an anomalous anti-Walker circulation emerges in the tropical Pacific, with an anomalous subsiding during 110°E–120°E and an anomalous ascending branch in SEC. These two branches of anomalous current are in the same longitude and form a closed meridional circulation. Besides, there also exists an anticyclone anomaly in the Northwest Pacific (NWP), transporting water vapor into SEC. These circulation configurations induced by the warm phase of EP ENSO-like SSTA are consistent with those of monopole mode positive anomaly year. The good correspondence between EP ENSO warm event and the positive monopole mode also helps to support the corresponding relationship between the EP ENSO-like SSTA and monopole mode of SEC autumn rainfall. After the diagnosis of the perturbation omega equation, the anomalous subsiding branch over SEC, as the key link of EP ENSO-like warm phase SST anomaly, is mainly related with the anomalous relative vorticity advection transported by basic zonal wind and temperature advection transported by meridional wind anomaly. As for the dipole mode, it is related to the CP ENSO-like SSTA, but the corresponding relationship is weaker than that of the monopole mode and EP ENSO-like SSTA. In special, during the warm phase of CP ENSO-like SSTA, an anomalous cyclone appears in the NWP and prevailing sinking motion over SEC, both of which favors the appearance of positive anomaly of the dipole mode. Specially, the local anomalous vertical motion mainly depends on anomalous relative vorticity transported by basic meridional wind. Generally speaking, the monopole (dipole) mode is closely associated with the EP (CP) ENSO-like SSTA, demonstrating some correspondence.
the north-south activities of summer monsoon [13–16]. Compared to spring and summer seasons, the autumn is a less rainfall season, but the temporal and spatial variations of autumn precipitation are more complex [17], with more frequent drought [18]. Winter precipitation in SEC accounts for more than 10% of the total annual precipitation, which has a significant 2–4 year cycle and interannual variation characteristics [19, 20]. Winter precipitation occurs not only in the form of precipitation but also in the form of snowfall. In the winter of 2008, severe freezing rain and snow disasters occurred, with an enormous loss in economically prosperous SEC [21, 22].

The interannual variation of precipitation in SEC is affected by many factors, such as western Pacific subtropical high, India-Burma trough, subtropical westerly jet, typhoon activity, monsoon, North Atlantic oscillation (NAO), and even black carbon aerosol, very important one of which is the key region sea surface temperature (SST) [23–26]. So the relationship between SEC rainfall and SST has attracted a lot of attention [22, 27, 28]. It has been investigated that the interannual variability of the tropical Pacific SST [13, 14, 29], as well as the tropical India Ocean, has important effects on the SEC rainfall [30, 31]. For instance, the SSTAs over the Maritime Continent (MC) can influence the SEC summer rainfall by modifying the cross-equatorial flows [32, 33]. When South Indian Ocean dipole STA pattern index (RSIOPP) is in its positive (negative) years, the summer rainfall is abnormally sufficient (deficient) in SEC [6]. This dipole-type oscillation in an east-west direction of the STA in the subtropical South Indian Ocean can affect winter rainfall anomaly in South China [33].

It has been recognized that ENSO is the strongest air-sea interaction phenomenon associated with Indo-Pacific SST at the annual scale, whose warm (cold) phase is named El Niño (La Niña) event, respectively. It can be divided into two types (EP ENSO and CP ENSO) based on the difference of maximum STA locations. The EP-ENSO is characterized by the warmest (coldest) STA anomalies in the eastern equatorial Pacific, and the CP ENSO features maximum (minimum) STA anomalies are over the central equatorial Pacific [34]. EP-ENSO is referred to the classical ENSO, well-known by meteorological community, but CP ENSO is gradually known for the last few decades. The spatial patterns, dynamics, and evolution of this new type of ENSO have been discussed in detail earlier studies [35, 36]. STA related to ENSO can exert an remote influence on SEC autumn rainfall. When positive STA occurs in the equatorial central Pacific and negative STA occurs in the MC, the Hadley circulation in East Asia weakens and then SEC summer rainfall increases [37]. STA related to ENSO also can exert an influence on SEC rainfall by modifying the cross-equatorial flows [32, 33]. Moreover, EP ENSO and CP ENSO have asymmetric impact of their positive and negative phases on boreal summer rainfall over SEC [39]. Zhang et al. [40] found that the two types of El Niño have opposite impacts on the NWP atmospheric circulation during the boreal autumn and have different impacts on autumn rainfall over SEC. Besides, Feng and Li [11] also found the different influences of CP El Niño and EP El Niño on spring rainfall over SEC. It is interesting that the anomalous summer rainfall around the SEC region varies in-phase (out-of-phase) with the precursory winter rainfall anomaly during the El Niño/La Niña decaying (developing) years [41].

Compared with the other seasons, the study about the effect of ENSO on autumn precipitation is less. The autumn precipitation in SEC has obvious double mode characteristics [17]. The EOF analyses of tropical Pacific SSTA since 1979 indicate that the tropical Pacific SST has EP ENSO-like and CP ENSO-like leading modes [11, 39], and both of the EP ENSO-like and CP ENSO-like SSTA have significant and different effects on SEC autumn rainfall [40]. So it is natural to consider what the specific connection is, between the double leading modes of SEC autumn and that of the tropical Pacific STA in recent decades.

2. Data and Methods

The SEC is selected as research region spanning from 22.5°N–30°N and 110°E–120°E. All stations (74 meteorological stations) in the SEC region are chosen from the whole country 553 station rainfall datasets provided by National Climate Center (NCC) in China. The monthly reanalysis data JRA-55 are used [42]. The data are available with a horizontal resolution of 1.25°×1.25°. Monthly-average SST is HadISST version 1.1 from the Hadley Center, with a horizontal resolution of 1°×1° [43]. The autumn refers to the mean of September, October, and November. The study focuses on the period during 1971–2010. Correlation, empirical orthogonal function (EOF) analysis, fast Fourier transformation (FFT) high-pass filter (remain below 9-year signal), etc. are applied in this paper.

There are many kinds of indices used to describe EP ENSO-like and CP ENSO-like STA anomaly. Based on the approach used by Karori et al. [39], apply Nino 3 and EMI indices to describe EP ENSO-like and CP ENSO-like STA, respectively. Nino 3 is defined as regional average of Nino 3 (5°S–5°N, 150°W–90°W) STA (available at http://www.cpc.noaa.gov/data/indices/). The EMI is defined as (SSTA)A–0.5{(SSTA)B–0.5(SSTA)C} [35], where (SSTA)A, (SSTA)B, and (SSTA)C represent (A: 10°S–10°N, 165°E–140°W), (B: 15°S–5°N, 110°E–70°W), and (C: 10°S–20°N, 125°E–145°E) regional average of SSTA respectively.

3. The Relationship between the Interannual Variation of Autumn Precipitation in SEC and SSTA in the Tropical Pacific

As shown in Figure 1, the interannual variation of autumn rainfall over SEC, mainly including the region marked by the rectangle, is more remarkable, compared to the rest region in China. Therefore, the 74 stations in the rectangle are selected to conduct the research in the paper.

As demonstrated in Figure 2(a), the autumn rainfall over SEC features significant interannual variability, with difference exceeding 200 mm per season between the maximum rainfall (2002 year) and the minimum rainfall
In the meantime, the rainfall there has obvious decadal reduction around 1990 year. In order to study the interannual variability, it is necessary to exclude the decadal change signal. Subtract its mean value from each value during 1971–1990 in Figure 2(a) to obtain a new subsection, and also subtract its mean value from each value in the other subsection during 1991–2010 to obtain another new subsection. The two new subsections form a new sequence, also spanning 1971–2010, and then are normalized into the new sequence, as shown in Figure 2(b).

As shown in Figure 2(b), the rainfall years above one standard deviation include 9 years: 1972, 1975, 1981, 1982, 1987, 1990, 1997, 2000, and 2002, and the years below one standard deviation are composed of 6 years: 1971, 1979, 1980, 1992, 1996, and 2007. These two groups are defined as positive anomaly year and negative anomaly year of SEC rainfall, respectively.

As displayed in Figure 3, the significant correlation regions between the interannual variation sequence of SEC rainfall and SST are mainly concentrated in the tropical Pacific. The tropical East Pacific SST, mainly in the Nino 3 region, is positively correlated with precipitation in SEC, but the “C” type region to its west is negatively correlated with rainfall over SEC. However, the significant t-test areas are mainly located in the East Pacific; namely, when the precipitation over SEC is more, the tropical East Pacific SST exhibits positive anomaly. SSTA related to ENSO may be closely connected with the interannual variation of SEC autumn rainfall.

The approach of 1971–1990 and 1991–2010 fragments minus each average has roughly removed the decadal variation of autumn rainfall in SEC, and the associated results above have preliminarily confirmed that SEC autumn rainfall is significantly correlated with ENSO-like SSTA. In order to further study the relationship between SEC autumn rainfall and ENSO-like SSTA, we must more precisely extract interannual variation information. Hence, we use the FFT high-pass filtering method to deal with precipitation data in each station over SEC.

After the filtering, conduct an EOF analysis on the rainfall and it can be known that there are two leading interannual modes, with the first mode being the uniformly positive (negative) anomaly precipitation over SEC (referred to monopole mode) and the second mode being the dipole pattern with less (more) rainfall in southeastern part and more (less) rainfall in northwestern region (referred to dipole mode). They account for the total variance up to 39.7% and 11.5%, respectively (Figures 4(a) and 4(b)). As shown in the correlation pattern between the EOF first mode temporal serial PC1 and SST, when the SST is warm (cold), the monopole mode exhibits more (less) rainfall (Figure 4(e)), which illustrates that EP ENSO-like SSTA is closely associated with the monopole mode of interannual variation of SEC autumn rainfall.
From the correlation between the dipole mode temporal serial PC2 and SST, it can be seen that the dipole mode is closely related to tropical central Pacific SST anomaly. When tropical central Pacific is warmer (colder), the southwestern part has more (less) rainfall and the northern part has more (less) rainfall (Figure 4(f)). This suggests that CP ENSO-like SST anomaly is significantly connected with the dipole mode. Moreover, the correlation coefficient of PC1 and Nino 3 index is up to 0.46, and the correlation coefficient between PC2 and EMI index is −0.30, both through the significance test at the 90% confidence level, which further identifies that, to some extent, the monopole (dipole) mode corresponds to and EP (CP) ENSO-like SST anomaly.

4. The Physical Process of EP ENSO-Like SST Anomaly Influencing Monopole Mode over SEC

Although the previous studies revealed that NWP anomalous anticyclone plays a vitally important role in linking ENSO with SC winter rainfall anomalies [21, 27], now, ENSO has changed a lot and been divided into two types. Under such a scenario, in order to deeply study the correspondence, it is necessary to explore what the mechanisms convey through the remote influences of the EP ENSO-like SST anomaly to the monopole mode over SEC rainfall.


As seen from the difference of 850 hPa wind and vorticity field, compared with the negative anomaly years, there exists an anomalous anticyclone in NWP during the positive anomaly years. Its ambient currents transport warm and wet air into SEC, accompanying significant positive anomaly (Figure 5(a)) and moisture convergence (Figure 5(b)). And, there is an anomalous Walker circulation in tropical Pacific, with an anomalous subsiding during 110°E–120°E (Figure 5(c)), an anomalous ascending branch in SEC (Figure 5(d)) and both constitute the closed meridional circulation. These are the circulation configuration of the monopole mode anomaly year over SEC.

4.2. The Circulation Pattern Induced by EP ENSO-Like SST Anomaly. Due to the emergence of monopole modal anomaly year, generally with the certain anomalous circulation pattern similar as Figure 5, we regress the same meteorological fields on the Nino 3 index to check whether the similar anomalous circulation pattern similar to Figure 5 reappears. If it happens, this would indicate that EP ENSO-like SST can exert influences on the monopole mode of SEC autumn rainfall indeed.

As demonstrated in the regression map of 850 hPa wind on the Nino 3 index, when the thermal eastern Pacific warms up, an anomalous anticyclone emerges over the South China Sea (SCS) stretching to NWP, with its ambient current conveying moisture into SEC (Figures 6(a) and 6(b)). In the same time, an anomalous anti-Walker circulation in the tropical Pacific appears, and its updraft branch is mainly located in the tropical eastern Pacific and its downdraft branch is located in 110°E–120°E closely connected with SEC (Figure 6(c)). The subsiding branch of anomalous anti-Walker circulation and the prevailing anomalously ascending airflow in the SEC form a closed local meridional circulation (Figure 6(d)). The circulation anomaly patterns in Figures 6(a)–6(d) coincide with those in Figures 5(a)–5(d), indicating that EP ENSO-like SST anomaly can cause the variation of the monopole modal over SEC. When EP ENSO-like SST anomaly emerges, its impact on the monopole mode is as similar as the schematic diagram shown in Figure 6(e): the eastern tropical Pacific SST anomalies in the tropical Pacific are warmer, exciting anomalous anti-Walker circulation in the tropical Pacific, with descending branch from SCS to NWP. The subsiding branch and the rising airflow over SEC form a closed anomalous meridional circulation, which further imposes effect on the monopole mode. In addition, an anomalous anticyclone over SCS to WNP also can affect the monopole mode of SEC autumn rainfall.

EP ENSO event can be considered as the significant anomaly of EP ENSO-like SST anomaly, so whether or not EP ENSO events correspond to the rainfall anomalous years of the monopole mode can be seen as another measure to inspect the extent of EP ENSO-like SST mode's connection with the SEC monopole mode of rainfall. According to the year-to-year SST anomaly type, the EP ENSO warm event including 1972, 1982, 1986, and 1997, three of which except...
1986, are the positive anomaly years of the autumn precipitation monopole mode over SEC. This further supports the close relationship between the EP ENSO-like SSTA and the monopole mode of autumn precipitation in SEC, and there is a strong possibility that they have a certain corresponding relationship.

4.3. Diagnosis of Anomalous Vertical Movement over SEC. It is known that vertical motion is closely related to precipitation. Obtained from the above, the anomalous descending airflow is the key link, by which EP ENSO-like SSTA impacts influence on the monopole of SEC autumn rainfall interannual variability. The diagnosis of

Figure 4: The EOF of rainfall after FFT high-pass filter (retain signal below 9 years): the first spatial mode (a) and corresponding temporal coefficient (c) and the second spatial mode (b) and corresponding temporal coefficient (d). (e, f) The correlation pattern between PC1, PC2, and autumn SST and 0.26, 0.31, and 0.4 denote critical values of significance t-test at 90%, 95%, and 99% confidence level, respectively.
quasi-geostrophic $\omega$ equation (1) favors to investigate the possible reasons of the vertical motion happening, and perturbation equation (2) helps to explore the happening reasons of anomalous vertical motion over SEC.

The $A$ term in equation (1) is the Laplace term of the Omega, which is equal to the Omega multiplied by a negative coefficient. The $B$ term is the variation of the absolute vorticity advection with the height, the $C$ term is the Laplacian of the quasi-geostrophic temperature advection, and the $D$ term is Laplacian of diabatic heating. Only to consider the impact of atmospheric internal dynamic processes, the $D$ term is ignored. Equation (1) is expanded into a perturbation equation (2). The $B$ term is expanded into $B_1$–$B_7$ terms, and $C$ is expanded into $C_1$–$C_6$ terms, which help to further explore which terms of vorticity advection and temperature advection play more major roles in the arising of anomalous vertical motion over SEC:

Figure 5: The difference between positive anomaly year and negative anomaly year: (a) 850 hPa horizontal wind (vector: m·s$^{-1}$; red vector: through the significance $t$-test at 90% confidence level) and vorticity (shadow: $10^{-5}$ s$^{-1}$; dotted part: exceeding the significant test at 90% confidence level), (b) the column-integrated water vapor flux (vector: g·kg$^{-1}$·m·s$^{-1}$; red vector: through the significance $t$-test at 90% confidence level) and its divergence (shadow: g·kg$^{-1}$·m$^2$·s$^{-1}$), (c) latitudinal wind, vertical motion (vector, Omega multiplied by $-100$) for cross section along the $5^\circ$S–$5^\circ$N, and (d) meridional wind, vertical motion (vector, Omega multiplied by $-100$) for cross section along the $110^\circ$E–$120^\circ$E shadings are through the significance $t$-test at the 90% confidence level. The SEC is marked by the rectangle.
Figure 6: (a) 850 hPa wind field (vector, m·s⁻¹), (b) column-integrated water vapor flux (unit: g·kg⁻¹·m·s⁻¹), (c) the regression of zonal wind and vertical velocity (omega multiplied by −100) cross section along 5°S–5°N on the Nino 3 index, and (d) the regression of meridional wind and vertical velocity (omega multiplied by −100) along 110°E–120°E on the Nino 3 index. Red vector in (a, b) and shadings in (c, d) through significant inspection at the 90% confidence level. (e) Schematic diagram showing anomalous Walker circulation associated with EP ENSO-like SST anomaly, the latitudinal circulation in tropical Pacific denotes the anomalous Walker circulation and to its northwest side is the anomalous meridional owning the joint descending branch in tropical Western Pacific. The shadings represent the SST anomaly during the positive phase years of EP ENSO (unit: °C), and dotted region is the significant area through the 90% significance t-test.
Because the left term is equal to the anomalous Omega multiplied by a negative coefficient, the positive (negative) value terms of $B1$–$B7$ and $C1$–$C6$ would support the arising of anomalous ascending (descending) motion. In the following, we choose 850 hPa to diagnose vertical motion anomalies by calculating the anomalies of each term on the right-hand side of equation (2).

As depicted in Table 1, during the warm phase of EP ENSO, $B2$, $B7$, and $C4$ terms are the main contributors of anomalous ascending motion over SEC. The term $B2$ is closely related to the advection of anomalous relative vorticity by the basic latitudinal flow, $B7$ is related to the meridional advection of planetary vorticity by the meridional wind anomaly, and $C4$ is related to the meridional temperature advection by the meridional wind anomaly. In contrast, $B4$, $B5$, and $C2$ terms provide the main negative contributions for the anomalous ascending motion over SEC during the warm phase of EP ENSO. The term $B4$ is closely related to the relative vorticity advection by the meridional wind anomaly, $B5$ is related to the advection of anomalous relative vorticity by the meridional wind, and $C2$ is related to the anomalous temperature advection by the latitudinal wind. The relative important 6 items would be diagnosed and analyzed in more detail in Figure 7.

We first investigate term $B2$ and find that the basic latitudinal wind in SEC autumn is easterly (namely, negative value), and $\frac{\partial \zeta_g^i}{\partial x}$ is generally the unanimous negative value over SEC except the northwest and southeast part, the multiplicative between both of which is the $B2$ term. The dotted area denotes the region where $\zeta_g^i$ induced by Nino 3 SSTA has passed the significance $t$-test at the 90% confidence level. Therefore, when the warm phase of EP ENSO occurs, the $B2$ term will produce significant anomalies. The anomalous spatial pattern is conducive to the occurrence of the anomalous ascending motion in SEC so is conducive to the appearance of monopole mode positive year.

As depicted in Figure 7(b), the meridional wind anomaly over SEC excited by Nino 3 SSTA is southward, and the rest region except the northwest part has passed the significance $t$-test at 90% confidence level. The shading indicates $\frac{\partial T^i}{\partial y}$, not shown as the uniformly positive or negative over SEC. So, during the warm phase of EP ENSO, in general, according to the area average value shown in Table 1, the $B4$ term provides negative contributions to the monopole positive year appearance. But, specially, the shadings with the positive (negative) value generate the positive (negative) contribution to the occurrence of the monopole mode of SEC autumn rainfall.

It is displayed in Figure 6(c) that the basic meridional wind in SEC autumn is northward (negative) and $\frac{\partial \zeta_g^i}{\partial y}$ is marked by shadings and also presents dipole pattern, the multiplication between both of which is $B5$. Owing to $\zeta_g^i$ triggered by Nino 3 SSTA through 90% significance $t$-test at the 90% confidence level (shown in the dotted area), consider the anomaly of $B5$ significant. So, when the EP ENSO warm events emerge, the regional average (shown in Table 1) shows $B5$, providing a positive contribution to SEC rainfall monopole mode positive anomaly years. However, specially, the $B5$ term plays different role for the anomalous ascending motion appearance, with negative (positive) value shadings providing positive (negative) contribution.

From Figure 7(d), it can be seen that the anomalous meridional wind caused by Nino 3 SSTA is southerly over SEC and the red vector is through the 90% confidence $t$ test. $\frac{\partial f}{\partial y}$ also includes positive value and negative value regions. During the warm phase of EP ENSO, the area average demonstrated in Table 1 is the positive value indicating positive contribution to the occurrence of the SEC monopole mode. But, the spatial pattern shown in Figure 7(d) reveals that $B7$ generates positive contribution to monopole mode positive anomaly year only in the southeast part of SEC and negative contribution in northwest part.

From Figure 7(e), we can see that the basic zonal wind in SEC is easterly (negative) and $\frac{\partial T^i}{\partial x}$ is marked by the shadings. However, the SSTA in the Nino 3 area cannot cause a significant change of $T^i$ over SEC (hardly not the dotted area). Therefore, when the EP ENSO warm event occurs, although the regional mean value of $C2$ (Table 1) is larger, the role it plays may be limited.

As shown in Figure 7(f), the anomalous meridional wind over SEC inspired by SSTA in the Nino 3 area is southward (positive value), nearly the entire area is through the 90% confidence $t$ test (as shown in the red vector); $\frac{\partial T}{\partial y}$ is uniformly negative, and the multiplication of both of which is also uniformly negative. Then, after Laplace processing, the calculation result is related to $C4$, hardly uniformly positive over the whole SEC. So, when the EP ENSO warm event arises, the $C4$ item would be beneficial to the anomalous rising movement in the SEC.
Table 1: The area average of related to Nino 3 index 850 hPa regression anomaly of B1–B7 and C1–C6 over SEC (unit: $10^{-19}$ m$^{-1}$s$^{-1}$kg$^{-1}$).

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<td></td>
<td>0.09</td>
<td>0.53</td>
<td>0</td>
<td>-0.18</td>
<td>-0.38</td>
<td>0</td>
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<td>-0.11</td>
<td>0.01</td>
<td>0.45</td>
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Figure 7: The diagnosis of B2 (a), B4 (b), B5 (c), B7 (d), C2 (e), and C4 (f) related to the Nino 3 index: (a) anomalous relative vorticity advection transported by basic zonal wind (vector: basic zonal wind, unit: ms$^{-1}$; shading: $\zeta_g^'/\partial x$, unit: $10^{-11}$ m$^{-1}$s$^{-1}$); (b) meridional relative vorticity advection carried by meridional wind anomaly (vector: meridional wind anomaly, unit: ms$^{-1}$; shading: $\zeta_g^'/\partial y$, unit: $10^{-11}$ m$^{-1}$s$^{-1}$); (c) anomalous relative vorticity advection transported by basic meridional wind (vector: basic meridional wind, unit: ms$^{-1}$; shading: $\zeta_g^'/\partial y$, unit: $10^{-11}$ m$^{-1}$s$^{-1}$); (d) planetary vorticity advection carried by meridional wind anomaly (vector: meridional wind anomaly, unit: ms$^{-1}$; shading: $\zeta_g^'/\partial y$, unit: $10^{-11}$ m$^{-1}$s$^{-1}$); (e) anomalous temperature advection delivered by basic zonal wind (vector: basic zonal wind, unit: ms$^{-1}$; shading: $\partial T^'/\partial x$, unit: $10^{-5}$ km$^{-1}$); (f) temperature advection carried by meridional wind anomaly (vector: meridional wind anomaly, unit: ms$^{-1}$; shading: $\partial T^'/\partial y$, unit: $10^{-5}$ km$^{-1}$). The perturbation of a physical quantity (such as vorticity) is the regression coefficient, obtained by this physical quantity regression on the standardized Nino 3 index. The red vector and the dotted area are through the 90% confidence $t$-test.
In general, during the EP ENSO warm events, B2, B7, and C4 terms are beneficial for contributing to the occurrence of monopole mode positive year, but mainly B2 and C4 play more major roles.

5. The Physical Process of CP ENSO-Like SSTA Influencing Dipole Mode over SEC

In the Section 4, we check the circulation of monopole mode anomaly year, and EP ENSO-like SSTA motivating circulation, both of which are consistent with each other. Based on this, summarize the physical process of the CP ENSO-like SSTA influencing dipole mode of the interannual variability of SEC autumn rainfall. In the following, we would use similar approaches to reveal how the CP ENSO-like SSTA exerts impact on the dipole mode of SEC rainfall.

On the basis of the one standard deviation of PC2, to select positive and negative anomaly years, the positive anomaly years are 1972, 1976, 1977, 1989, and 1994 and the negative anomaly years are 1974, 1975, 1993, and 2010. Based on this, the difference of associated meteorological elements is conducted (positive anomaly year minus negative anomaly year). Specially, positive (negative) anomaly of SEC autumn rainfall is a dipole pattern, with less (more) precipitation in the southeast part and more (less) precipitation in the northwest part.

From the difference of 850 hPa wind and vorticity field, it can be seen that, compared with the negative anomaly years, there exists a significant cyclone anomaly in NWP and a significant anticyclone anomaly in the sea-land interface of SCS, with northward current controlling SEC (Figure 8(a)). The vorticity in Figure 8(a) is characterized by positive anomaly in the north part and negative anomaly in the south part, and the column-integrated water vapor flux and its divergence also perform similar corresponding features, with slight convergence over SEC (Figure 8(b)). Figure 8(c) manifests that an anomalous anti-Walker circulation appears in the tropical Pacific, with the ascending branch located in 160°E–160°W and descending branch in 110°E–120°E. And, this subsiding branch and the sinking branch on the same meridian over SEC (20°N–30°N) cannot form a local close meridional circulation.

CP ENSO-like SSTA can exert a remote influence on the dipole mode of SEC rainfall by inducing the anomalous anticyclone in the SCS-land interface and the local sinking motion over SEC. But the anomalous Walker circulation cannot be a bridge to convey CP ENSO-like SSTA’s influence to the dipole mode, which is different to the monopole mode.

As presented in the regression map of 850 hPa wind and vorticity on EMI index, when the tropical central Pacific warms up, an anomalous cyclone emerges over the NWP (Figures 9(a) and 9(b)), with an anti-Walker circulation in the tropical Pacific and the subsiding branch located in 110°E–120°E (Figure 9(c)). And in the same meridian, there is a sinking branch over SEC and a closed meridional circulation with the subsiding branch of anomalous anti-Walker circulation cannot be formed (Figure 9(d)).

Generally, the anomalous circulation in Figures 9(a) and 9(b) differentiates that in Figures 8(a) and 8(b) a little, but circulation anomaly in Figures 9(c) and 9(d) are similar to that in Figures 8(c) and 8(d). These illustrate that the circulation anomaly induced by CP ENSO-like SSTA may provide important impact on the dipole mode, but not the only factor.

The diagnoses associated with the EMI index of the B1–B7 and C1–C6 terms in equation (2) are shown in Table 2. As demonstrated in Table 2, when the CP ENSO-like SSTA emerges, B5, C1, and C4 terms provide main positive contribution to local descending motion over SEC. Compared with the strong correspondence between monopole mode and EP ENSO-like SSTA, the corresponding relationship between the dipole mode and CP ENSO-like SSTA is relative weak, so only further analyze the maximum value term B5 in Table 2.

As shown in Figure 10, the basic meridional wind over SEC is northerly (negative) and $\partial \zeta / \partial y$ is shaded, presenting as the dipole pattern, the multiplication of both of which is B5, with the dipolar type. In the dotted area, $\zeta$ induced by CP ENSO-like SSTA are through the significance t-test at the 90% confidence level, which means the B5 anomaly is significant there. So, when the warm phase of CP ENSO-like SSTA appears, the anomaly of B5 provides contribution for the anomalous ascending motion in the north part and subsiding motion in the south part over SEC, namely, supporting the positive anomaly year appearance of the dipole mode.

6. Conclusions and Discussion

6.1. Conclusions. There exists significant interannual variations in autumn precipitation over SEC, and the maximum difference between the more-rainfall-year and the less-rainfall-year autumn rainfall sum can be more than 200 mm. The significant area between interannual variation sequence of autumn rainfall in SEC and tropical SST is mainly located in the tropical Middle and East Pacific, where the difference of SST is most significant between the more rainfall year and less rainfall year of SEC. This illustrates that SEC autumn rainfall is closely related to the Middle and East tropical SST, and in especial, the monopole mode of autumn rainfall interannual variability over SEC is closely related to EP ENSO-like SSTA and the dipole mode is associated with CP ENSO-like SSTA, with the correlation coefficients between PC1 and Nino 3 index, and PC2 and EMI index reach up to 0.46 and 0.3, respectively.

The differences of circulation between the monopole mode positive year and negative year are featured by an anomalous anticyclone in the NWP, transporting water vapor into SEC, and an anomalous anti-Walker circulation in the tropical Pacific, with subsiding branch located in the tropical western Pacific, and the local ascending branch in the SEC form a closed meridional circulation. It is interesting that EP ENSO-like SSTA can trigger the similar circulation anomaly, which supports that the monopole mode connects the EP ENSO-like SSTA closely. In addition, the EP ENSO warm event years generally correspond to the
Figure 8: The difference between the positive year and negative year of dipole mode: (a), (b), (c), and (d) same as (a), (b), (c), and (d) in Figure 5. (a) 850 hPa $u; v$ & vorticity diff. (b) Moisture cliff & divergence diff. (c) $u; w^* - 100$ diff. (d) $v; w^* - 100$ diff.

Figure 9: Continued.
positive anomaly years of the monopole mode, which also offers the support for the correspondence between the monopole mode of SEC autumn rainfall and the EP ENSO-like SSTA.

During the warm phase of EP ENSO-like SSTA, the local anomalous subsiding motion over SEC is mainly caused by the anomalous relative vorticity advection transported by basic zonal wind and temperature advection transported by meridional wind anomaly, through diagnosing the omega perturbation equation. These reveal the further physical process which supports the corresponding relationship between the monopole mode and EP ENSO-like SSTA.

The circulation difference between the positive anomaly year and the negative anomaly year of the dipole mode is characterized by an anomalous anticyclone over the SCS-land interface and local anomalous sinking motion over SEC. But, the circulation anomalies triggered by CP ENSO-like SSTA mainly include the anomalous anticyclone in NWP and the local subsiding motion over SEC. Both differentiate a little. So the dipole mode of rainfall is associated with the CP ENSO-like SSTA, but not as strong as that between monopole mode and EP ENSO-like SSTA. By conducting diagnosis of the perturbation omega equation, anomalous relative vorticity transported by basic meridional wind is the most helpful term to confirm the correspondence between dipole mode of interannual variation of SEC autumn rainfall and CP ENSO-like SSTA.

6.2. Discussions. The SEC rainfall is widely influenced by tropical Pacific SST, especially the ENSO-like SSTA. But, in recent decades, the ENSO-like SSTA performs differently, and this paper investigates the relationship between interannual variation of SEC autumn rainfall and two types of ENSO-like SSTA (EP ENSO-like and CP ENSO-like SSTA) and obtains some significant conclusions. However, some questions remained also need to make a further inquiry.

For instance, we ascertain that anomalous Walker circulation is one of the key bridges, by which EP ENSO-like SSTA can exert remote influence on the SEC autumn rainfall monopole mode. But, the anomalous Walker circulation...
cannot convey the remote impact from CP ENSO-like SSTA to SEC autumn rainfall dipole mode, so we only emphasize the cyclone anomaly over NWP. Whether or not there exists other atmosphere process about this issue need to be found out.

Besides, the anomalous circulation in the anomalous year of the dipole mode is not absolutely consistent with the circulation anomaly induced by CP ENSO-like SSTA, indicating that the dipole mode can be influenced by other factors besides the CP ENSO-like SSTA. So, the possible other reasons for variation of the dipole mode need to be surveyed in detail afterwards.

Finally, there are many indicators for defining EP ENSO and CP ENSO [35, 36, 39, 44], but only Nino 3 (EMI) is selected to depict EP (CP) ENSO in this paper. Using different indices may lead to a little difference in the conclusions of this paper, but it will not affect the main conclusions of this paper.

Data Availability

The monthly reanalysis JRA-55 data used to support the findings of this study have been deposited in the ftp://ds.data.jma.go.jp repository. The monthly average SST data used to support the findings of this study have been deposited in the http://badc.nerc.ac.uk/view/badc.nerc.ac.uk_ATOM__dataent_hadisst repository. The observational precipitation data used to support the findings of this study have been deposited in the http://data.cma.cn/data/detail/dataCode/A.0012.0001.html repository.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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