Tracing the source of ENSO simulation differences to the atmospheric component of two CGCMs

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Abstract

To explore why the Community Earth System Model (CESM) exhibits too strong El Niño–Southern Oscillation (ENSO), its atmospheric component is replaced by another Atmospheric General Circulation Model (AGCM). Differences among the two simulations and another ‘parent’ model are then analyzed with reference to their underlying mechanisms. The results indicate that too large ENSO amplitude in the CESM is reduced to half by the new AGCM, mainly due to shortwave radiation feedback. Weaker shortwave radiation feedback in the CESM is found to be closely related to the too negative feedbacks of the cloud fraction and cloud liquid amount in the lower layers.

Keywords: ENSO amplitude; CESM; CESM-GAMIL2; shortwave radiation feedback

1. Introduction

The El Niño–Southern Oscillation [ENSO; i.e., the large-scale sea surface temperature (SST) anomalies that occur every 2–7 years in the central and eastern tropical Pacific] is the dominant mode of climate variability over seasonal to interannual timescales (Wang et al., 2012). ENSO fluctuations have a large impact on the ecology of the tropical Pacific as well as global climate through atmospheric teleconnections (McPhaden et al., 2006). Therefore, understanding and predicting ENSO is critical for scientists and governments worldwide. In recent decades, climate/earth system models have made steady advances in simulating ENSO characteristics (Guilyardi et al., 2012a, 2012b). For example, the ENSO amplitudes in the Coupled Model Intercomparison Project Phase 5 (CMIP5) models better converge around observations than those in the CMIP3 models (Guilyardi et al., 2012; Wu and Kim, 2010; Kim and Yu, 2012; Bellenger et al., 2014).

However, two important ENSO-related feedbacks remain underestimated in CMIP5 models: the wind–SST feedback and the heat flux–SST feedback. The wind–SST feedback, also known as the Bjerknes feedback, is measured as the regression coefficient between zonal wind stress in the Niño4 region (5°S–5°N, 160°E–210°E) and SST anomalies averaged over the Niño3 region (5°S–5°N, 150°W–90°W), and is underestimated by 20–50% in CMIP5 models. The heat flux–SST feedback, measured as the regression coefficient between net heat flux at the surface and SST anomalies in the Niño3 region, is underestimated by a factor of two (Bellenger et al., 2014; Kim et al., 2014). The heat flux–SST feedback comprises of four components: latent heat (LH), shortwave radiation (SW), longwave radiation (LW) and sensible heat (SH), of which LH and SW are the dominant components (Lloyd et al., 2009, 2012). The wind–SST feedback is a positive feedback and can enhance the ENSO amplitude, whereas the heat flux–SST feedback is a negative feedback that can act to dampen SST anomalies (Lloyd et al., 2009, 2012). Guilyardi et al. (2009) showed that the L’Institut Pierre-Simon Laplace Coupled Model (Version 4; IPSL CM4) correctly simulated ENSO amplitude when using the Kerry–Emanuel (KE) convection scheme; however, this outcome resulted from error compensation between the too weak Bjerknes feedback and the too weak heat flux feedback. These feedback errors likely originated from cloud-related processes, such as the convective parameterization scheme (Neale et al., 2008; Guilyardi et al., 2009), non-convective condensation processes (Li et al., 2014) and their uncertain parameters (Watanabe et al., 2011). SST biases (Sun et al., 2009) and the atmosphere–ocean coupling process (Lloyd et al., 2012). As these factors are highly complex and general circulation model (GCM)-dependent, it is difficult to determine how a single atmospheric general circulation model (AGCM) contributes to the feedback errors and ENSO amplitude. In this study, the community earth system model (CESM), known to simulate a strong ENSO, is selected to be coupled with the atmospheric component of the Flexible Global Ocean-Atmosphere-Land System Model (Grid-point Version 2; FGOALS-g2), which has an ENSO simulation close to observation (Bellenger et al., 2014; Kim et al., 2014). The ENSO amplitudes simulated using CESM, the new constructed CGCM and another ‘parent’ model FGOALS-g2 are then...
analyzed to further reveal the mechanisms that underlie the atmospheric feedbacks that affect the ENSO, with an emphasis on factors that contribute to weak SW feedback in the CESM.

2. Model, experimental setup and data

2.1. Model and experimental setup

The CESM (version 1.2.0) developed by the National Center for Atmospheric Research (NCAR) is used to simulate ENSO events in this study. For simplification, the ecosystem and chemistry components of the CESM are not included in the model. The atmospheric model used in the CESM is the Community Atmosphere Model (Version 4.0; CAM4; Neale et al., 2013), with an approximate 2° finite volume grid in the horizontal direction and a 30-layer hybrid pressure sigma coordinate in the vertical direction. The land surface model employed by the CESM is the Community Land Surface Model (Version 4.0; CLM4; Oleson et al., 2010), which shares the same horizontal grid as CAM4. The CESM ocean model is the Parallel Ocean Program (Version 2; POP2; Smith et al., 2010), and the CESM uses the Los Alamos sea ice model (Version 4; CICE4; Hunke and Lipscomb, 2008), which uses a displaced pole grid with a horizontal resolution of 1° that is compatible with POP2.

To investigate how different AGCMs simulate ENSO amplitudes, the Grid-point Atmospheric Model of IAP LASG (Version 2; GAMIL2) is integrated with the CESM (herein referred to as CESM-GAMIL2). The only difference between the CESM and the CESM-GAMIL2 is the atmospheric component. GAMIL2 employs a dynamical core that includes a finite difference scheme and a two-step shape-preserving advection scheme (TSPAS). In addition, the GAMIL2 uses a hybrid horizontal grid consisting of a 2.8° Gaussian grid between 65.58°N–5°S and 65.58°N and a weighted equal-area grid poleward from 65.58°, and a 26-layer sigma coordinate in the vertical direction (Li et al., 2013; Wang et al., 2004). Furthermore, GAMIL2 is the atmospheric component of FGOALS-g2, which produces an ENSO simulation (e.g. the amplitude and the ENSO-related feedbacks) close to observations as a participant in the CMIP5 (Bellenger et al., 2014; Kim et al., 2014).

To eliminate the influence of any external forcing, the CESM and CESM-GAMIL2 are run under pre-industrial (PI) conditions and integrated over 500 years. The first 100 years are model spin-up and monthly simulations from the following 200 years (i.e. years 101–300 in the simulation) are used to conduct ENSO analyses.

2.2. Validation datasets

The following datasets are used to verify model performance: The SST is from the merged products of HADISST1 [Met. Office Hadley Centre sea ice and SST dataset (1870 onward)] and OI.v2 [National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation SST Version 2 dataset (November 1981 onward)] (Hurrell et al., 2008). The cloud cover and LWP for the period from 1984–2009 are obtained from the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1999). The LWP from the Special Sensor Microwave Imager (SSMI; 1992–2009) is also used for comparison (Weng et al., 1997). The precipitation dataset for the period from 1984–2009 is obtained from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997) and from the Global Precipitation Climatology Project (GPCP; Adler et al., 2003). The Vertical velocities at 500-hPa and surface wind stress data are supplied by the 40 year European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40), which covered the period 1958–2001 (Uppala et al., 2005). Finally, objectively Analyzed Air–Sea Fluxes (OAFlux) combined with ISCCP values of short and longwave radiation are used for the period 1984–2009 (Yu and Weller, 2007).

3. Results

3.1. ENSO variability

Area-averaged monthly SST anomalies (SSTA) over the Niño3 region (5°N–5°S, 150°E–90°W) provide an index typically used to represent ENSO variability. Time series of the Niño3 index from HadISST observations and the CESM-GAMIL2 and CESM PI-control runs are compared in Figure 1. The PI-control simulation (years 101–300) from another 'parent’ model (i.e. FGOALS-g2 from CMIP5) is also included for comparison. Compared with observations, the CESM simulates a much stronger SSTA variation, whereas the CESM-GAMIL2 shows relatively weak variability, and the FGOALS-g2 exhibits a variability most closely matching observations. When quantifying the ENSO amplitude using the Niño3 index standard deviation, the HadISST is approximately 0.81 K, the CESM-GAMIL2 is 0.64 K, the FGOALS-g2 is 0.779 K and the CESM is 1.25 K. Analogous standard deviations based on the Niño3.4 (5°N–5°S, 160°E–150°W) index are 0.77, 0.543, 0.778 and 1.22 K, while the Niño4 (5°N–5°S, 160°E–210°E) index gives 0.56, 0.40, 0.495 and 0.97 K for HadISST, CESM-GAMIL2, FGOALS-g2 and CESM, respectively. These results show that the ENSO amplitude in CESM is twice as strong as that in CESM-GAMIL2 (the large ENSO amplitudes in CESM were also shown in other studies, e.g. Kang et al., 2014; Bellenger et al., 2014), independent of index selection, and the observation value lies between the two models, while FGOALS-g2 is much closer to observations. Based on this result, ENSO variability is herein represented by the Niño3 index.

Previous studies have suggested that ENSO amplitude shows a negative correlation with the strength
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Figure 1. Time series of the Niño3 (5°N–5°S, 150°–90°W) index for (a) HadISST observations during 1901–2000, (b) CESM-GAMIL2, (c) FGOALS-g2 and (d) CESM during years 101–300 in the PI-control run.

3.2. Atmospheric feedbacks

On the basis that the only difference between the CESM-GAMIL2 and the CESM is the atmospheric model, atmospheric processes and feedbacks that govern the large difference in ENSO amplitude are explored, with FGOALS-g2 results included for comparison. Atmospheric dynamic and thermal feedbacks in the observation and three simulations are listed in Table 1. Bjerknes feedbacks for the three models compare well in spite of μ being too weak with respect to observations, while heat flux feedbacks, α, vary significantly. The value for α in the CESM is −8.71 W m⁻² K⁻¹, about half of the values of −18.64 and −17.02 W m⁻² K⁻¹ simulated in CESM-GAMIL2 and FGOALS-g2, respectively. The latter two are much closer to −16.70 W m⁻² K⁻¹ provided by the ERA40 and −15.92 W m⁻² K⁻¹ provided by OAFlux. This result may indicate that a weak α value means the CESM cannot effectively suppress El Niño warming and thus produces a stronger ENSO. As shown in Table 1, the SW feedback, αSW, is the main cause of the α difference among the models, although the LH feedback, αLH, also plays a role.

To further understand the impact of αSW on SSTA, a composite analysis of SW flux anomalies and SSTA during El Niño events is performed (Figure 3). Each El Niño event in the models (13 in CESM-GAMIL2, 13 in FGOALS-g2 and 17 in CESM) is defined as an SSTA in Niño3 greater than 1.5 times its standard deviation for at least three consecutive months (Lloyd et al., 2012). Each event in the observation is selected according to the El Niño definition provided by the Climate Prediction Center (Null, 2015), where weak and moderate events are included. In OAFLUX, negative SW anomalies occur at the end of El Niño warming due to the time required to establish a sufficient SST to trigger convection (Guilyardi et al., 2009). In CESM-GAMIL2, negative SW anomalies cover almost the entire warming episode and rapid warming is suppressed, conducive to a weak El Niño. Conversely, for the CESM, large positive SW anomalies occur in the eastern Pacific at the start of an El Niño event, thereby amplifying El Niño development. The evolution of SW anomalies in FGOALS-g2 is closest to that in OAFlux in the eastern Pacific, and correspondingly, the El Niño strength of FGOALS-g2 is much closer to observations. Stronger negative SW anomalies are collocated with weaker positive interannual SSTA in the CESM-GAMIL2 compared with the CESM, consistent with their feedback results obtained by linear regression. In the western and seasonal cycle in the CESM is more easily disrupted than in CESM-GAMIL2. A dynamical interpretation of the inverse relationship between the annual cycle strength and the ENSO amplitude in the eastern equatorial Pacific, which requires further study using the CESM, is presented by An and Choi (2013) using the Geophysical Fluid Dynamics Laboratory Couple Climate Model (Version 2.0; GFDL-CM2.0).

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Figure 2. Normalized power spectra of full monthly Niño3 SST for (a) HadISST, (b) CESM-GAMIL2, (c) FGOALS-g2 and (d) CESM. The red values indicate the percentage of total spectral energy in the annual and semi-annual cycles, respectively.

Table 1. Coefficients of linear regression against SST of the surface net heat flux, shortwave radiation, and latent heat (W m\(^{-2}\) K\(^{-1}\)); total, convective, and stratiform precipitation (mm day\(^{-1}\) K\(^{-1}\)); total liquid water path (g m\(^{-2}\) K\(^{-1}\)); 500hPa vertical velocity (hPa day\(^{-1}\) K\(^{-1}\)); and total-, high-, middle-, and low-cloud fraction (% K\(^{-1}\)) over the Niño-3 region and average annual Bjerknes feedback in the Niño4 region (10\(^{-3}\) Nm\(^{-2}\) K\(^{-1}\)) from observations, CESM-GAMIL2, FGOALS-g2 and CESM, and their Niño3 amplitudes (K).

| Niño3 | Observation | CESM-GAMIL2 | FGOALS-g2 | g2 | CESM |
|-------|-------------|-------------|-----------|----|------|
| α     | -16.70/-15.92 (ERA40/OAFlux) | -18.14 | -17.02 | -8.71 | |
| \(a_{SW}\) | -11.32/-5.63 (ERA40/OAFlux) | -11.40 | -9.05 | -2.19 | |
| \(a_{LW}\) | -6.40/-9.50 (ERA40/OAFlux) | -9.19 | -9.45 | -6.20 | |
| μ     | 1.1.06 (ERA40) | 8.24 | 8.06 | 9.05 | |
| \(α_{pr}\) | 1.11/1.03 (GPCP/CMAP) | 1.40 | 1.14 | 1.08 | |
| \(α_{prc}\) | -0.90 | 0.74 | 0.95 | |
| \(α_{prl}\) | -0.50 | 0.40 | 0.13 | |
| \(α_{LWP}\) | 19.99/4.42 (SSM/I/ISCCP) | 13.47 | 10.55 | 10.22 | |
| \(α_{W500}\) | -9.42 (ERA-40) | -11.40 | -9.48 | -7.79 | |
| \(α_{cloud}\) | 4.52 (ISCCP) | 4.78 | 3.67 | 3.11 | |
| \(α_{LWP}\) | 3.45 (ISCCP) | 4.18 | 4.20 | 9.00 | |
| \(α_{Cldhgh}\) | 2.76 (ISCCP) | 3.51 | 2.97 | 4.52 | |
| \(α_{Cldlow}\) | -0.42 (ISCCP) | 4.16 | 2.41 | -3.34 | |

central Pacific, CESM reproduces the observed evolutions of negative SW anomalies during El Niño development period, while the other two models produce the negative SW anomalies only during mature period.

As reported previously, SW flux is associated mainly with the extent of cloud cover, the cloud liquid water path and dynamical circulation. Thus, the SW feedback is decomposed into cloud fraction feedback, LWP feedback and dynamics (vertical velocity at 500 hPa) feedback (Lloyd et al., 2012; Li et al., 2014). The Niño3 averaged feedbacks of the total cloud fraction (\(α_{cloud}\)), total LWP (\(α_{LWP}\)), and dynamics (\(α_{W500}\)) in CESM-GAMIL2 are 4.78% K\(^{-1}\), 13.47 g m\(^{-2}\) K\(^{-1}\) and -11.40 hPa day\(^{-1}\) K\(^{-1}\), respectively, while in CESM they are 3.11% K\(^{-1}\), 10.22 g m\(^{-2}\) K\(^{-1}\) and -7.79 hPa day\(^{-1}\) K\(^{-1}\), respectively. All three component feedbacks contribute to weak SW feedback in the CESM. For FGOALS-g2, both the \(α_{SW}\) and its three component feedbacks are intermediate between those of the CESM and the CESM-GAMIL2, and are much closer to the latter, suggesting the dominate role of \(α_{SW}\) in the atmospheric model. Furthermore, the vertical distributions of the cloud fraction and the cloud liquid amount (CLDLIQ) feedbacks (Figure 4) show that in CESM, negative cloud fraction and CLDLIQ feedbacks...
Figure 3. Composite El Niño evolution along the equator for the shortwave flux anomaly (shading) and SST anomaly. The contour interval for SST is 0.4 K. (a) OAFLUX (which includes ISCCP radiative fluxes; 1984–2009), (b) CESM-GAMIL2, (c) FGOALS-g2 and (d) CESM.

below 700 hPa are the main causes of weaker $\alpha_{\text{cloud}}$ and $\alpha_{\text{lwp}}$ as well as positive SW anomalies in the eastern Pacific. The too negative cloud fraction feedback and LWP feedback in the lower layers are the common problem in most CMIP5 models, possibly arising from the same root as the ‘too few too bright’ low-cloud problem (Li et al., 2015, pers. comm.). The small stratiform rainfall feedback in models may be one important factor (Li et al., 2014).

4. Discussion and conclusions

The ENSO simulations of this study are conducted using two CESM-based GCMs (i.e. CESM and CESM-GAMIL2) that differ only in their atmospheric components. The ENSO amplitudes simulated by the two models are different; e.g. the standard deviation of the Niño3 index in the CESM is up to twice that in CESM-GAMIL2. The strong amplitude in the CESM is consistent with its weak seasonal cycle strength, which accounts for only 14.4% of the total energy compared with 30.7% in CESM-GAMIL and 35.6% in observations. Less energy within the seasonal cycle indicates that more is available for interannual signals (Guilyardi, 2006).

For comparison, another ‘parent’ model (i.e. FGOALS-g2 from CMIP5) is also included, and the differences in the simulations of ENSO amplitude are attributed to differences in two atmospheric feedbacks, i.e., the positive Bjerknes feedback and negative heat flux feedback, with a main contribution from the heat flux feedback. In the CESM, the weak negative heat flux feedback, approximately half the size of the corresponding feedback calculated from observations and the CESM-GAMIL2 simulation, is found to be incapable of effectively dampening El Niño warming, thereby favoring a strong ENSO. Among the four components of heat flux feedback, the SW component is found to be the main cause of weak
heat flux feedback in the CESM, although the LH component also played a role. Further examination indicates that the negative low-cloud fraction feedback and the negative low-cloud liquid amount feedback are the main contributors to weaker $\alpha_{SW}$ in the CESM in the Niño3 region; this result may be associated with its small stratiform rainfall feedback (Li et al., 2014).

ENSO amplitudes in FGOALS-g2 and CESM-GAMIL are moderately different. Therefore, the role of ocean feedbacks in ENSO simulations should be further investigated. In addition, as ENSO simulations are related to their climatological mean state (Guil-yardi, 2006), their relationship between the ENSO amplitude and the climatological mean state in the CESM and CESM-GAMIL, as well as their uncoupled models, should be explored in future studies. Moreover, the inverse relationship between the mechanism of ENSO amplitude and season cycle merits further investigation. The significance of differences in ENSO amplitude as well as error bars in longer time scales (such as millennial scale) will also be researched in future.

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