Corrigendum: Improved simulation of two types of El Niño in CMIP5 models

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Improved simulation of two types of El Niño in CMIP5 models

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Abstract
Using the coupled general circulation models (CGCMs) participating in phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5), simulations of the two types of El Niño event are evaluated. Previous studies using CMIP3 models pointed out that most of the models tend to simulate a single type of El Niño, and have serious problems in simulating the two types of El Niño independently. On the average, the CGCMs in CMIP5 have slightly better performance in simulating the two types of El Niño event independently with more distinct spatial patterns, compared to those in CMIP3. It is demonstrated that the precipitation response to Cold Tongue El Niño is one of the important factors in simulating the two types of El Niño independently in coupled models, and this precipitation response is closely related to the dry bias over the equatorial eastern Pacific.

Keywords: warm pool El Niño, two types of El Niño events, CMIP3, CMIP5

1. Introduction

Recently, several studies have reported that there are two types of El Niño event, depending on the zonal distribution of equatorial sea surface temperature anomalies (SSTAs) using observational data. The new type of El Niño is named as the Warm Pool El Niño (WP El Niño), whose action center is shifted to the west compared to that of the conventional El Niño (Cold Tongue El Niño, or CT El Niño), whose SSTAs develop in the eastern equatorial Pacific where the cold tongue is located (Larkin and Harrison 2005, Ashok et al. 2007, Kao and Yu 2009, Kug et al. 2009, Kim et al. 2009, Holland 2009). Because the observational data are limited due to the short record, several studies have utilized coupled models as a tool to examine the existence of the two types of El Niño events and their different evolution mechanisms (Yeh et al. 2009, Kug et al. 2010, Yu and Kim 2010).

One may ask how well the two types of El Niño are reproduced in coupled models. A few studies have actually assessed the fidelity of current models in simulating the two types of El Niño event. Yu and Kim (2010) analyzed long-term integrations of the pre-industrial runs of the CMIP3 models to compare simulated characteristics of the central Pacific (WP-type) El Niño and the eastern Pacific (CT-type) El Niño with the observed ones. They concluded that most of the CMIP3 models can produce the WP El Niño realistically; on the other hand, only few of the models can reproduce the CT El Niño with realistic amplitude. Ham and Kug (2011) examined how well CMIP3 models simulate the two types of El Niño independently. They found that most models had a serious problem in simulating the two types of El Niño independently. In particular, the models tended to have a problem in simulating distinctive precipitation responses to different zonal sea surface temperature (SST) distributions. They argued that the eastern Pacific dry bias might be
responsible for this insensitive response of precipitation to the difference in zonal SSTA location.

Now, new versions of climate models are available in the CMIP5 archives, which include the latest version of models participating in CMIP3 released a few years ago. In this study, we will investigate whether CMIP5 climate models have improved simulation of the two types of El Niño. In addition to the model comparison, it is more desirable to understand the underlying dynamics of the two types of El Niño event in the CMIP3 and CMIP5 models. Therefore, we will demonstrate what a key factor is in simulating the two types of El Niño.

2. Model and data

We analyzed the historical runs by 21 climate models participating in CMIP5. The historical run was carried out under changing solar–volcanic forcing and anthropogenic forcing from 1850 to 2005. The 21 models were chosen based on their availability. In order to compare with the 21 CMIP5 models, 21 models from CMIP3 were also analyzed from the 20c3m simulation. Model references, information on the institutions where the models were run, and integration periods are summarized in Table 1.

### Table 1. Description of models in the CMIP3 and CMIP5 archives.

| Archive | Modeling group | Model number in figure 1(b) | CMIP ID | Integration period (years) | Number of ensemble members |
|---------|----------------|----------------------------|---------|---------------------------|---------------------------|
| CMIP5   | NASA/GISS      | 1                         | GISS-E2-R | 156                         | 2                         |
|         | Météo-France   | 2                         | CNRM-CM5 | 156                         | 9                         |
|         | NCAR           | 3                         | CCSM4    | 156                         | 1                         |
|         | NOAA/GFDL      | 5                         | GFDL-ESM2M | 145                       | 1                         |
|         | NOAA/GFDL      | 6                         | GFDL-CM3 | 145                         | 1                         |
|         | INM            | 11                        | INM-CM4  | 156                         | 1                         |
|         | BCCR           | 13                        | BCC-CSM1.1 | 156                      | 3                         |
|         | CSIRO-QCCCE    | 15                        | CSIRO-Mk3-6-0 | 156                      | 10                        |
|         | Hadley Centre/Met. Office | 16 | HadGEM2-CC | 145                   | 1                         |
|         | NCC            | 20                        | NorESM1-M | 156                         | 1                         |
|         | IPSL           | 23                        | IPSL-CM5A-MR | 156                     | 1                         |
|         | CCSR, JAMSTEC  | 24                        | MIROC5   | 156                         | 1                         |
|         | MRI            | 25                        | MRI-CGCM3 | 156                         | 3                         |
|         | CSIRO-BOM      | 26                        | ACCESS1-0 | 156                        | 1                         |
|         | LASG           | 27                        | FGOALS-g2 | 110                         | 1                         |
|         | CCSR, JAMSTEC  | 31                        | MIROC-ESM | 156                        | 3                         |
|         | Hadley Centre/Met. Office | 32 | HadGEM2-ES | 145                       | 4                         |
|         | IPSL           | 33                        | IPSL-CM5A-LR | 156                   | 4                         |
|         | MPI-M          | 36                        | MPI-ESM-LR | 156                        | 3                         |
|         | CCCMA          | 39                        | CanESM2  | 156                         | 5                         |
|         | NOAA/GFDL      | 41                        | GFDL-ESM2G | 145                      | 1                         |
|         | University of Bonn, KMA | 4     | MIUB-ECHO-G | 141                        | 5                         |
|         | CCCMA          | 7                         | CCCMA_CGCM3.1_t63 | 151                  | 1                         |
|         | CCCMA          | 8                         | CCCMA_CGCM3.1 | 151                     | 5                         |
|         | NOAA/GFDL      | 9                         | GFDL-CM2.1 | 140                        | 3                         |
|         | Météo-France   | 10                        | CNRM-CM3 | 140                         | 1                         |
|         | NCAR           | 12                        | NCAR_PCM1 | 110                        | 4                         |
|         | MPI            | 14                        | MPI_ECHAM5 | 140                      | 4                         |
|         | CCSR, JAMSTEC  | 17                        | MIROC3.2_HIRES | 101                    | 1                         |
|         | BCCR           | 18                        | BCCR-BCM2.0 | 150                     | 1                         |
|         | NCAR           | 19                        | NCAR-CCSM3.0 | 140                    | 4                         |
|         | CCSR, JAMSTEC  | 21                        | MIROC3.2_MEDRES | 151                  | 3                         |
|         | LASG           | 22                        | IAP_FGOALS-g1.0 | 150                | 3                         |
|         | Hadley Centre/Met. Office | 28 | UKMO-HadGEM1 | 140                       | 2                         |
|         | MRI            | 29                        | MRI-CGCM2.3.2a | 150                  | 5                         |
|         | CSIRO-QCCCE    | 30                        | CSIRO-Mk3.0 | 130                        | 3                         |
|         | IPSL           | 34                        | IPSL-CM4  | 141                         | 1                         |
|         | INM            | 35                        | INM-CM3.0 | 131                         | 1                         |
|         | CSIRO-QCCCE    | 37                        | CSIRO-Mk3.5 | 130                        | 3                         |
|         | Hadley Centre/Met. Office | 38 | UKMO-HadCM3 | 140                       | 2                         |
|         | NOAA/GFDL      | 40                        | GFDL-CM2.0 | 140                        | 3                         |
|         | INGV           | 42                        | INGV_ECHAM4 | 100                        | 1                         |

For comparison with the model results, we used observed SST data from 1970 to 2009 (ERSST V.2; Smith and Reynolds 2004) and precipitation data from 1980 to 2009 (GPCP; Adler et al 2003).
3. Results

In order to investigate how well the two types of El Niño are simulated in CMIP5, we firstly compare the SST variability over the eastern and central Pacific in CMIP3 and CMIP5 coupled models. Ham and Kug (2011) showed the distribution of the NINO3 and NINO4 indices in CMIP3 simulations, and pointed out that the two indices were significantly dependent on each other in most coupled models, which implies that CMIP3 models tend to simulate a single type of El Niño rather than the two types.

Similarly, we checked the relation between NINO3 and NINO4 SSTAs in the CMIP5 models in order to examine the independence of the two types of El Niño. Figure 1 shows the correlation coefficients between NINO3 and NINO4 SSTAs in the observations and models, which roughly measure the independence. Note that the correlation is calculated only using El Niño events. For the multi-ensemble members, each ensemble member is treated as an independent time-series. For example, three ensemble members with 150 years are treated as a single ensemble member with 450 years. In the observation, the correlation coefficient between the NINO3 and NINO4 indices is −0.28, implying that the NINO4 SSTAs vary independently of the NINO3 SSTAs to a large extent. However, most climate models show positive correlation between the two indices, which means that the two indices have strong dependence. Only six models (one CMIP3 model and five CMIP5 models) simulate a similar degree of negative correlation to that observed.

Nonetheless, it is evident that the CMIP5 models tend to simulate a more independent relationship between the two SSTAs indices than the CMIP3 models. The multi-model ensemble (MME) of correlation values are 0.50 and 0.35 for CMIP3 and CMIP5 models, respectively. When we separated the CMIP3 and CMIP5 models into best-half and worst-half groups, the CMIP5 groups always showed lower correlation than the CMIP3 groups, indicating more independence of the two types of El Niño simulation. These results suggest that the CMIP5 climate models have improved in terms of their ability to simulate the two types of El Niño independently to some extent, though they still underestimate the independence between the two types of El Niño event compared to observations.

In order to understand why the CMIP5 climate models have more independence of the two types of El Niño, we examine the spatial patterns of the two types of El Niño. To compare the CMIP5 and CMIP3 models, multi-model ensembles (MMEs) of SST and precipitation composites are shown. To remove the dependence of the El Niño magnitude, SST and precipitation composites are normalized by dividing composited NINO3 (NINO4) SSTAs for CT (WP) El Niño in each model before calculating the MME. Figure 2 shows the MMEs of SSTAs and precipitation anomalies along the equator (5°S–5°N) in the CMIP3 and CMIP5 models. Overall, the models simulate similar patterns of CT and WP El Niño events to those observed, but some differences are found in terms of the detailed structures. For the WP El Niño, the CMIP3 models simulate the SSTAs shifted too
Figure 2. MMEs of equatorial (5°S–5°N) SST (left panel), and precipitation (right panel) anomalies during WP (upper panel) and CT (lower panel) El Niño events, using the CMIP3 (blue) and CMIP5 (red) models.

Far to the western Pacific compared to those observed. The CMIP5 models have a similar problem, but it is considerably improved. For the CT El Niño, the models tend to simulate a stronger central Pacific SSTA than that observed, but the CMIP5 simulations exhibit relatively small SST magnitude compared to that of CMIP3 simulations.

Compared to the SSTA patterns, the simulated precipitation patterns exhibit more serious biases. In general, the models simulate too strong precipitation anomalies over the west of the dateline for the WP El Niño, and too weak precipitation anomalies over the eastern Pacific for the CT El Niño. Although the CMIP3 and CMIP5 models have common problems, the CMIP5 models have slightly improved precipitation patterns. The precipitation anomalies associated with the CT El Niño are larger over the eastern Pacific in the CMIP5 models; in particular, the precipitation anomaly at the east of 120°W is increased by 87% in the CMIP5 models. This enhanced precipitation response to the ENSO-related SST anomalies reinforces the eastern Pacific SSTAs in turn by producing strong local westerly anomalies.

Ham and Kug (2011) argued that the precipitation responses to the eastern Pacific warming are critical for independent simulation of the two types of El Niño using the CMIP3 models. In order to clearly compare the precipitation responses to the CT El Niño forcing, we calculate the zonal center of the precipitation pattern during the El Niño events. The centroid of the precipitation pattern is defined as follows:

$$\text{Centroid} = \frac{\int P(x)x \, dx}{\int P(x) \, dx},$$

where $P(x)$ denotes the El Niño composite of precipitation anomalies averaged over 5°S–5°N, and $x$ denotes the longitude. The zonal integration is executed over 120°E–90°W. Note that the calculated centroid of the precipitation anomaly approximately estimates the longitudinal center of the El Niño-related positive precipitation anomaly.

As shown in figure 3(a), the zonal location of the precipitation response to the CT El Niño is closely related to the independence of the two types of El Niño. The correlation between the zonal location and the independence is −0.64, which is significant at 99% confidence level. It means that the model tends to simulate the two types of El Niño more independently as the precipitation center for CT El Niño is shifted further to the east. We also checked the similar relationship between the precipitation center of the WP El Niño and independence of the two types of El Niño, but the correlation was only −0.30 (not shown). As expected, the zonal location of the precipitation center during the CT El Niño in the CMIP5 models tends to be shifted further east than that in the CMIP3 models with lower correlation between NINO3 and NINO4. For example, 67% and 33% among the CMIP5 and CMIP3 models simulate the center to the east of 160°W, respectively. However, most models simulate the center shifted to the west of the observed center. For example, only three models from CMIP5 simulate the center to the east of the observed center (figure 3(a)). This indicates that the climate model would have a similar precipitation pattern of the CT El Niño to that observed as its precipitation center is shifted to the east.

Based on these results, it is expected that more accurate simulation of the precipitation pattern will lead to more realistic independence of the two types of El Niño in the CMIP5 models. The degree of accuracy of the precipitation pattern is estimated by the pattern correlation between the simulated and observed precipitation composites over the tropical Pacific (120°E–80°W, 15°S–15°N). Figure 3(b)
shows the relation between the independence and the pattern correlation. The negative correlation (i.e. $-0.53$) between them suggests that a model with better pattern correlation tends to simulate stronger independence. In addition, the CMIP5 models tend to simulate a more realistic precipitation pattern (i.e., higher pattern correlation), which leads to more independence of the two types of El Niño.

However, it is still problematic that some models have poor performance in simulating the observed precipitation pattern of the CT El Niño, and these models always fail to simulate the two types of El Niño independently. This suggests a future direction for model improvement. On the other hand, the independence between the two types of El Niño event is not likely to be dependent on the pattern correlation among the models whose pattern correlation is above 0.8, implying that other factors in determining the independence for the two types of El Niño may exist. Nonetheless, results from figure 3 suggest that the realistic precipitation response is at least a necessary condition for a better simulation of the two types of El Niño.

One of the important factors for simulating a realistic precipitation response to the CT El Niño is a climatological state in a climate model. It is well known that the state-of-the-art coupled models have common biases over the tropical Pacific, characterized by excessive cold tongue and double Intertropical Convergence Zones (ITCZs) (e.g., Wittenberg et al 2006). These biases cause excessive suppression of convective activity over the equatorial cold tongue region which can considerably suppress local atmospheric variability (Watanabe et al 2011, Kim et al 2011, Ham et al 2012). For example, under a strong climatological sinking motion and resultant low-level divergence, an anomalous surface heating can hardly produce anomalous precipitation because the anomalous convergence needs to overcome the climatological divergence. In addition, the strong stability due to the excessive cold tongue leads to a weak anomalous ascending response to the anomalous surface heating, indicating a weak precipitation response. Therefore, it is quite difficult for the climate model to produce an anomalous precipitation response to the surface warming if the model has a serious dry bias in the eastern Pacific (Ham and Kug 2011). Therefore, the precipitation response to the warming over the eastern Pacific tends to be shifted to the west when the eastern Pacific is too dry.

Figure 4(a) shows the relation between the climatological precipitation averaged over the central and eastern Pacific ($160^\circ$E–$100^\circ$W, $5^\circ$S–$5^\circ$N) and the zonal location of the precipitation response to the CT El Niño in the climate models. It is obvious that there is a significant linear relationship between the two, indicating that more mean precipitation in the cold tongue region leads to eastward shift of the anomalous precipitation response during the El Niño. The correlation is 0.75, which is significant at 99% confidence level. As discussed above, the mean precipitation is related to the mean sinking motion and stability over the eastern Pacific, which can control the precipitation variability.

In addition, it is found that more models in the CMIP3 than in the CMIP5 have serious dry bias (less than 2 mm/day), which may be linked to poor ability in simulating the two types of El Niño independently. Figure 4(b) supports this argument that there is a significant correlation between the climatological precipitation and independence of the two types of El Niño; that is, more precipitation leads to more independence of the two types of El Niño.

4. Summary and discussion
A total of 42 climate models from the CMIP3 and CMIP5 archives are used to validate the hypothesis on the models’ fidelity in simulating the two types of El Niño event proposed by Ham and Kug (2011). Model analyses clearly support the fact the precipitation response to the eastern Pacific SST plays a crucial role in realistic simulation of the two independent types of El Niño event. The results in this study further support the findings of Ham and Kug (2011) that the models’ fidelity in simulating the climatological precipitation over the equatorial cold tongue region is one of the key factors.
for better capturing the eastward shift of the precipitation response.

Compared with CMIP3 models, CMIP5 models show some improvement in simulating the independence of the two types of El Niño. The CMIP5 models tend to simulate more independence of the two types of the El Niño event compared to those in CMIP3. The improvement is related to the fact that the eastward shift of the precipitation response to the CT El Niño is clearer in the CMIP5 models, which is related to the increased climatological precipitation over the equatorial cold tongue region. However, note that even though the CMIP5 models show some improvement, most of them still underestimate the independence of the two types of El Niño. This is related to the fact that the zonal location of the precipitation pattern associated with the CT El Niño is shifted westward compared to the observed one.

Although we showed that the zonal location of the atmospheric responses is closely related to the climatological precipitation over the cold tongue region, some wet-biased models still simulate westward-shifted precipitation anomalies of the CT El Niño, which simulates less independence of the two types of El Niño. This may be because we are looking at a particular observational period when the independence happens to be strong. Otherwise, there is the possibility that there is another common bias in simulating precipitation responses to cold tongue SST variation. Because most climate models have been tuned to simulate deep convection reasonably, there can be a problem in simulating precipitation over the cold tongue region where the precipitation processes are somewhat different. Both possibilities should be further addressed in future studies.

Although we investigated the current models’ fidelity in simulating the two types of El Niño, our evaluation is mostly based on the pattern difference, rather than the dynamical process. It is still controversial whether the two types of El Niño are dynamically different modes in the tropical coupled system. Kug et al. (2009, 2010) argued based on analyses of observational data and one particular model simulation that the zonal advective and heat flux feedbacks are key processes for the SST evolution of the WP El Niño, which is distinct from that of the CT El Niño to some extent. They further showed that the dynamical evolution of the WP El Niño cannot be explained by the conventional ENSO theories. It is important to know whether climate models simulate the different dynamical processes between the two types of El Niño event. Although we focused on the atmospheric response in this study, oceanic adjustment processes can be also important in determining the different dynamical evolutions of the two types of El Niño. Further detailed analyses are required to evaluate the fidelity of models and support observational findings.

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Figure 4. (a) Scatter diagram between the zonal location of the precipitation center during CT El Niño events and climatological precipitation over the eastern Pacific. (b) Scatter diagram between NINO3 and NINO4 correlation and climatological precipitation over the eastern Pacific (160°E–100°W, 5°S–5°N) from observation (gray), CMIP3 (blue), and CMIP5 (red).
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