Response of Southern China Winter Rainfall to El Niño Diversity and Its Relevance to Projected Southern China Rainfall Change

QIANG WANG
State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China, and Centre for Southern Hemisphere Oceans Research, CSIRO Marine and Atmospheric Research, Aspendale, Victoria, Australia

WENJU CAI AND WENXIU ZHONG
Physical Oceanography Laboratory/CIMST, Qingdao National Laboratory for Marine Science and Technology, Ocean University of China Qingdao, China, and Centre for Southern Hemisphere Oceans Research, CSIRO Marine and Atmospheric Research, Aspendale, Victoria, Australia

LILI ZENG
State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China

LIXIN WU
Physical Oceanography Laboratory/CIMST, Qingdao National Laboratory for Marine Science and Technology, Ocean University of China Qingdao, China

DONGXIAO WANG
State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, and University of Chinese Academy of Sciences, Beijing, China

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ABSTRACT

Responding to El Niño diversity, greater winter southern China (SC) rainfall is associated with an anomalous warming in the eastern tropical Pacific, but less rainfall with an anomalous warming in the central tropical Pacific. Compared with other widely used indices, the first two principal components of sea surface temperature anomalies in the tropical Pacific better represent the influences of the different El Niño anomaly patterns on winter SC rainfall. This is because these two indices can distinguish a zonal shift of the west North Pacific anticyclone, which conveys the tropical Pacific influence on SC rainfall. At a positive phase, the first principal component features a pattern similar to that of a canonical El Niño, whereas the second component is characterized by a warming in the central Pacific. Based on these two indices, performance of phase 5 of the Coupled Model Intercomparison Project models in simulating the SC rainfall response to El Niño is evaluated. About half of the models cannot reproduce the response to either principal component. The majority of the remaining models can only simulate the response to one principal component, and only five models produce a reasonable response to both principal components. Importantly, changes to SC rainfall in the future depend on the simulation of the SC rainfall response. Models that simulate the teleconnection of SC rainfall with only the first (second) principal component project an increase (decrease) in SC rainfall. Projection of a rainfall change in models that simulate the teleconnection with both principal components, that is, a moderate increase in SC winter rainfall, is more credible.

a Current affiliations: School of Atmospheric Sciences, and Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Guangzhou, and Southern Marine Science and Engineering Guangdong Laboratory, Zhuhai, China.

Corresponding author: Dr. Dongxiao Wang, dxwang@scsio.ac.cn

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1. Introduction

In winter, southern China (SC) experiences limited rainfall because of strong winter northwesterly winds in the lower troposphere; these winds carry southward cold and dry air masses (Chang et al. 2005; Jia et al. 2011). Interannual variability of winter SC rainfall is mainly attributed to East Asian winter monsoon (EAWM; Zhou and Wu 2010; Zhou 2011) and El Niño–Southern Oscillation (Zhou et al. 2010). A weak EAWM or El Niño event induces anomalous southwesterly winds over the South China Sea (SCS), which transports moisture from the SCS to SC, conducive to SC rainfall (Zhou and Wu 2010; Zhou 2011).

El Niño–Southern Oscillation (ENSO) is a coupled ocean–atmosphere phenomenon in the tropical Pacific, which exerts a great influence on China’s climate variability (Weng et al. 1999; Chang et al. 2000; Wang et al. 2000; Wang and Zhang 2002; Zhou and Chan 2007; Zhou et al. 2010). In boreal summer and fall of an El Niño developing year, less rainfall is observed over northern China, which is associated with an anomalous barotropic cyclone over East Asia (Huang and Wu 1989; Wu et al. 2003). A wetter belt from SC to eastern central China and Japan is observed during the autumn season of an El Niño developing year until the following spring (Huang and Wu 1989; Chen 2002; Wu et al. 2003). In the summer of an El Niño decaying year, there is a tripolar pattern of rainfall anomalies in China, with negative rainfall anomalies covering northern China and SC, and positive anomalies over central China (Huang and Wu 1989; Zhang et al. 1999; Feng and Hu 2004; Xue and Liu 2008).

Many studies have reported that an anomalously weak Walker circulation and its associated anomalous anticyclone over the western North Pacific (WNP) are directly related to rainfall anomalies in China, serving as a key mechanism for enabling warm sea surface temperature (SST) anomalies in the eastern tropical Pacific to affect East Asian rainfall (Zhang et al. 1996; Wang et al. 2000; Chang et al. 2004). This WNP anticyclone develops in late fall of an El Niño developing year and persists until the following spring or early summer, inducing anomalously wet conditions along the East Asian polar front that stretches northeastward from SC to east of Japan (Wang et al. 2000). Variability of this WNP anticyclone modulates the East Asian climate during El Niño events (Feng and Li 2011; Feng et al. 2011; Wang and Wang 2013). Several dynamic mechanisms have been proposed to explain the formation of this WNP anticyclone during El Niño events. These include a suppressed convection over the WNP induced by an anomalously weak Walker circulation (Zhang et al. 1996), Rossby wave response related to the WNP cold SST anomalies (Wang et al. 2000), an Indian Ocean capacitor effect (Yang et al. 2007; Xie et al. 2009), and nonlinear atmospheric interactions between the annual cycle and ENSO variability (Stuecker et al. 2013, 2015).

A new El Niño type (El Niño Modoki) has been identified recently, which is defined by its warm SST anomalies centered over the central tropical Pacific (Ashok et al. 2007). This new type of El Niño is also referred to as the “dateline El Niño” (Larkin and Harrison 2005), “central Pacific (CP) El Niño” (Kao and Yu 2009), and “warm pool El Niño” (Kug et al. 2009). The second empirical orthogonal function (EOF) of SST anomalies is used to distinguish an El Niño Modoki from a canonical El Niño (Ashok et al. 2007). Climate anomalies are significantly different between canonical El Niño and El Niño Modoki over many parts of the globe (Ashok et al. 2007; Weng et al. 2007; Huang and Huang 2009; Taschetto et al. 2009; Feng and Li 2011; Feng et al. 2011; Wang and Wang 2013). El Niño Modoki events have occurred more frequently in recent decades (Yeh et al. 2009; Lee and McPhaden 2010; Takahashi et al. 2011), and the East Asian climate anomalies related to ENSO also appear to change on interdecadal time scales (Zhou and Chan 2007; Ding et al. 2010; Xie et al. 2010; Wang and Wang 2013).

The different influences of canonical El Niño and El Niño Modoki on East Asian rainfall are rather conspicuous (Yuan and Yang 2012). During the summer of a developing year, El Niño Modoki exerts a strong influence on the maritime regions, but its impact is weak over China (Ashok et al. 2007). During the fall of a developing year, there is increased rainfall over SC related to canonical El Niño, but the influence from El Niño Modoki is insignificant (Zhang et al. 2011). Wang and Wang (2013) used a rainfall index to identify El Niño Modoki years with increased and decreased SC fall rainfall, and divided El Niño Modoki into El Niño Modoki I and El Niño Modoki II, corresponding to positive and negative rainfall anomalies in SC, respectively. Previous studies have suggested that there is no significant correlation (Feng et al. 2011; Wang and Wang 2013) between SC winter rainfall and the El Niño Modoki index (EMI; Ashok et al. 2007), but there is a possibility that the lack of a relationship is due to the opposing impacts of different types of ENSO events that are included in an ENSO index. However, the second principal component of tropical Pacific SST anomalies that accounts for the main features of El Niño Modoki (Ashok et al. 2007) may be a more reasonable index to describe the influence of El Niño Modoki on SC rainfall.

The Coupled Model Intercomparison Project (CMIP) was established to serve as a primary tool for estimating future climate variability and change (Kharin et al. 2007). Phase 5 of CMIP (CMIP5) models perform better than phase 3 of CMIP (CMIP3) models in simulating the
observed spatial patterns of the two types of El Niño and have a significantly smaller intermodel diversity in ENSO intensities (Kim and Yu 2012). Two factors (i.e., the amplitude and the spatial structure of the ENSO SST pattern in the tropical central and eastern Pacific) determine the relationship between ENSO and East Asian–western Pacific (EAWP) climate in CMIP5 models (Gong et al. 2014). An eastward shrinking of the ENSO SST pattern weakens the climatic response to ENSO over the EAWP in CMIP5 models, but a westward expansion of the SST pattern shifts the anomalous Walker circulation too far west and results in unrealistic EAWP rainfall anomalies (Gong et al. 2015). However, these studies mainly focus on the canonical El Niño, and some important issues remain open, such as the performance of the regional climate response to the two types of El Niño in CMIP5 models, and the relevance to regional rainfall projection.

In this paper, we use the first two principal components of SST anomalies in the tropical Pacific to assess the influence of El Niño on SC rainfall, to evaluate the performance of CMIP5 models in simulating the response of SC rainfall to various El Niño events, and to examine the implications. The paper is organized as follows: Datasets and indices are introduced in section 2. Section 3 analyzes suitable indices to represent the influence of El Niño diversity on SC rainfall. In section 4, simulations of SC rainfall response to the two types of El Niño in CMIP5 models, and implication for climate projection are evaluated. Conclusions are given in section 5.

2. Data and methods

Monthly mean atmospheric reanalysis datasets are taken from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; Kalnay et al. 1996), with 2.5° × 2.5° horizontal resolution and 17 vertical pressure levels from 1000 to 10 hPa. Rainfall data are from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC; Chen et al. 2002), on a 0.5° latitude–longitude grid. Monthly mean SSTs are from the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) with 1° × 1° horizontal resolution (Rayner et al. 2003). We focus on the El Niño mature phase and all variables are averaged over the boreal winter season of December–February (DJF). Because of data availability, 1951–2010 is used as the historical period.

The climate model data used in this study have been taken from CMIP5 (https://pcmdi.llnl.gov/cmip5). The CMIP5 simulations employ historical anthropogenic and natural forcing until 2005, and thereafter the forcing follows RCP8.5. A total of 39 models were analyzed. The historical and future periods refer to 1951–2010 and 2011–70, respectively. As most models run at different resolutions, we regreidded all model data using bilinear interpolation onto a 1° longitude by 1° latitude grid, which can still resolve large-scale rainfall features. We also checked the results in a situation in which data were interpolated onto a 2° longitude by 2° latitude grid, and found that the conclusions are unchanged.

Several indices are constructed as discussed below.

1) PC 1 and 2: EOF analysis has been applied to the tropical Pacific SST anomalies, and the first two PCs normalized by their respective standard deviations are used.

2) E and C indices: Following Takahashi et al. (2011), an E index and C index from the EOFs of SST anomalies are used to describe canonical El Niño and El Niño Modoki, respectively.

\[
E \text{ index} = \frac{PC1 - PC2}{\sqrt{2}},
\]

\[
C \text{ index} = \frac{PC1 + PC2}{\sqrt{2}}.
\]

The E and C indices are independent (the correlation between them is zero) and properly depict the complexity of ENSO, describing the regimes of extreme warm events, and ordinary cold/moderately warm event, respectively (Takahashi et al. 2011). The first two EOFs are shown in Figs. 1a and 1b and the SST anomaly regression patterns with respect to the E index and C index are shown in Figs. 1d and 1e.

3) El Niño Modoki index (EMI): Following Ashok et al. (2007), an EMI has also been used to describe El Niño Modoki; this has been used in many SC rainfall–ENSO teleconnection studies (Feng et al. 2010, 2011; Wang and Wang 2013) and is used here for comparison with other indices.

\[
EMI = [SSTA]_C - 0.5 \times [SSTA]_E - 0.5 \times [SSTA]_W,
\]

where the square brackets with a subscript represent the area-averaged SST anomalies (SSTA) over the central Pacific region C (10°S–10°N, 165°E–140°W), the eastern Pacific region E (15°S–5°N, 110°–70°W), and the western Pacific region W (10°S–20°N, 125°–145°E), respectively.

The correlation between Niño-3 and E index is 0.82, and that between EMI and C index is 0.89.

4) SC rainfall anomalies: Rainfall anomalies are averaged over the area marked by the black rectangle in Fig. 2a (20°–30°N, 100°–122°E).

5) SC rainfall changes: Future SC rainfall changes that depend on global warming are calculated as:
SC rainfall changes = \((SC\ Rainfall_{\text{future}} - SC\ Rainfall_{\text{historical}})/(\text{[SSTA]}_{\text{future}} - \text{[SSTA]}_{\text{historical}})\), 

where the square brackets represent the global-averaged SST anomalies (SSTA), and the subscript future and historical indicate the periods 2011–70 and 1951–2010, respectively.

The Niño-3.4 index higher than 0.5°C for six consecutive months or longer is defined as an El Niño event. Thus, 14 El Niño events are identified (1957/58, 1963/64, 1965/66, 1968/69, 1972/73, 1982/83, 1986/87, 1991/92, 1993/94, 1994/95, 1997/98, 2002/03, 2004/05, 2009/10) during the historical period (i.e., 1951–2010), and their associated PC1 and PC2 are plotted in Fig. 1c and their E and C indices in Fig. 1f. Using one standard deviation for the E index and 0.5 standard deviations for the C index as the criteria, all the canonical El Niño events (e.g., the 1972, 1982, and 1997 extreme El Niños) are located in the

![Fig. 1.](image-url)
FIG. 2. Relationship between SC rainfall with (a) Niño-3, (b) E index, (c) PC1, and (d) composite SC rainfall anomalies for years with large positive SC rainfall anomalies (larger than one standard deviation); (e)–(g) as in (a)–(c), but for EMI, C index, and PC2; (h) as in (d), but for years with negative SC rainfall anomalies (smaller than one negative standard deviation). (i) Composite SC rainfall anomalies for years of La Niña (i.e., 1955/56, 1970/71, 1973/74, 1975/76, 1988/89, 1999/2000, 2007/08). The white dots indicate that the correlation exceeds the 95% significance level based on a Student’s t test. The black box in (a) indicates the area that is used to calculate the averaged SC rainfall anomalies.
lower-right corner of Fig. 1f, but typical El Niño Modoki events are found in the top-left corner.

3. Response of SC rainfall to El Niño diversity reflected by different indices

a. SC rainfall associated with different ENSO indices

We used ENSO indices to estimate their contribution to total SC rainfall variance (Table 1). Niño-3 or E index can explain about 30% of total SC rainfall variance, while PC1 gave a smaller percentage, that is, 24.3%. Both the EMI and C index gave negligible explained percentages, which were 0.4% and 2.1%, respectively. However, PC2 can explain 8.3% of total SC rainfall variance, which demonstrates that PC2 itself is more suitable than the C index or the EMI for estimating the influence of the warming in the central tropical Pacific on SC rainfall. The bivariate linear regression of SC rainfall onto PC1 and PC2 can contribute to about 32.6% of total SC rainfall variance, which is equal to that of E index and C index, because the E index and C index were a linear transformation of PC1 and PC2. However, the explained percentage of a bivariate linear regression onto Niño-3 and EMI is smaller than Niño-3 alone.

To elucidate the influence of El Niño diversity on SC rainfall, correlations of the SC rainfall with ENSO indices are examined (Fig. 2). For a canonical El Niño, there is a significant positive SC rainfall anomaly, which is reflected by all three indices (Figs. 2a–c). The correlation patterns are similar to the pattern of positive SC rainfall anomalies (Fig. 2d), which demonstrates that warm anomalies in the eastern tropical Pacific favor SC rainfall. However, neither the EMI (Fig. 2e) nor the C index (Fig. 2f) gives a significant negative relationship between SC rainfall and warm anomalies in the tropical central Pacific, which is consistent with previous findings (Feng et al. 2010; Yuan and Yang 2012; Wang and Wang 2013). A previous study has also pointed out that dry conditions dominate SC when there is an El Niño Modoki (Feng et al. 2010), but the widely used EMI or C index does not represent the maximum influence of El Niño Modoki on SC rainfall. Further, there is a significant negative correlation with PC2 (Fig. 2g), which is consistent with a pattern of negative SC rainfall anomaly (Fig. 2h). Ashok et al. (2007) highlighted that the main features of El Niño Modoki can be captured by the second EOF of SST anomalies in the tropical Pacific; that is, the unique warming in the central equatorial Pacific (Fig. 1b). It appears that the PC2 itself is more suitable for estimating the influence of warming in the central tropical Pacific on SC rainfall than C index. As Niño-3 and the E index (or EMI and C index) give similar results, only E index and C index are discussed as a comparison with PC1 and PC2, in the following sections.

When a La Niña occurs, there is negative SC rainfall anomaly (Fig. 2i). However, its composite pattern is quite different from the pattern of negative SC rainfall anomalies (Fig. 2h), which that the negative SC rainfall anomalies are more related to the PC2 than a La Niña.

b. SC rainfall anomalies and patterns of tropical Pacific warming

To identify the SST anomaly patterns that are most effective at controlling the SC rainfall anomalies, we construct composites of SST anomalies for El Niño years with positive and negative SC rainfall anomalies (Figs. 3a,b). The pattern associated with high SC rainfall and that of a canonical El Niño are rather similar (cf. Fig. 3a and Figs. 1a,d), confirming that a canonical El Niño
Niño leads to positive SC rainfall anomalies. However, the pattern associated with lower SC rainfall is rather different from that associated with the $C$ index (cf. Fig. 3b and Fig. 1e; the partial correlation is low at 0.28). The pattern corresponding to low SC rainfall is in fact closer to the pattern of PC2 shown in Fig. 1b (the partial correlation is 0.83); both feature maximum warm anomalies farther to the west ($175^\circ$E, compared to $160^\circ$W). Differences between Fig. 3b and Fig. 1b in other locations arise from the fact that Fig. 3b captures all SST anomalies, not only related to SC rainfall but also unrelated, as it is obtained through a composite analysis.

The tropical Pacific SST anomaly pattern associated with the $C$ index is different from the pattern associated with PC2, and the rainfall-reducing effect of the $C$ index is not as strong as that represented by PC2 because the $C$ index includes a component of positive PC1 (Fig. 1e), which offsets the impact associated with PC2. This leads to a stronger relationship between SC rainfall anomalies and PC2 than with the $C$ index (Figs. 2d–f). In other words, warming in the central tropical Pacific is the key feature that weakens SC rainfall, and PC2 is a better index to estimate its influence on SC rainfall.

c. Mechanism

To understand the mechanism, we examine circulation anomalies to understand the mechanisms for SC rainfall variability associated with various El Niño events. To show information of different vertical levels, we regress 1000-hPa geopotential height anomalies and 850-hPa moisture transport anomalies onto the $E$ index; (b)–(d) as in (a), but for PC1, $C$ index, and PC2, respectively. Areas within the gray contours filled with white dots indicate where the regression exceeds the 95% significance level, based on a Student’s $t$ test. The blue contours are coastlines.

![Image](https://example.com/image.png)

**Fig. 4.** (a) Pattern of regression coefficients of 1000-hPa geopotential height anomalies (shaded; unit: gpm) and 850-hPa moisture transport anomalies (vector; units: g m s$^{-1}$ kg$^{-1}$) onto the $E$ index; (b)–(d) as in (a), but for PC1, $C$ index, and PC2, respectively. Areas within the gray contours filled with white dots indicate where the regression exceeds the 95% significance level, based on a Student’s $t$ test. The blue contours are coastlines.
SC rainfall. For a high C index, the WNP anticyclone center shifts west, which only weakens the meridional moisture transport over SCS, but does not shut it down (Fig. 4c). Thus, the correlation between SC rainfall and C index is not significant (Figs. 2e,f). However, for high PC2, the anticyclone is weak and centered right over the SCS, blocking the meridional moisture transport from the SCS and inducing a significant reduction of SC rainfall (Fig. 2g).

This suggests that both the E index and PC1 can suitably represent the positive influence of canonical El Niño on SC rainfall, as they have a similar warming pattern in the tropical Pacific, which generates an eastward shift of the WNP anticyclone and enhance the meridional moisture transport from the SCS to SC. However, the tropical Pacific warming pattern associated with the C index involves a component of positive PC1 and thus fails to fully represent the influence of tropical central Pacific anomalies on SC rainfall. However, the PC2 can extract the main tropical central Pacific warming features, which result in dry conditions over SC by the westward shift of the WNP anticyclone. Thus, PC1 and PC2 should be used to assess the performance of SC rainfall response to El Niño diversity in CMIP5 models, because a conspicuous correlation provides a clear criterion to benchmark models.

4. Assessment of CMIP5 simulation of SC rainfall response to El Niño diversity

a. SC rainfall anomalies associated with two types of El Niño in CMIP5

We examined 39 CMIP5 models and applied EOF analysis to the historical and future periods of each model. Following the above discussion, we use the correlation of SC rainfall with PC1 and PC2 from the historical period to evaluate the performance in simulating the response of SC rainfall to El Niño (Fig. 5).

Based on the 90% significance level (a mean correlation amplitude of 0.38) of a Student’s t test, 19 models (about half of the models) fail to simulate the response of SC rainfall to either type of El Niño. Nine (eight) models only simulate the teleconnection between SC rainfall and PC1 (PC2). Only five models (about one-eighth of the total) can produce a reasonable SC rainfall response to both PC1 and PC2, although their responses are less significant than in observations. Increasing the statistical significance level to the 95% would greatly reduce the number of models that are classified as able to simulate the response of SC rainfall to either type of El Niño. To give an explanation of the model response, two groups of models have been defined: group 1 (group 2) contains models that can simulate the response to PC1 (PC2) (Fig. 5).

b. Physical explanations

The ensemble mean of regression patterns of SST anomalies and circulation anomalies associated with various El Niño events is examined to understand the varied performances of different models.

Comparing the ensemble mean regression SST anomaly patterns of group 1 and group 2 onto PC1 (Figs. 6a,b), it is found that the main warming features over the tropical Pacific are similar to the observations for both groups (Fig. 1d). However, the cold SST anomalies of group 2 in the WNP extend farther west than those of group 1. Responding to the cold SST anomalies, the WNP anticyclone is established, which is the key factor that dictates the influence of warm SST anomalies in the tropical Pacific to SC (Wang et al. 2000). For group 1, the cold SST anomalies occur east of the Philippines, which is quite similar to the observations (cf. Fig. 6a and Fig. 1d). The ensemble WNP anticyclone center is then located to the east of the Philippines and its western flank induces strong southerly wind anomalies over the SCS, consistent with the observations (cf. Fig. 6c and Fig. 4a). Therefore, the teleconnection between SC rainfall and canonical El Niño is reproduced in the models of group 1. However,
the WNP cold SST anomalies of group 2 are shifted westward with their core covering the eastern SCS (Fig. 6b), where the center of the WNP anticyclone occurs (Fig. 6d). The meridional moisture transport from the SCS to SC weakens, leading to a nonsignificant relationship between SC rainfall and canonical El Niño.

The situation is just the opposite for the ensemble mean regression SST anomaly patterns of group 1 and group 2 onto PC2 (Figs. 7a,b). The group 2 ensemble mean SST anomaly pattern of group 2 (from a regression analysis) resembles the zonal tripole pattern in the tropical region with a central equatorial Pacific warming flanked by colder SST anomalies on both sides along the equator (cf. Fig. 7b and Fig. 1b). Therefore, the anticyclone is squeezed right over the SCS, blocking the meridional moisture transport from the SCS to SC and inducing a negative relationship between SC rainfall and El Niño Modoki (Fig. 7d). However, the group 1 SST anomalies of group 1 associated with PC2 cannot reproduce the zonal tripole pattern, and its warming region extends farther west, covering the entire west Pacific and half of the SCS (Fig. 7a). As a result, the associated WNP anticyclone disappears (Fig. 7c), and the relationship between SC rainfall and El Niño breaks down.

c. Implications for future changes of SC rainfall

Based on the two groups of CMIP5 models, possible diversity in SC rainfall changes in models have been investigated (Fig. 8). In Fig. 8, the correlation between SC rainfall and PC1 is derived from historical simulations of each model, and the SC rainfall change is derived from Eq. (3). We investigate SC rainfall future changes by comparing changes in the two groups of models.

For the models of group 1, there is a significant positive relationship between the SC rainfall changes and the ability to simulate the El Niño influence on SC rainfall as represented by PC1 (Fig. 8a). In response to greenhouse warming, extreme El Niño events characterized by establishment in eastern equatorial Pacific convection is projected to occur more frequently (Cai et al. 2014, 2018). Models with a greater relation between SC rainfall and PC1 systematically produce a larger SC rainfall change, indicating its relevance to the projected change. By contrast, in this group,
there is no such relationship between SC rainfall change and PC2–SC rainfall correlation (Fig. 8b).

For group 2, for models in which the teleconnection between SC rainfall and PC1 is weak (group 2), the intermodel relationship between the SC rainfall changes and the PC1-SC rainfall correlation is weaker (Fig. 8c). Instead, the PC2–SC rainfall correlation is relevant to future SC rainfall projection (Fig. 8d).

Based on the above discussion, we can obtain different maps of SC rainfall changes (Fig. 9). For group 1 models, in which the canonical El Niño dominates the SC rainfall anomalies, larger positive SC rainfall changes cover most of SC (Fig. 9a). The ensemble mean of group 2 SC rainfall mainly presents a reduction in SC rainfall with only a narrow and weak belt of increase in the middle (Fig. 9b). The ensemble mean of SC rainfall changes of the best five models (Fig. 5) is similar to that of group 1, with larger amplitude of SC rainfall changes (Fig. 9c).

We applied EOF analysis onto the simulated SST anomalies of 1951–2070, and calculated the standard deviation (STD) of the two periods PCs (i.e., 1951–2010 and 2011–70), respectively. Large increase ensemble STD of projected PC1 in group 1 (i.e., from 30.8 to 73.7) demonstrates the enhancement of the PC1-associated SST anomaly pattern, which favors an increase in SC rainfall. The same situation occurred for PC2 in group 2, but for a slight increase of its projected STD (i.e., from 36.9 to 41.5).

Arguably other factors also impact mean rainfall change, as indicated by differences between the mean rainfall change patterns (Fig. 9) and correlation patterns (Fig. 2). However, these projected mean rainfall changes shown in Fig. 9 suggest that the realism of simulation of the present-day rainfall response to ENSO diversity is relevant for the projection, and that at least some mechanisms for projected changes are similar to those operating for the rainfall response to ENSO. The majority of climate models projected a mean SST warming pattern featuring a faster warming in the equatorial eastern Pacific (Cai et al. 2015), similar to the $E$ index pattern, and a faster warming in the equatorial than the off-equatorial Pacific, including the central Pacific. The projected changes shown in Fig. 9 are therefore consistent with a response to the mean warming pattern.

5. Conclusions

The WNP anticyclone is a key factor conveying the effect of the tropical Pacific warming to SC rainfall, and its zonal shift results in different SC rainfall responses.
The WNP anticyclone shifts farther east when the warm anomalies in the eastern tropical Pacific occur, as represented by PC1, which enhances meridional moisture transport from the SCS to SC, leading to increased SC rainfall. On the other hand, the warm anomalies in the central tropical Pacific, as represented by PC2, shift the WNP westward, reducing the meridional moisture transport from the SCS to SC.

All indices (i.e., Niño-3, E index, and PC1) that are commonly used to represent the canonical El Niño can give a significant positive relationship with SC rainfall. However, the C index or EMI, which are commonly used to represent El Niño Modoki, are not as effective for depicting the westward shift of the WNP anticyclone, although overall they are associated with reduced SC rainfall. The SST anomaly pattern associated with a C index includes a component of PC1, such that the SST anomaly pattern associated with the lowest SC rainfall is rather different from that associated with the C index. The anticyclone associated with the PC2 SST anomaly pattern is located right over the SCS, blocking the meridional moisture transport, and therefore representing a situation in which SC experiences significantly decreased rainfall.

PC1 and PC2 can be used to estimate the influence of various El Niño events on future SC rainfall changes. Based on the two indices, the performance in simulating the response of SC rainfall to greenhouse warming in CMIP5 models has been evaluated. About half of the models cannot reproduce the response of SC rainfall to either PC1 or PC2 SST anomaly pattern. Five models give a reasonable response of SC rainfall to both PC SST patterns. Nine (eight) models can only simulate the observed response of SC rainfall to PC1 (PC2). Therefore, these models can be separated into two groups; that is, ones that can simulate the SC rainfall response to PC1, and ones that can simulate the response to PC2.

Simulation of SST anomalies in the west tropical Pacific is key to reproducing the SC rainfall response. For PC1, the models of group 1 give a pattern with a cooling in the west tropical Pacific, and the associated WNP anticyclone center is located to the east of the Philippines.
This induces a large meridional moisture transport from the SCS to SC, resulting in significant correlation between the SC rainfall and canonical El Niño. However, the west tropical Pacific cooling in group 2 shifts farther west, as does the center of the WNP anticyclone, which is not favorable for meridional moisture transport over the SCS, and the connection between the SC rainfall and El Niño breaks down. For PC2, the models of group 2 correctly simulate the cooling in the west tropical Pacific and the location of the WNP anticyclone center, and give a reasonable SC rainfall response. For the models of group 1, the cooling in the west tropical Pacific shifts west and weakens, and the tropical Pacific east to the Sulawesi Sea is totally occupied by warming SST anomalies, resulting in the disappearance of the WNP anticyclone. Therefore, the models of group 1 fail to simulate the SC rainfall response to PC2.

Future changes of SC rainfall depend on the simulated SC rainfall response to PC1 and PC2. For the models of group 1, a reasonable simulation of SC rainfall response to PC1 leads to a projected SC rainfall increase. The increased SC rainfall in the future covers most of SC. However, the models of group 2 only simulate the SC rainfall response to PC2, and their ensemble mean rainfall change projects a general reduction in SC rainfall with only a narrow and weakened south–north oriented belt of increase in central SC. Projection of a rainfall change in models that simulate the teleconnection with both principal components, that is, a moderate increase in winter SC rainfall, is more credible.

It is appropriate to point out that the SC winter rainfall changes are not solely controlled by the rainfall–ENSO relationship. Further studies are needed to determine other factors that might be relevant to SC winter rainfall projection.

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