Ocean Sci. Discuss., 11, 1129–1147, 2014
www.ocean-sci-discuss.net/11/1129/2014/
doi:10.5194/osd-11-1129-2014

Ocean Science
Discussions
Open Access

Evaluation of the eastern equatorial Pacific SST seasonal cycle in CMIP5 models

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Received: 19 February 2014 – Accepted: 25 March 2014 – Published: 10 April 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The annual cycle of sea surface temperature (SST) in the eastern equatorial Pacific (EEP) with the largest amplitude in the tropical oceans is poorly represented in the coupled general circulation models (CGCMs) of the Coupled Model Intercomparison Project phase 3 (CMIP3). In this study, 18 models from CMIP5 projects are evaluated in simulating the annual cycle in the EEP. Fourteen models are able to simulate the annual cycle, and four still show erroneous information in the simulation, which suggests that the performances of CGCMs have been improved. The results of multi-model ensemble (MME) mean show that CMIP5 CGCMs can capture the annual cycle signal in the EEP with correlation coefficients up to 0.9. For amplitude simulations, EEP region 1 (EP1) near the eastern coast shows weaker results than observations due to the large warm SST bias from the southeastern tropical Pacific in the boreal autumn. In EEP region 2 (EP2) near the central equatorial Pacific, the simulated amplitudes are nearly the same as the observations because of the presence of a quasi-constant cold bias associated with poor cold tongue climatology simulation in the CGCMs. To improve CGCMs in the simulation of a realistic SST seasonal cycle, local and remote climatology SST biases that exist in both CMIP3 and CMIP5 CGCMs must be resolved at least for the simulation in the central equatorial Pacific and the southeastern tropical Pacific.

1 Introduction

The eastern equatorial Pacific (EEP) is a key region for El Niño–Southern Oscillation (ENSO) which affects weather, extreme events and climate globally. Although the equatorial region is dominated by the semi-annual cycle of solar radiation, the SST seasonal variation in the EEP exhibits a strong annual cycle with the March–April warm phase and August–October cold phase (Mitchell and Wallance, 1992; Nigam and Chao, 1996), which is different from that in the western equatorial Pacific with the semi-annual cycle due to the sun crossing the equator twice. Substantial attention has been devoted to investigate mechanisms of the SST annual cycle (Mitchell and Wallance, 1992; Giese and Carton, 1994; Xie, 1994, 2004; Mechoso et al., 1995; Nigam and Chao, 1996; Dewitt and Edwin, 1999). Numerous physical processes have been hypothesized to contribute to the generation of the annual cycle in the EEP, such as wind–evaporation–SST feedback, stratus–SST feedback, and upwelling–SST feedback. Because the annual cycle in the EEP involves complex dynamical and physical interaction among climate subsystems, it can serve as an indicator for the performance of the coupled general circulation models (CGCMs).

Since the pioneer work of developing a climate model by Manabe and Bryan (1969), CGCMs have achieved significant progress and can provide credible basic climate simulation, particularly through several important climate model intercomparison programs such as the Coupled Model Intercomparison Project (CMIP), the Paleoclimate Modelling Intercomparison Project (PMIP), and the Cloud Feedback Model Intercomparison Project (CFMIP).Climate models as the climate process research and projection tools become more and more important. Despite the progress made in the climate system and models, model biases still persist for state-of-the-art CGCMs in simulating the SST seasonal cycle in the EEP (Mechoso et al., 1995; Covey et al., 2000; Latif et al., 2001; Xie et al., 2007). Several years ago, De Szoeke et al. (2008) compared the results of 14 global CGCMs in phase 3 of the CMIP (CMIP3), and pointed that most of these models simulate two cold phases in the EEP SST rather than a single cold phase, as observed. For example, the simulation of the Community Climate System Model version 3 (CCSM3), which is one of state-of-the-art CMIP3 models, has a robust SST semi-annual cycle in the EEP. This problem was regarded as one of six challenges for the further development of CCSMs (Collins et al., 2006). Recently several studies have reported that the EEP SST annual cycle has been improved in their climate models (Gent et al., 2011; Yu et al., 2013). The model outputs of the CMIP phase 5 (CMIP5) were released several years ago, which include the latest version of models participating in CMIP3 and many new models. Therefore, a natural question is how effectively the annual cycle is reproduced in CMIP5 models.

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This study aims to use the outputs of the CMIP5 historical simulations to evaluate the EEP SST annual cycle simulation of the newest versions of coupled models. A brief description of the models and validation datasets used in this study are presented in Sect. 2; Sect. 3 presents the simulation of CMIP5 models; Sect. 4 provides the conclusion and discussion.

2 Models and datasets

In this study, historical model simulations used are summarized in Table 1. This new generation of CMIP5 CGCMs was developed by 12 scientific organizations across 10 countries, and the simulations have been submitted to the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for the Intergovernmental Panel on Climate Change Fifth Assessment Report (Taylor et al., 2012). The historical simulation was integrated from pre-industry spin-up results and was then forced by solar, volcanic, aerosol, and greenhouse gas forcings for 1850–2005. In this study, we select the monthly data from 1949 to 2005 for analysis.

Simulation results were compared with the observations of the SST dataset, which is the monthly data from National Oceanic and Atmospheric Administration extended reconstructed sea surface temperature version 3b (ERSST v3b, hereafter ERSST) (Smith et al., 2008). This dataset is gridded data generated by using in situ and satellite SST, in addition to improved statistical methods that allow for stable reconstruction with sparse data. To compare with model simulations, we also used the ERSST monthly data from 1949 to 2005.

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3 Results

3.1 Comparisons

The annual cycle is one of the major features of SST variability in the EEP (Mitchell and Wallance, 1992; Nigam and Chao, 1996; Xie, 1994, 2004). As shown in Fig. 1, the observed ERSST show that the EEP SST reaches the peak at 27 °C during March and April and exhibits a minimum of 23 °C during September and October. This annual cycle, approximately 4 °C in amplitude, is mainly restricted in the region between 110° W and 85° W along the equator. We define the region from 110° W to 85° W and 5° S to 5° N as EP1. The annual cycle is almost non-existent to the west of 140° W. The transition region (140° W–110° W and 5° S–5° N) shows a much weaker annual cycle compared with that in EP1; we define this region as EP2. The warming in EP1 tends to propagate westward and takes a one-month lead over EP2 in the warm phase (see ERSST in Fig. 1). After June, the variations in EP1 and EP2 are in the same phase, which suggests that the physical mechanisms dominating the warm and cold phases in the EEP vary. Therefore, in this study, two regions of EP1 and EP2 are selected for analysis.

The major characteristics of the annual cycle in the EEP are effectively represented in fourteen models classified as group 1, which include CanESM2, CCSM4, CSIRO-MK3-6-0, FIO-ESM, GFDL-ESM2G, GISS-E2-H, GISS-E2-R, HadCM3, HadGEM2-CC, HadGEM2-ES, IPSL-CM5A-MR, IPSL-CM5B-LR, MPI-ESM-LR, and MPI-ESM-P. These model results suggest that the CGCMs in CMIP5 show improvement in capturing the annual cycle of the EEP SST from the most recent generation CGCMs of CMIP3 (which are not effective in simulating the annual SST cycle in the EEP). However, four models classified as group 2, which include GFDL-CM3, INMCM4, MRI-CGCM3, and NorESM1-M, demonstrate the semi-annual cycle; they are still not able to simulate the realistic annual cycle of the EEP SST. Among the models in group 1, CanESM2, FIO-ESM, GISS-E2-H, GISS-E2-R, HadCM3, and IPSL-CM5B-LR have a weaker seasonal variation in the EP1 region in comparison with the observations. In addition, the annual

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cycle of the EEP in CSIRO-MK3-6-0 extends to 180° W, and the westward propagation process from EP1 to EP2 exists in both warm and cold seasons (Fig. 1, CSIRO-MK3-6-0). This implies that the westward Rossby-wave propagation mechanism (Xie, 2004) in the warm phase of observations is over-exaggerated in CSIRO-MK3-6-0.

The regional average SSTs, shown in Fig. 2, are used to show the seasonal cycle in the EEP. The EP2 SST is observed to follow the EP1 SST variation in March and April; and in the following seasons, EP2 SST varies in the same phase as EP1, but with weaker amplitude (Fig. 2, ERSST and multi-model ensemble (MME)). However, the CMIP5 CGCMs in the present study are not able to accurately represent this feature. Most models, including CanESM2, CCSM4, CSIRO-MK3-6-0, GFDL_CM3, GFDL-ESM2G, GISS-E2-H, GISS-E2-R, HadGEM2-CC, HadGEM2-ES, INMCM4, IPSL-CM5A-MR, IPSL-CM5B-LR, MPI-ESM-LR, and MPI-ESM-P, show that EP1 leads EP2 by one to two months during the course of one year, whereas two models, FIO-ESM and HadCM3, demonstrate that both EP1 and EP2 follow the same phase. A comparison of the results of multi-model ensemble (MME) mean and observation reveals that CMIP5 CGCMs can capture the annual cycle signal in both the EP1 and EP2 regions. In addition, the correlation coefficients between MME and observations are up to 0.9.

It is notable that the SST amplitude of MME (2.7 °C) in EP1 is weaker than that observed (3.8 °C), whereas in EP2 (2.1 °C), it is nearly the same as that observed (2.4 °C). For the MME simulation in EP1, weaker amplitude is due to the cold bias in the boreal spring at its high peak, and in particular, the warm bias up to 1.0 °C in the boreal autumn at its low peak. However, for the MME simulation in EP2, a quasi-constant cold bias is present throughout the year; therefore, the amplitude is the same as that observed. To determine the reason behind the variance in amplitudes of MME in EP1 and EP2, we trace the sources of the model deficiencies in the following section.

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3.2 Analysis

Figure 3a shows that, in the region of EP1, the seasonal cycle of CGCMs is in phase with the observations. However, the MME exhibits cold SST bias during the boreal spring (Fig. 3c) and warm bias (Fig. 3d) during the cooling phase after July. The SST bias in the models reduces the amplitude of EP1 annual cycle. The September–October–November warm bias in EP1 expands from the southeast tropical Pacific, where the warm bias exists throughout the year. The model annual cycle in EP2 (Fig. 3b) shows a cold bias within 1 °C throughout the year, except in November and December. This cold equatorial SST bias in this region is associated with the excessive cold tongue bias, which is a classic tropical bias in CGCMs that still exists in CMIP5 models (Li and Xie, 2014; Wang et al., 2014).

The zonal mean of SST bias pattern in EP1 (Fig. 4a) and EP2 (Fig. 4b) shows that both EP1 and EP2 have the cold SST bias in February–March–April–May. The cold bias in EP2 extends to the boreal winter. In EP1, however, the warm SST bias develops in August and expands from the southeast Pacific associated with a southward wind bias (Fig. 4a). In the boreal summer, the southeast trade wind dominates in the EP1 region. Therefore, the southward wind bias decreases the southeast trade winds over EP1 and leads to weaker latent heat loss from the ocean. Thus, a warm SST bias develops. Furthermore, an eastward wind bias develops in EP1 in August, and this westerly wind bias enhances the EP1 warm bias through Bjerknes feedback. The warm bias in EP1 causes a weaker annual cycle simulation in the models, in contrast to the observations. Therefore, understanding the causes of the warm bias of EP1 in the cold phase will contribute to improvements in the next-generation CGCMs for EEP annual cycle simulations.

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4 Conclusions and discussion

We conduct a comprehensive evaluation of the performances of CMIP5 CGCMs in simulating the annual cycle in the EEP. 14 out of 18 models are able to capture the major characteristics of the annual cycle. In addition, a comparison of the results of MME with the observations reveal that CMIP5 CGCMs can capture the annual cycle signal in both the EP1 and EP2 regions with correlation coefficients up to 0.9.

In comparison with the observations, for the MME simulation in EP1, both the cold bias along the equator in the warm phase and the warm bias in the cold phase led to a weaker annual SST cycle in CGCMs. In EP2, however, the amplitude was nearly identical to that observed because a quasi-constant cold bias persisted throughout the year. Known as an excessive cold tongue, this problem is common and still exists in CMIP5 models (Li and Xie, 2014). To improve the abilities of the CGCMs in simulating a realistic SST seasonal cycle, both the local and remote climatology SST bias (Wang et al., 2014), which exists in both CMIP3 and CMIP5 CGCMs, must be resolved, at least for the climatology simulation of the cold tongue region and the southeastern tropical Pacific.

Acknowledgements. This research was supported by the National Basic Research Program of China (973 Program) grant 2010CB950500 and International Cooperation Project of Ministry of Science and Technology of China 2011DFA20970. The authors wish to acknowledge the ESG-PCMDI for providing the CMIP5 model datasets.

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Table 1. The list of the CMIP5 models whose simulations are analyzed in this study.

No.	Model	Model Center	Reference
1	CanESM2	Canadian Centre for Climate Modelling and Analysis (Canada)	Chylek et al. (2011)
2	CCSM4	National Center for Atmospheric Research (United States)	Gent P. R. et al. (2011)
3	CSIRO-Mk3-6-0	Australian Commonwealth Scientific and Industrial Research Organization Marine and Atmospheric Research, and Queensland Climate Change Centre of Excellence (Australia)	Rotstayn et al. (2010)
4	FIO-ESM	First Institute of Oceanography (China)	Qiao et al. (2013)
5	GFDL-CM3	Geophysical Fluid Dynamics Laboratory (United States)	Griffies et al. (2011)
6	GFDL-ESM2G		Dunne et al. (2012)
7	GISS-E2-H	Goddard Institute for Space Studies (United States)	Shindell et al. (2013)
8	GISS-E2-R		
9	HadCM3	Met Office Hadley Centre (UK)	Smith et al. (2010)
10	HadGEM2-CC		
11	HadGEM2-ES		
12	inmcm4	Institute for Numerical Mathematics (Russia)	Volodin (2010)
13	IPSL-CM5A-MR	Institute Pierre Simon Laplace (France)	Hourdin et al. (2013a)
14	IPSL-CM5B-LR		(Hourdin et al., 2013b)
15	MPI-ESM-LR	Max Planck Institute for Meteorology (German)	Giorgetta et al. (2013)
16	MPI-ESM-P		
17	MRI-CGCM3	Meteorological Research Institute (Japan)	Yukimoto et al. (2011)
18	NorESM1-M	Norwegian Climate Centre (Norway)	Tjiputra et al. (2013)

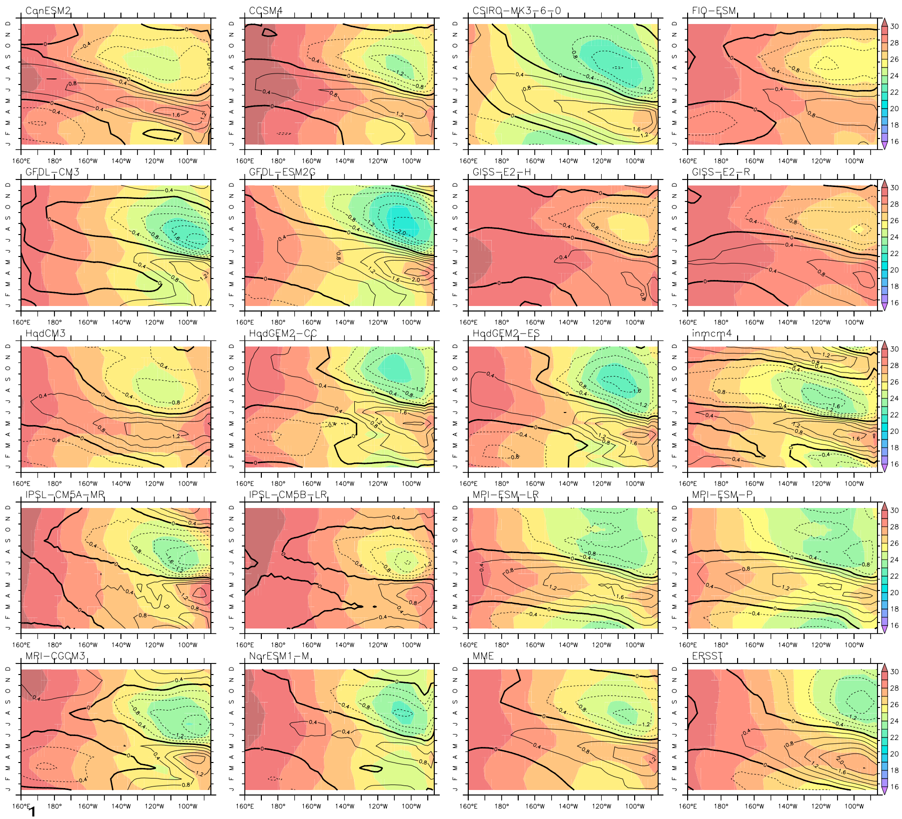

Fig. 1. Seasonal cycle of eastern equatorial Pacific (EEP) sea surface temperature (SST); Shading represents climatological SST; contours represent anomalies relative to annual mean.

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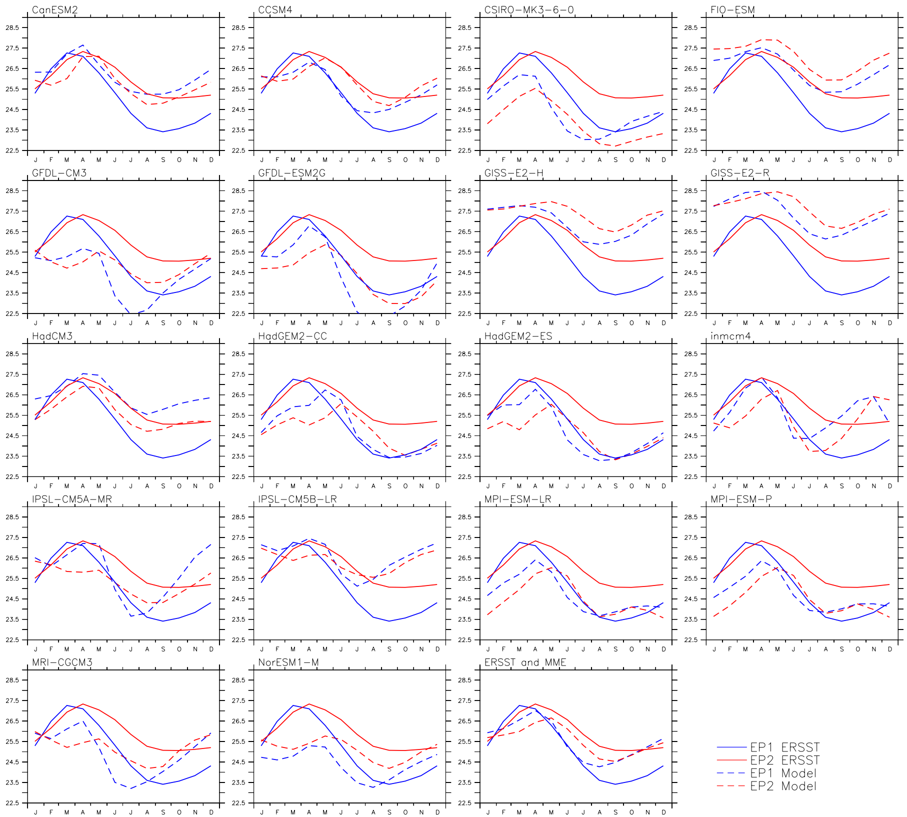

Fig. 2. Eastern equatorial Pacific (EEP) sea surface temperature (SST) seasonal cycles for EEP region 1 (EP1; 110–85° W, 5° S–5° N; blue line) and EEP region 2 (EP2; 140–110° W, 5° S–5° N; red line).

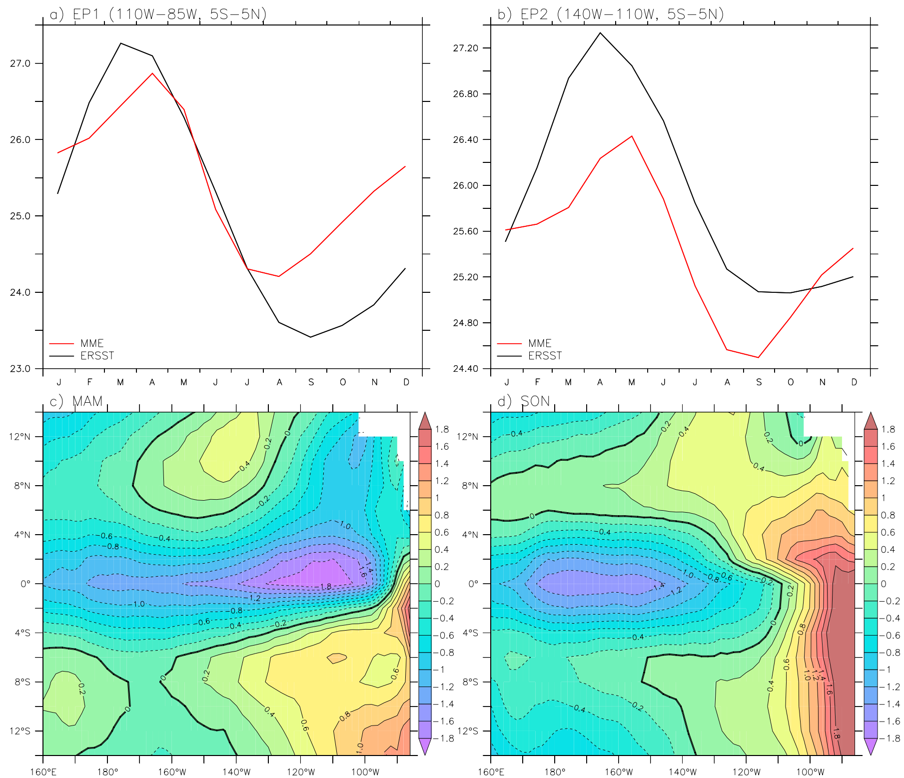

Fig. 3. Multi-Model Ensemble (MME) mean sea surface temperature (SST) for eastern equatorial seasonal cycle (**a** and **b**) and tropical eastern bias in spring **(c)** and autumn **(d)**.

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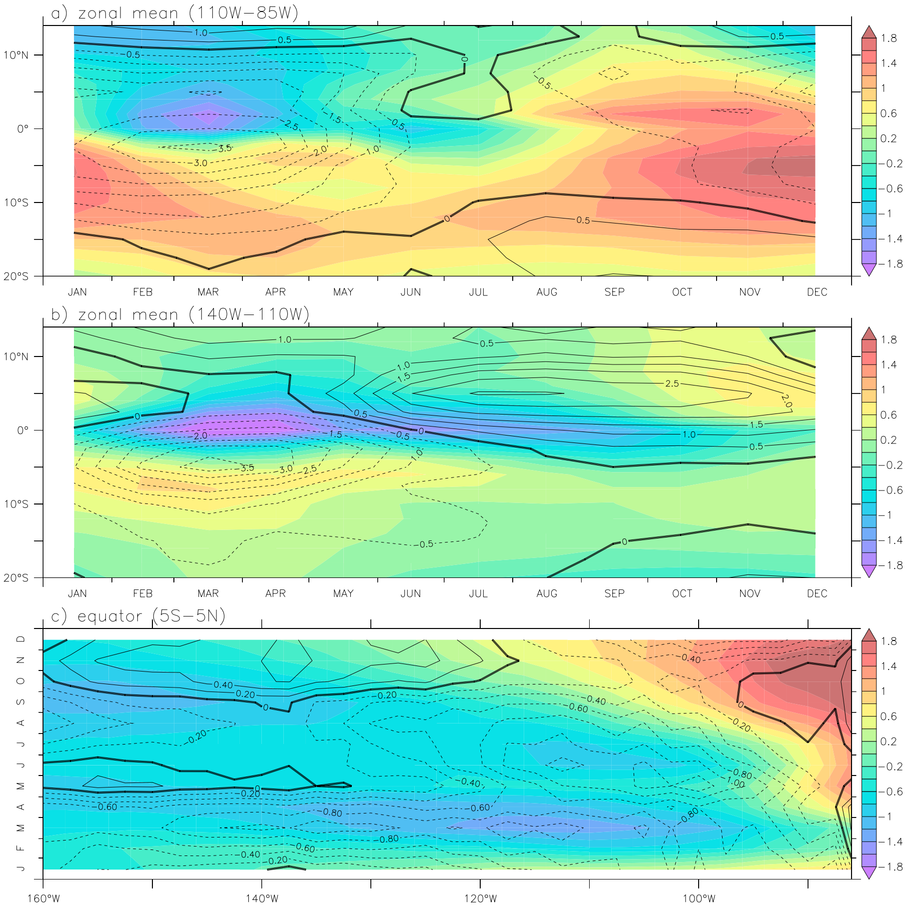

Fig. 4. Evaluation of multi-model ensemble (MME) sea surface temperature (SST) bias (shading), surface northward wind bias (**a** and **b**, contours), and eastward wind bias (**c**, contours)

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