Changes in the tropical Pacific SST trend
from CMIP3 to CMIP5 and its implication of ENSO

Sang-Wook Yeh, Yoo-Geun Ham and June-Yi Lee

Department of Environmental Marine Science, Hanyang University, Ansan, Korea
2 Global Modeling and Assimilation Office, NASA/GSFC, Greenbelt, MD 20771
3 Goddard Earth Sciences Technology and Research Studies and Investigations, Universities Space Research Association, Columbia, MD 21044
4 Department of Meteorology and International Pacific Research Center, University of Hawaii, Hawaii.

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Abstract

This study assesses the changes in the tropical Pacific sea surface temperature (SST) trend and ENSO amplitude by comparing a historical run of the Coupled Model Intercomparison Project (CMIP) phase 5 dataset and the CMIP phase 3 dataset. The results indicate that the magnitude of the SST trend in the tropical Pacific basin has significantly reduced from CMIP3 to CMIP5, which may be associated with the overestimation of the response to natural forcing and aerosols by including Earth System Models in CMIP5. Moreover, the patterns of tropical warming over the second half of the twentieth century have changed from a La Nina-like structure in CMIP3 to an El Nino-like structure in CMIP5. Further analysis indicates such changes in the background state of the tropical Pacific and an increase in the sensitivity of the atmospheric response to the SST changes in the eastern tropical Pacific have influenced the ENSO properties. In particular, the ratio of the SST anomaly variance in the eastern and western tropical Pacific increased from CMIP3 to CMIP5, indicating that a center of action associated with the ENSO amplitude has shifted to the east.
1. Introduction

The El Nino and Southern Oscillation (ENSO) is the most prominent interannual variability on Earth. Changes in the amplitude and frequency of the ENSO can affect the occurrence of climate extremes around the globe (McPhaden et al., 2006).

In 2007, the Intergovernmental Panel on Climate Change released its Fourth Assessment Report (Solomon et al. 2007), which concludes that the warming of the Earth is unequivocal. Furthermore, recent studies have shown that global warming may significantly influence ENSO properties by altering the background state of the tropical Pacific (Timmermann et al., 1999; Fedorov and Philander, 2000; Koutavas et al., 2006; Li et al., 2011). Hence, subtle patterns of evolving tropical Pacific sea surface temperatures (SSTs) induced by global warming could have a disproportionate effect on the climate in many regions of the world (Xie et al., 2010; Shin and Sardeshmukh, 2011). Therefore, it is crucial to correctly simulate the structure of changes in the ocean SST in response to external forcings in order to understand the changes in ENSO properties. Consequently, this issue has been thoroughly examined using the Third Coupled Model Intercomparison Project (CMIP3) multi-model database; yet, in spite of such efforts, there is little agreement in the climate community as to whether the structure of the mean SST changes is trending toward an El Nino-like pattern or a La Nina-like pattern under the global warming (Collins et al., 2005, 2010; Vecchi et al., 2008). In addition, it is still not clear whether the ENSO amplitude has been enhanced, reduced, or has not altered significantly under these mean state changes.

Likewise, observations in the ocean SST with a period of more than 100 years indicate a diversity of structural changes (Deser et al., 2010). For example, a warming trend with an El Nino-like pattern has been identified during recent decades (Graham, 1995; Trenberth and Hoar, 1996), but some evidence suggests that the zonal SST gradient across
the tropical Pacific has increased (Cane et al. 1997; Karnauskas et al., 2009, An et al. 2012).

In spite of this information, some results consistently indicate that the linear trend in the western tropical Pacific is larger than that in the eastern tropical Pacific for the second half of the twentieth century. Table 1 shows the average linear trend in the western tropical Pacific (5°N-5°S, 120°E-170°W) and in the eastern tropical Pacific (5°N-5°S, 150°W-90°W) for the period of 1950-2010 from the various observed SST datasets. Clearly, the linear trend in the western Pacific is larger than that in the eastern Pacific in all SST datasets, indicating that the zonal SST gradient across the tropical Pacific has become strong. Consequently, since the CMIP5 multi-model datasets have recently been released, it is useful to compare the structure of the tropical Pacific SST changes during a similar time period (i.e., after 1950) using the CMIP3 and CMIP5 datasets. Furthermore, it is interesting to examine how changes in the ocean SST structure under global warming from CMIP3 to CMIP5 may be associated with changes in the ENSO amplitude.

Thus, the intent of this paper is to compare the SST trends from the tropical Pacific using CMIP3 coupled general circulation models (CGCMs) and CMIP5 CGCMs and to examine how such changes in SST trends are associated with changes in the ENSO amplitude. We directly compare CMIP3 CGCMs with CMIP5 CGCMs, noting that the CMIP5 CGCMs have been improved from the CMIP3 CGCMs, following the recommended CMIP5 specifications (http://cmip-pcmdi.llnl.gov/cmip5/forcing.html).

2. Data and Methodology

The observed SST information used in Table 1 are from the Hadley Centre SST dataset (HadISST, Rayner et al., 2003), the extended reconstruction SST Version 3 (ERSST V3) dataset (Smith and Reynolds, 2004), the NOAA Climate Diagnostic Center dataset, the Kaplan SST dataset (Kaplan et al., 1998), and the ECMWF ORA-3 SST dataset (Balmaseda
et al., 2008).

We use ten CGCM simulations selected from a historical run (i.e., from a twentieth-century run) that have SST datasets from both the CMIP3 and CMIP5 multi-model databases. Table 2 shows the official CMIP3 and CMIP5 model names for each modeling center. Some CMIP5 CGCMs are specified as Earth System Models (e.g., CanESM2, HadGEM2-CC, HadGEM2-ES, and MIROC-ESM in Table 2), which respond to specific time-varying concentrations of various atmospheric constituents, such as greenhouse gases and other components of the atmosphere, ocean, and sea ice. These models are coupled to biogeochemical components, which account for the exchange of carbon between the ocean, atmosphere, and terrestrial biosphere carbon reservoirs. Additionally, in some simulations, these models may incorporate components such as interactive prognostic aerosols, chemical elements, and dynamic vegetation (Taylor et al., 2011). For example, CanESM2 is the latest generation Canadian CGCM that originated from CCCMA_CGCM3_1_T63 in CMIP3, and it includes an interactive carbon cycle, an interactive sulfur cycle, and the effect of a sulfate aerosol on cloud brightness (Gillett et al., 2012). Furthermore, CMIP5 CGCMs recognize that some CGCMs perform simulations with a higher resolution or a more complete treatment of the atmospheric chemistry than CMIP3 CGCMs. Hence, detailed explanations for each CGCM can be found at http://cmip-pcmdi.llnl.gov/cmip5/experiment_design.html, as well as in various related papers (Taylor et al., 2009, 2011).

3. Results

To illustrate the response of tropical Pacific SST patterns to global warming over the second half of the twentieth century, specifically highlighting the difference between CMIP3 and CMIP5, Figs. 1a and 1b display the ensemble-averaged linear trends simulated by the historical run of ten CMIP3 and CMIP5 CGCMs for the period of 1950 to 2000, respectively.
The simulation of the CMIP3 CGCM (Fig. 1a) exhibits a maximum SST trend in the central tropical/off-equatorial Pacific region. The central Pacific Ocean is projected to experience the greatest amount of warming, whereas the southeast Pacific Ocean is expected to warm less. Interestingly, this expectation is largely consistent with the observed spatial pattern of SST change over the beginning of the twenty-first century, which is averaged over 22 CMIP3 CGCMs under a mid-range emission scenario (IPCC Special Report on Emission Scenarios (SRES) A1B (see Fig. 1 in Clement et al., 2010). Moreover, although the overall pattern of linear trends in the CMIP3 deviates from the observations in some regions (not shown here), it is consistent that the SST trend in the western tropical Pacific is larger than that in the eastern tropical Pacific (see Table 3), indicating that zonal SST gradient across the tropical Pacific has become strong during the second half of the twentieth century.

It is striking, then, that the magnitude of the linear trend of SSTs in the tropical Pacific basin is reduced significantly in the CMIP5 (Fig. 1b) compared to the CMIP3 (Fig. 1a). While the linear trend of the CMIP3 is around 1.0–1.2°C in the western and central tropical Pacific, it is around 0.4–0.6°C for the CMIP5. Furthermore, it is not clear why this reduction occurred, particularly because the CMIP3 and CMIP5 datasets were acquired during the same historical period. However, it is possible that the CMIP5, which includes some CGCMs with an Earth System Model component, overestimates the response to natural forcings and aerosols. In a previous study (Gillett et al., 2012), for example, a relatively low and tightly-constrained estimate of the transient climate response and relatively low projections of twenty-first century warming under the representative concentration pathway is simulated using CMIP5 CanESM2, which employed an Earth System Model from CMIP3 CCCMA_CGCM3_1_T63. This result prompts the need to examine additional models and the detailed physical processes within them in order to identify the changes from CMIP3 to
Figure 1 also indicates that the location of the maximum SST trend has shifted to the east from CMIP3 to CMIP5, resulting in a warming trend in the eastern tropical Pacific that is larger than that in the western tropical Pacific in CMIP5. This shift suggests that the zonal SST gradient across the tropical Pacific has become weak (Table 3). To examine similar structural changes in the SST trend from CMIP3 to CMIP5 in more detail, Fig. 2 displays the east-west trend difference (i.e., the western tropical Pacific minus the eastern tropical Pacific) for each CGCM, as well as their ensemble means and the observation. Note that the east-west trend difference in the observation is based on the four different SST datasets as shown in Table 1. If the trend difference is above (below) zero, it represents a La Nina-like (El Nino-like) structure of the SST trend over the second half of the twentieth century, indicating that warming in the western (eastern) tropical Pacific is more dominant than that in the eastern (western) tropical Pacific. The ensemble mean, which is denoted in the right-hand side of Fig. 2, indicates that the patterns of tropical warming over the second half of the twentieth century have significantly changed from a La Nina-like structure in CMIP3 to an El Nino-like structure in CMIP5. While eight out of the ten patterns represent a La Nina-like structure of the SST trend in CMIP3, six out of the ten patterns represent an El Nino-like structure in CMIP5. Except for two CGCMs (i.e., IPSL_CM4 and MIROC3_2 HR), eight CGCMs show an east-west trend difference that has been reduced from CMIP3 to CMIP5. Among them, the sign of the east-west trend difference has changed in five CGCMs (i.e., BCCR_BCM2_0, CCCMA_CGCM3_1_T63, HadGEM1, INMCM3_0, and MRI_CGCM2_3_2a).

One can expect that such changes may influence the ENSO properties for both the CMIP3 and CMIP5 because the background state of the tropical Pacific has evolved between the two databases. In particular, this study focuses on the shift in an SST center of action...
associated with the ENSO amplitude, which is known to have changed significantly due to the mean state change (Yeh et al., 2009). To illustrate this effect, Fig. 3 displays the ratios of SSTA variance in the eastern tropical Pacific (i.e., NINO3 region, 150°W-90°W, 5°N-5°S) to that in the western tropical Pacific (NINO4 region, 160°E-150°W, 5°N-5°S) from CMIP3 to CMIP5. It also displays their ensemble means and the observation. Note that an increase in this ratio indicates that a center of action associated with an ENSO amplitude has shifted to the east from CMIP3 to CMIP5. Overall, the ratio of the SSTA variances increase from CMIP3 to CMIP5 based on the comparison of the ensemble mean ratios. Furthermore, the increase in the SSTA variance ratio of the aforementioned five CGCMs, in which the sign of the east-west trend difference switched from CMIP3 to CMIP5, is more prominent. That is, the ensemble mean ratio in the five CGCMs increases from CMIP3 (1.13) to CMIP5 (1.38).

Changes in the spatial patterns of tropical warming can induce a change in the ratio of the SSTA variance in the eastern and western tropical Pacific from CMIP3 to CMIP5. In other words, a greater amount of warming in the eastern tropical Pacific compared to the western tropical Pacific in CMIP5 (i.e., an El Nino-like structure of the SST trend) can amplify the SSTA variability in the eastern tropical Pacific through enhanced air-sea coupled processes (Choi et al., 2009). To measure the air-sea coupling strength over the eastern tropical Pacific, Fig. 4 displays the ensemble mean regression coefficients between the mean SST and the mean precipitation over the NINO3 region for ten CMIP3 and CMIP5 CGCMs. An increase in this regression coefficient indicates that the atmospheric response to ocean SST changes has become more sensitive in the eastern tropical Pacific. Moreover, these coefficients systematically increase in CMIP5, suggesting an enhanced SSTA variance in the eastern tropical Pacific in CMIP5. Consequently, this study posits that both an El Nino-like structure of the SST trend and an increase in the sensitivity of the atmospheric response to
SST changes in the eastern tropical Pacific from CMIP3 to CMIP5 may contribute to enhancing the ratio of the SSTA variance in the eastern and western tropical Pacific regions.

4. Summary and Discussion

Various observation data sources present discrepancies between the SST trends in the tropical Pacific throughout the twentieth century (Deser et al., 2010). Nevertheless, the four SST datasets used in this study indicate that the linear trend in the western Pacific is larger than that in the eastern Pacific in all SST datasets, suggesting that a zonal SST gradient across the tropical Pacific has become strong over the second half of the twentieth century (1950-2010). To verify this effect, the CMIP3 and CMIP5 multi-model datasets were utilized to simulate the tropical Pacific SST trends throughout a historical run from 1950-2000. It was found that the magnitude of the linear trend of the SST in the tropical Pacific basin reduced significantly from CMIP3 to CMIP5, which might be associated with the inclusion of an Earth System Model component in the CMIP5 dataset. The patterns of tropical warming over the second half of the twentieth century evolve from a La Nina-like structure in CMIP3 to an El Nino-like structure in CMIP5. Such changes influence the ENSO properties in these two datasets by altering the background state of the tropical Pacific. In particular, the ratio of the SSTA variance in the eastern and western tropical Pacific was found to have increased from CMIP3 to CMIP5, indicating that a center of action associated with the ENSO amplitude had shifted to the east for CMIP5.

Consequently, we contend that both an El Nino-like structure of the SST trend and an increase in the sensitivity of the atmospheric response to SST changes in the eastern tropical Pacific from CMIP3 to CMIP5 contribute to an enhanced ratio of the SSTA variance in the eastern and western tropical Pacific regions. Yet, we do not exclude the possibility that an increase in the sensitivity of the atmospheric response to SST changes in the eastern tropical
Pacific could cause a change in the tropical SST trend pattern from CMIP3 to CMIP5. In other words, an increase in the coupled air-sea process in the eastern tropical Pacific may be able to enhance the ratio of the SSTA variance between the eastern and western tropical Pacific regions. Then, this enhanced SSTA variance could induce a change in the tropical Pacific background state toward an El Nino-like structure via a nonlinear mechanism (Timmermann, 2002; Rodgers et al., 2004; Yeh et al., 2004).

**Reference**


Li, J., et al. (2011), Interdecadal modulation of El Nino amplitude during the past millennium. *Nature Climate Change*, 1, 114-118. DOI: 10.1038/NCLIMATE1086


Table 1. The observed difference in the trends between the western tropical Pacific (5°N-5°S, 120°E-170°W) and the eastern tropical Pacific (5°N-5°S, 150°W-90°W) (Unit: °C/100 yr) from 1950 to 2010.

<table>
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<tr>
<th>SST dataset</th>
<th>Observed WP – CP Trend (°C/100 yr)</th>
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<tbody>
<tr>
<td>Hadley SST</td>
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<tr>
<td>ERSST Version 3</td>
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<tr>
<td>Kaplan SST</td>
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<tr>
<td>ECMWF ORA3</td>
<td>0.80</td>
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Table 2. Model Descriptions used in this study.

<table>
<thead>
<tr>
<th>Modeling Center</th>
<th>Model Number</th>
<th>CMIP3 Model Name</th>
<th>CMIP5 Model Name</th>
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<tbody>
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<td>BCCR-BCM2-0</td>
<td>BCC-CSM1.1</td>
</tr>
<tr>
<td>CCCMA</td>
<td>2</td>
<td>CCCMA-CGCM3.1-t63</td>
<td>CanESM2</td>
</tr>
<tr>
<td>Météo-France</td>
<td>3</td>
<td>CNRM-CM3</td>
<td>CNRM-CM5</td>
</tr>
<tr>
<td>CSIRO Atmospheric Research</td>
<td>4</td>
<td>CSIRO-MK3.5</td>
<td>CSIRO-Mk3-6-0</td>
</tr>
<tr>
<td>Hadley Centre / Met Office</td>
<td>5</td>
<td>HadCM3</td>
<td>HadGEM2-CC</td>
</tr>
<tr>
<td>Hadley Centre / Met Office</td>
<td>6</td>
<td>HadGEM1</td>
<td>HadGEM2-ES</td>
</tr>
<tr>
<td>INM</td>
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<td>INMCM3-0</td>
<td>INM-CM4</td>
</tr>
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<td>IPSL-CM5A-LR</td>
</tr>
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<td>CCSR, JAMSTEC</td>
<td>9</td>
<td>MIROC3-2-HR</td>
<td>MIROC-ESM</td>
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<tr>
<td>MRI</td>
<td>10</td>
<td>MRI-CGCM2-3-2a</td>
<td>MRI-CGCM3</td>
</tr>
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</table>
Table 3. The Multi-Model Ensemble (MME) difference in the trends between the western tropical Pacific (5°N-5°S, 120°E-170°W) and the eastern tropical Pacific (5°N-5°S, 150°W-90°W) (Unit: °C/100 yr) from 1950 to 2000 in the CMIP3 and CMIP5 models.

<table>
<thead>
<tr>
<th>CMIP Archives</th>
<th>MME of WP – CP Trend (°C/100 yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMIP3</td>
<td>0.12</td>
</tr>
<tr>
<td>CMIP5</td>
<td>-0.07</td>
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Figure 1. The linear trends of SSTA from 1950 to 2000 in (a) CMIP3 Multi-Model Ensemble (MME), and (b) CMIP5 MME. (Unit: °C/100 yr).
Figure 2. The difference of trends over the western Pacific from that over the eastern Pacific from 1950 to 2000 (Unit: °C/100yr). The positive value indicates that the western Pacific trend is greater than the eastern Pacific trend (La Nina-like). Note that -1 in x-axis denotes the ensemble mean from the four different SST datasets in observations and 0 denotes the multi-model ensemble from the CMIP3 (black bar) and the CMIP5 (red bar), while each number from 1 to 10 denotes the corresponding climate model shown in Table 2.
Figure 3. The ratio of the standard deviation (STD) of the NINO3 index to that of the NINO4 index from CMIP5 (red bars) and CMIP3 (black bars) models during 1950-2000. Note that -1 in x-axis denotes the ensemble mean from the four different SST datasets in observations and 0 denotes the multi-model ensemble from the CMIP3 (black bar) and the CMIP5 (red bar), while each number from 1 to 10 denotes the corresponding climate model shown in Table 2.
Figure 4. The multi-model ensemble of precipitation regression coefficients over the NINO3 region with respect to the NINO3 SSTA (Unit: mm/day/°C) during 1950-2000 using CMIP3 (black bar) and CMIP5 (red bar) CGCMs.