ENSO combination mode and its influence on seasonal precipitation over southern China simulated by ECHAM5/MPI-OM

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ABSTRACT
Recent studies show that a combination mode (C-mode) represents the seasonally modulated dynamics of ENSO, which plays an important role in maintaining the western North Pacific anomalous anticyclone. This C-mode could obviously influence the East Asian climate, especially since the contribution of ENSO to southern China's precipitation has weakened since the late 1990s. This paper evaluates whether the C-mode and its influences on precipitation over southern China can be realistically described by the climate model ECHAM5/MPI-OM. The authors find that the model is able to reproduce the spatial and temporal variability of the C-mode and the asymmetric responses of air–sea interactions during El Niño events. The findings have implications for ECHAM5/MPI-OM being a valuable tool for simulating and predicting the C-mode-related seasonal precipitation over southern China.

1. Introduction
Stemming from large-scale air–sea interactions, ENSO is the most prevalent interannual variability phenomenon and its influence can be felt around the globe (Ropelewski and Halpern 1987; Philander, Rogério Dos Santos, and Alex Soares de Souza 1990; Neelin et al. 1998; Trenberth and Caron 2000; Alexander et al. 2002). Previous studies have revealed that the meridional antisymmetric ENSO combination mode (C-mode) results from the nonlinear atmospheric interaction between ENSO variability and the SST annual cycle. It shows a significant variability of near–annual combination time periods of approximately 10 months as well as a stronger one of approximately 15 months (Stuecker et al. 2013). Furthermore, the C-mode illustrates meridional antisymmetric patterns related to the equator both in the atmosphere and in SST anomalies (Du et al. 2009; Stuecker et al. 2013, 2015).

Previous studies suggest that this C-mode, occupying most dominantly during strong El Niño, is of great significance in terminating the El Niño life period along with the rapid southward movement of westerly anomalies (Vecchi 2005; Vecchi and Harrison 2003; Lengaigne et al. 2006; Stuecker et al. 2013). Moreover, it also has an essential role in developing and maintaining the anomalous western North Pacific anticyclone (WNPAC) (Stuecker et al. 2015). The WNPAC can cause a stronger transport of water vapor towards East Asia and significantly affect anomalies of East Asian precipitation (Zhang, Min, and Su 2017). Owing to its importance in ENSO seasonally modulated dynamics and its influence on East Asian climate-related ENSO, it is crucial to evaluate the simulation of the C-mode by models.

Many examinations have been conducted to assess the performance of models in simulating the C-mode (Weisheimer et al. 2009; Li et al. 2016; Zhang et al. 2016a). For example, Ren et al. (2016) proposed that most models in CMIP5 can capture the dimensional distribution of the C-mode, but only half of them are able...
to capture the spectral peak near the annual cycle. Even increasing the horizontal resolution cannot improve the accuracy of the C-mode simulation, according to Wan, Ren, and Wu (2018). It is currently not clear which characteristics of models contribute a realistic C-mode simulation. The main purpose of this study is to examine the atmospheric and oceanic response of the C-mode and its influences on the southern China precipitation simulated by ECHAM5/MPI-OM.

2. Model and datasets

The ECHAM5/MPI-OM coupled climate model consists of ECHAM5.4 at T63 spectral resolution (1.875° × 1.875°) as the atmospheric part and MPI-OM as the oceanic part. The model simulates the mean state and does not request a flux adjustment to maintain a stable climate. For more information about the model, see Marsland et al. (2003), Jungclaus et al. (2006), and Wolff, Maier-Reimer, and Legutke (1997). The model shows good performance in climate prediction at seasonal to decadal timescales (Keenlyside et al. 2005; Keenlyside et al. 2008) and can reproduce similar realistic aspects of climate variability such as ENSO and the Pacific Decadal Oscillation (Oldenborgh, Philip, and Collins 2005; Zheng 2014; Luo, Zheng, and Zhu 2017).

A 600-year pre-industrial climate control was performed, and the analysis concentrated on prominent climate variables such as surface wind, SST, and SLP over the tropical Pacific. For comparison, we used monthly surface wind, SLP, and precipitation from NCEP–NCAR (1961–2010) (Kalnay et al. 1996). The dataset of the SST anomalies (1961–2010) is the same as that in Wan, Ren, and Wu (2018).

In this work, we first performed an EOF analysis on the surface wind anomalies, followed by linear regression. In addition, we applied composite and spectral analysis in the same way as that in Stuecker et al. (2013) and Zhang et al. (2016b). The winter of the El Niño developing phase was defined as December–January–February (DJF(0)), and the decaying months in the following spring were defined as March–April–May (MAM(1)).

3. Results

3.1. Dimensional distribution of the C-mode in the simulation

We conducted EOF analysis on the surface wind anomaly over the Pacific (10°S–10°N, 100°E–60°W). The results reveal that the first EOF (EOF1) comprises the tropically quasi-symmetric surface wind anomalies over the western-central Pacific that are related to ENSO and feature the anomalous Walker circulation. Specifically, the westerly wind anomalies in the model extend into the western Pacific slightly too far compared to the observation. Moreover, the first principle component (PC1; ENSO signal) of the model describes a significant interannual variability, and each peak of PC1 corresponds to an El Niño event (e and f).

In combination with the positive phase of the second principle component (PC2; C-mode signal), the second EOF (EOF2) catches the WNPAC and the central South Pacific anomalous cyclone and features the atmospheric structure of the C-mode, which is in good agreement with the observation. This meridional antisymmetric wind pattern of the C-mode is generated from the annual cycle of SST and ENSO variability (Stuecker et al. 2013). It is worth noting that the WNPAC in the model moves slightly too far westward compared to that in the observation.

3.2. Asymmetric SST and SLP response of the C-mode in the simulation

We regressed the SST anomalies as well as the SLP anomalies onto PC1 and PC2 in the simulation validated by the observation (Figure 2). The dimensional patterns of SST and SLP associated with the first pattern (ENSO mode) as well as the second pattern (C-mode) are successfully described by the model. However, the simulated warm center associated with ENSO over the tropical central-eastern Pacific is larger and spreads to the western Pacific in contrast to the observation. A previous study described the structure of the SST anomaly over the tropical Pacific and explained that it was quite realistic; however, its reach into the western Pacific was slightly too far away (Zheng 2014). Similarly, the simulated warm center associated with the C-mode over the tropical eastern Pacific is larger as well (Figure 2(d)), which is partly attributable to the stronger simulation of this ENSO mode. Previous work noted that models with better performance in simulating realistic ENSO are more likely to reproduce the C-mode more realistically (Ren et al. 2016). However, ECHAM5/MPI-OM tends to emphasize the warm SST anomaly in the western Pacific (Zheng 2014), which is largely responsible for the warm center associated with the C-mode over the tropical eastern Pacific.

At the same time, the simulation of SLP in both first two modes is stronger than that in the observation. Considering the meridional coarse resolution in the tropical ocean, the atmospheric role is prevailing in controlling major features of interannual SST variability, as in previous work (Gualdi et al. 2003; Guilyardi et al. 2004), which shapes the important characteristics of the interannual SLP variability.
Figure 1. The leading two EOF patterns of surface wind modes. Panels (a–d) show the wind anomalies (units: m s$^{-1}$) over the tropical Pacific from (a, b) observed and (c, d) simulated data obtained by an EOF decomposition. The shading indicates the regressed zonal wind anomalies. Panels (e, f) are the normalized PCs for observations and the model.

Figure 2. SST (shading; units: °C) and SLP (contours; units: mb) anomalies regressed onto (a, b) PC1 and (c, d) PC2 for (a, c) observation and (b, d) the model (right). Values exceeding the 95% confidence level are displayed.
3.3. Phase-locking and power spectrum

As shown in previous studies, the C-mode takes an essential part in the rapid transition of strong El Niño (Vecchi 2005; Vecchi and Harrison 2003; Lengaigne et al. 2006) and in establishing the WNPAC (Wang, Wu, and Lukas 1999; Stuecker et al. 2013). Hence, the composite seasonal evolution of ENSO and the C-mode are illustrated in Figure 3(a). The El Niño events were selected following the same principle as shown in previous work (Zheng 2014). The composite analysis of El Niño describes a seasonal evolution of a typical El Niño event, which develops in spring or summer, reaches a peak in autumn or winter, and decays in the following spring. Different from ENSO, the C-mode is negative in the El Niño developing autumn and then suddenly turns to positive, causing the peak to arrive in late winter or early spring and the decay in summer or early fall together with the El Niño mature stage (McGregor et al. 2012). Furthermore, the peak phase of the C-mode is consistent with ENSO, causing a delay of approximately two or three months compared with ENSO and showing a shorter cycle (Stuecker et al. 2013, 2015). The simulated C-mode resembles the observations well.

To further explain the connection between ENSO and the C-mode in the model, we calculated the power spectrum (Figure 3(b and c)). The spectral peaks of ENSO reveal obvious variability mainly in the interannual period of 2–8 years, as shown in previous studies (Stuecker et al. 2013). Moreover, the spectral peaks of PC2 (C-mode signal) at frequencies $1 - f_E$ or $1 + f_E$ (1 denotes the annual frequency and $f_E$ the frequency band of ENSO varying from 1/2 yr$^{-1}$ to 1/8 yr$^{-1}$) are characteristic of the C-mode that stems from the interaction between ENSO and the annual cycle (Stuecker et al. 2013). However, the peak frequency bands of the C-mode in the longer periods in the model overlap with ENSO, which is likely because the simulated ENSO mode is imperfect.

3.4. Simulated C-mode influences on seasonal precipitation over Southern China

Previous studies have revealed that ENSO has played a limited role in winter precipitation anomalies over southern China since the late 1990s (Geng et al. 2017; Jia and Ge 2017; Xu et al. 2018). In addition, the yearly air–sea

![Figure 3](image_url)
interaction is critical in capturing the climate anomalies over East Asia related to ENSO, especially the seasonal precipitation anomalies over China associated with the C-mode (Li, Zhang, and He 2016; Zhang et al. 2016b). While Zhang et al. (2016b) and Li, Zhang, and He (2016) recommended that the C-Mode has a positive influence on spring precipitation in southern China, the decadal variation in this positive influence has been less well studied. Therefore, we checked the ability of ECHAM5/MPI-OM to reproduce the ENSO-related seasonal rainfall over southern China. Using the ENSO signal alone can partially reconstruct precipitation anomalies in southern China (Figure 4(a)), and when including the influence of the C-mode the winter rainfall over southern China can be better disclosed by the model (Figure 4(c)). However, regardless of whether the ENSO or C-mode signal is used alone or together, the model is unable to reproduce the precise winter precipitation for southern China but appears to be able to reproduce it for the Yangtze River Valley (Figure 4(d-f)), because of the westward movement of both the simulated ENSO and the C-mode (Figure 1(c and d)). In the following spring, the positive precipitation anomalies extend from southern China to East China (Figure 5(c)). When we consider the ENSO signal alone, only a small part of the positive precipitation anomalies appears in the east. Including the C-mode can significantly improve the reconstruction of rainfall in East China (Figure 5(f)). Notably, the large-value areas with positive precipitation anomalies in the model obviously move westward, likely attributable to the simulated ENSO and the C-mode both moving westward. Hence, these results indicate that wintertime and springtime rainfall in southern China related to ENSO can be relatively realistic demonstrated by applying the ECHAM5/MPI-OM outputs.

4. Conclusions and discussion

In this paper we discuss the C-mode and its influences on seasonal precipitation over southern China as simulated by

![Figure 4. Precipitation (color shading; units: mm d⁻¹) and 850-hPa wind (vectors; units: m s⁻¹) anomalies during winter using linear regression for observation with (a) PC1, (b) PC2, and (c) both PC1 and PC2. (d–f) As in (a–c) but for the model.](image)
ECHAM5/MPI-OM. The results reveal that ECHAM5/MPI-OM can catch the dimensional distribution of ENSO as well as the C-mode associated with atmospheric and oceanic anomalies; however, the simulated ENSO mode moves slightly westward, which contributes dominantly to the behavior in simulating the C-mode, and the wintertime and springtime precipitation over southern China moving westward. In addition, this climate model not only can capture the rapid transition of the C-mode during late winter but also its spectral peaks near the annual cycle. However, the model reproduces the unreasonable power spectra in longer periods of the C-mode, perhaps because the performance of the ENSO mode is not ideal in the model.

This C-mode is of great value both in the termination of large El Niño events and in the development of the WNPAC, which also has a crucial part in the advance of ENSO-related climate anomalies, particularly related to East Asian seasonal precipitation. In addition, our work suggests that the C-mode is crucial in affecting wintertime and springtime rainfall over southern China during El Niño events, which are relatively realistically described by ECHAM5/MPI-OM. Improving the skill of simulating and predicting the seasonal precipitation anomalies over southern China related to the C-mode is of great importance to deepening our understanding of the mechanisms of East Asian seasonal precipitation. To achieve such a goal, it is essential to improve the ability of the model to replicate the precipitation climatology and the basic ENSO variability (Wan, Ren, and Wu 2018). For example, a more comprehensive initialization and a better availability of observations could be good choices to enhance the performance of the model to reproduce practical ENSO predictions (Zheng, Zhu, and Zhang 2007; Zheng et al. 2009; Zhu et al. 2013).

**Disclosure statement**

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