CMIP5 analysis of the interannual variability of the Pacific SST and its association with the Asian–Pacific oscillation

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ABSTRACT
This study analyzed the interannual variability of sea surface temperature (SST) over the Pacific in the historical simulation and under the Representative Concentration Pathways (RCPs, including RCP4.5 and RCP8.5) from 27 models archived in the Coupled Model Intercomparison Project Phase 5 (CMIP5). Its association with the Asian–Pacific oscillation (APO) was also investigated. The evaluation results showed that the multi-model ensemble mean (MME) and most of the individual models perform well in reproducing the relatively stronger interannual variability of SST over the North Pacific and tropical eastern Pacific. They can also capture reasonably well the observed in-phase and out-of-phase relationships of the APO with the SST in the above two regions, respectively. Under the RCP4.5 and RCP8.5 scenarios, the interannual variability of the SST over the North Pacific and the tropical eastern Pacific is projected by the MME to be weakened during 2050–99 compared to 1950–99. The majority of the CMIP5 models show the same projection as the MME. Besides, the MME projection indicates that the present relationship between the APO and the SST over those two regions would still be dominant under both RCPs. However, considerable discrepancies exist in the changes of the relationships among the individual models.

1. Introduction
It is well known from various empirical studies that Pacific sea surface temperature (SST) plays a profound role in climate system change. Its variation can give rise to significant anomalies of global and regional climate through feedbacks of air–sea interactions (e.g. Webster and Yang 1992; Zhang, Wallace, and Iwasaka 1996; Chang, Zhang, and Li 2000; Wang 2000; Lau et al. 2004; Wang, Yang, and Zhou 2008; Ding et al. 2011; Yu and Xie 2013; Li et al. 2014). Thus, past and future changes of the Pacific SST under global warming is a hot topic in climate change research.

The Coupled Model Intercomparison Project Phase 5 (CMIP5) provides a good opportunity to study this issue. Compared with CMIP3, CMIP5 offers a number of improvements in the simulation of the Pacific SST; for instance, the basic structure of the tropical SST and ENSO amplitude (Kim and Yu 2012; Yeh, Ham, and Lee 2012; IPCC 2013), and the projection of an increase in the Pacific SST under global warming scenarios (IPCC 2013). However, such studies have tended to focus on the mean state. Besides change in the climate mean state, change in the variance (to represent interannual variability) is another important indicator to measure climate change (e.g. Lu and Fu 2010; Ren et al. 2016). The question therefore arises as to the performance of CMIP5 models in simulating the interannual variability of the Pacific SST, and how it changes under the RCP scenarios.
In addition, the interannual variability of the Pacific SST has been documented to be closely associated with the Asian–Pacific Oscillation (APO)—a zonal atmospheric mode characterized by a seesaw pattern of change in the variability of the upper-tropospheric temperature between Asia and the North Pacific (Zhao, Zhu, and Zhang 2007). The positive phase of the APO is accompanied by warm SST in the North Pacific and cold SST in the eastern Pacific, and vice versa (Zhao, Cao, and Chen 2010; Zhou, Zhao, and Cui 2010; Liu, Zhao, and Chen 2011). Can such a linkage be captured by the CMIP5 models? Furthermore, in the context of a warming scenario, the APO has been projected to weaken towards the end of twenty-first century (Zhou 2016). Will the present relationship change in the future in response to a weakening of the APO?

With these questions in mind, the present study assessed the ability of CMIP5 models to simulate the interannual variability of the Pacific SST and its relationship with the APO. On this basis, their future changes under two warming scenarios were projected.

### 2. Data and method

The simulation results of the historical, RCP4.5 and RCP8.5 experiments from 27 CMIP5 models were used for the analysis. The historical experiment (His) represents the simulations of the twentieth century climate. The RCP4.5 and RCP8.5 experiments represent the medium-low and high radiative forcing scenarios where the radiative forcing is stabilized at 4.5 and 8.5 W m\(^{-2}\) by 2100, respectively.

![Figure 1](image-url)

Figure 1. (a–c) Interannual standard deviation of summer SST (°C) during 1950–99 for (a) the reanalysis, (b) MME-all, and (c) MME-best. Only values larger than 0.6 are shown. (d–f) Correlations between the SST and the Asian–Pacific Oscillation in summer for (d) the reanalysis, (e) MME-all, and (f) MME-best (MME: multi-model ensemble mean).

Note: Areas above the 95% confidence level are shaded.
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The CMIP5 models were: (a) ACCESS1.0; (b) ACCESS1.3; (c) BCC_CSM1.1; (d) CanESM2; (e) CCSM4; (f) CMCC-CM; (g) CMCC-CMS; (h) CNRM-CM5; (i) CSIRO Mk3.6.0; (j) FIO-ESM; (k) GFDL CM3; (l) GFDL-ESM2G; (m) GFDL-ESM2 M; (n) GISS-E2-H; (o) GISS-E2-R; (p) HadGEM2-CC; (q) HadGEM2-ES; (r) INM-CM4.0; (s) IPSL-CM5A-LR; (t) IPSL-CM5A-MR; (u) IPSL-CM5B-LR; (v) MIROC5; (w) MIROC-ESM; (x) MIROC-ESM-CHEM; (y) MPI-ESM-MR; (z) MRI-CGCM3; and (A) NorESM1-ME. For details regarding the models and forcings, refer to http://cmippcmdi.llnl.gov/cmip5.

To validate the CMIP5 models’ performance, reanalysis data including NOAA SST at 2° × 2° (Smith and Reynolds 2004) and NCEP–NCAR atmospheric temperature at 2.5° × 2.5° (Kalnay et al. 1996) were also exploited. Because the horizontal resolutions are different for different models, the model data were interpolated to the same grid as the reanalysis data before analysis.

The periods for analysis were 1950–99 for the historical simulation and 2050–99 for both RCP scenarios, and the focus was boreal summer (June–August). Following Zhao, Zhu, and Zhang (2007), the APO was measured by the difference in regional mean eddy air temperature (deviation from its zonal mean) between Asia (15°–50°N, 60°–120°E) and the North Pacific (15°–50°N, 180°–120°W) in the upper troposphere (500–200 hPa). The interannual variability of the SST was described by the standard deviation (SD). The SST–APO relationship was depicted by correlation. Before calculating the SD and correlation, linear trends of the data were removed. The MME method was applied because the consensus is that it provides more robust estimates (e.g. Gleckler, Taylor, and Doutriaux 2008; Gupta et al. 2013; Zhou et al. 2014; Jiang, Tian, and Lang 2016). For the calculation of the MME, two samples were adopted in this study. One (MME-all) was all 27 models, and the other (MME-best) was the 12 models with the ‘best’ performance.

3. Evaluation

Figure 1(a) displays the SD distribution of the Pacific SST in summer during 1950–99 in the reanalysis. Two maxima regions of the interannual SD are clear. One is located in the midlatitudes of the North Pacific and the other in the tropical eastern Pacific. The large interannual variability shown in the observation can be reproduced well by MME-all (Figure 1(b)), albeit the SD intensity is a little stronger over the western North Pacific and the SD center is slightly westward over the eastern Pacific.

The interannual variability of the summer SST over those two regions has been highlighted to be linked with the APO change (Zhao, Cao, and Chen 2010; Zhou, Zhao, and Cui 2010; Liu, Zhao, and Chen 2011). Their linkage is confirmed in Figure 1(d), which indicates positive correlation in the midlatitudes of the North Pacific and negative correlation over the tropical eastern Pacific. MME-all captures the observed correlation pattern well (Figure 1(e)), despite the fact that the areas above the 95% confidence level are smaller in the North Pacific and larger in the eastern Pacific. This result can also be obtained from the index correlation. If defining the regional mean SST over the region (30°–45°N, 140°E–160°W) and the region (10°S–10°N, 120°–80°W) (outlined as the rectangle in Figure 1(d)) to quantify the North Pacific SST (NPSST) and the eastern Pacific SST (EPSST), respectively, the APO–NPSST (APO–EPSST) correlation coefficient is 0.51 (−0.35) for the observation and 0.48 (−0.49) for MME-all, all above the 95% confidence level.
To further evaluate the performance of the models individually, a Taylor diagram of the SD pattern of the Pacific SST was plotted (Figure 2(a)), which summarizes how well patterns match each other in terms of spatial correlation, RMSE, and ratio of variances (Taylor 2001). As shown in Figure 2(a), the spatial correlations between the simulations and the observation are mostly above 0.7, the RMSEs of the simulations relative to the observation are in the range of 0.5–1, and the ratios of variances of the simulations to the observation are mostly between −0.5 and 0.5. Only four models (i, x, w, z) show spatial correlations below 0.7, and two models (v, m) show much larger variances than the other models. It is thus suggested that most of the models are capable of simulating the interannual variability of the Pacific SST well.

Figure 2(b) exhibits the scatter distribution of the simulated APO–NPSST and APO–EPSST correlations in summer. For the APO–NPSST relationship, all of the models yield positive correlations complying with the observation. The modeled correlation coefficients range from 0.13 to 0.72, and 18 models (67%) produce in-phase relationships significant above the 95% confidence level. As for the APO–EPSST relationship, apart from one model (MIROC-ESM) showing a positive correlation of 0.06, the remaining models all simulate negative correlations (−0.76 to −0.2) consistent with the observation, and 23 models (85%) show out-of-phase relationships significant above the 95% confidence level.

If taking into account the models’ behaviors synthetically in two aspects (i.e. standard deviation and significant correlations), the performances of 12 CMIP5 models (a, b, c, e, g, h, j, k, r, s, t, u) emerge as the ‘best’, which were taken as the members of MME-best. Compared with the MME-all simulation, the MME-best–simulated SD and correlation distributions are similar, but the correlations are more prominent over the North Pacific and eastern Pacific (Figure 1(c) and (f)).

4. Projection

Figure 3 shows the MME-projected SD change of summer SST during 2050–99 under the RCP4.5 and RCP8.5 scenarios. In both the MME-all projection and the MME-best projection, negative anomalies over the midlatitudes of the North Pacific and the tropical eastern Pacific are both found under the RCP4.5 scenario (Figure 3(a) and (c)), implying a weakening of the SST interannual variability if future emissions follow RCP4.5. The case under the RCP8.5 scenario is similar but with somewhat weaker change in amplitude, especially over the North Pacific (Figure 3(b) and (d)).

To investigate the consistency in projection among the individual models, the percentage changes in SD of the

![Figure 3](image-url). MME-projected standard deviation change of summer SST ($\times 10^{-1}^\circ C$) during 2050–99 relative to 1950–99 under RCP4.5 (left-hand panels) and RCP8.5 (right-hand panels): (a, b) MME-all; (c, d) MME-best (MME: multi-model ensemble mean). Note: Areas with absolute values larger than 0.4 are shaded.
respectively. All the ‘best’ models except FIO-ESM and INM-CM4.0 delineate a reduced SD under the RCP4.5 scenario, with the decreasing amplitude ranging from 2.7% to 16.4%. However, under the RCP8.5 scenario, 7 models (58%) show a weakening tendency and 5 models (42%) show an intensifying tendency. Thus, the decrease in SD is more consistent under the RCP4.5 scenario than under the RCP8.5 scenario. In the projection of MME-best, the SD reductions under the RCP4.5 and RCP8.5 scenarios are 6.7% and 2.0%, respectively.

For the EPSST interannual variability (Figure 4(b)), the range of the projected percentage changes is −27.1% to 20.9% under the RCP4.5 scenario and −27.3% to 29.0% under the RCP8.5 scenario. Similarly, the majority of the models (67%) project a decrease in the interannual variability under both RCPs. The MME-all projection indicates a weakening of the interannual variability by 6.9% and 5.8% under the RCP4.5 and RCP8.5 scenarios, respectively. Among the ‘best’ models, 10 (83%) show a decreasing tendency and 2 (17%) show an increasing tendency under RCP4.5. Under the RCP8.5 scenario, 7 models (58%) show a decreasing tendency, 4 (33%) show an increasing tendency, and 1 shows no change. As a result, MME-best projects a decrease of 5.7% and 3.9% under the RCP4.5 and RCP8.5 scenarios, respectively.

The projected APO–NPSST and APO–EPSST relationships under both RCPs are shown in Figure 5. The MME results suggest that the present relationships will still be dominant during 2050–99. Specifically, the APO–NPSST correlation coefficient in the MME-all (MME-best) projection is 0.33 (0.40) for RCP4.5 and 0.37 (0.44) for RCP8.5, which are significant above the 95% confidence level but slightly weaker than in the historical simulation. The APO–EPSST correlation coefficient in the MME-all (MME-best) projection is −0.38 (−0.43) for RCP4.5 and −0.44 (−0.54) for RCP8.5 (significant above the 95% confidence level). Compared with their counterpart in the historical simulation, the correlation is slightly weaker under the RCP4.5 scenario and slightly stronger under the RCP8.5 scenario. However, there are considerable discrepancies among the models. For the APO–NPSST relationship, half of the models project increased correlations and another half project decreased correlations for both RCPs. For the APO–EPSST relationship, 13 models (48%) show weaker correlations, whereas the remaining models show stronger or intact correlations under the RCP4.5 scenario. Under the RCP8.5 scenario, 16 models (59%) project enhanced correlations and 10 (37%) project reduced correlations.

5. Conclusion

Through comparison of historical simulations with reanalysis data for the period 1950–99, this study evaluated the
1950–99, the weakening amplitudes of the interannual SD in NPSST and EPSST during 2050–99, as projected by MME-all (MME-best), are 6.1% (6.7%) and 6.9% (5.7%) respectively for RCP4.5, and 3.5% (2.0%) and 5.8% (3.9%) respectively for RCP8.5. The majority of the models agree with the MME projection. Besides, the MME results suggest that the present APO–NPSST and APO–EPSST relationships will persist during 2050–99. However, compared to the historical simulation, the APO–NPSST correlation is projected to be slightly weaker under both RCPs, while the APO–EPSST correlation is projected to be slightly weaker (stronger) under the RCP4.5 (RCP8.5) scenario. Considerable discrepancies exist among the individual models.

Change in the interannual variability of a climate variable is not only important to measure climate change, but also for climate variability and climate prediction research.

Figure 5. Scatter diagrams of (a, b) the correlation coefficients between the Asian–Pacific Oscillation (APO) and the North Pacific SST (NPSST) and (c, d) the correlation coefficients between the APO and the eastern Pacific SST (EPSST), in summer, under the historical simulation (His; abscissa) and under the (a, c) RCP4.5 and (b, d) RCP8.5 scenario (ordinate). Notes: The dots indicate simulations of the individual models (marked by letters see Section 2 of the main text for their corresponding model names), with the red letters representing the 'best' models. The blue and red triangles indicate the MME-all and MME-best results, respectively (MME: multi-model ensemble mean).

The evaluations indicated that most of the models can capture well the large interannual variability of summer SST over the midlatitudes of the North Pacific and the tropical eastern Pacific. They can also reproduce the observed positive and negative correlations of the APO with the SST over those two regions during summer, respectively. Moreover, 18 (23) out of 27 models yield in-phase APO–NPSST (out-of-phase APO–EPSST) relationships significant above the 95% confidence level. These features are also simulated well by the MME (including MME-all and MME-best).

The MME projects a decreasing interannual variability of the NPSST and EPSST under both RCPs. Relative to
For instance, the intensity of the interannual variability of summer rainfall over South China has been found to have increased remarkably since 1992/93 (Fan, Xu, and Tian 2014), suggesting more extreme flooding or drought. Thus, the findings reported in this study are encouraging for understanding climate regimes in the context of global warming. Note that our results indicate a possible estimate of changes in the interannual variability of the Pacific SST and its relationship with the APO as a response to future warming. The warming scenario is of course one main driver for the weakening of the interannual variability of the Pacific SST. However, the detailed physical mechanisms underlying their changes remain unclear. In addition, previous studies (Zhao, Cao, and Chen 2010; Zhou, Zhao, and Cui 2010) have proposed that the APO plays a dominant role in the relationship between the APO and the Pacific SST. It is thus speculated that the possible weakening and eastward shifting of the APO in the future (Zhou 2016) may be responsible for future change in their relationship. Other processes might also contribute. Therefore, in-depth analysis is needed in future research regarding these issues.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was jointly supported by the National Natural Science Foundation [grant number 41275078]; the National Key Research and Development Program of China [grant number 2016YFA0600701].

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