Environmental Research Communications

LETTER

ENSO phase-locking behavior in climate models: from CMIP5 to CMIP6

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Abstract

The phase-locking behavior of El Niño-Southern Oscillation (ENSO) in models from Coupled Model Intercomparison Project (CMIP) phase 5 to phase 6 is assessed in terms of the locking-month of ENSO peak and the sharpness of locking tendency. Overall, a robust improvement exists in CMIP6. Compared to CMIP5, more CMIP6 models truly reproduce the locking-month in November-January. Meanwhile, the sharpness of phase-locking in CMIP6 models also improves, though most of them are still far from the observations. The locking-month is verified to be highly corresponding to the phase of seasonal modulation of ENSO’s instabilities. The sharpness is mainly controlled by the intensity of this modulation and noise. Compared to CMIP5, CMIP6 models generally simulate these affecting factors better. Besides, models displaying an exaggerated semi-annual variation of ENSO’s instabilities simulate the ENSO phase-locking relative-poorly, and these models show no reduction from CMIP5 to CMIP6.

1. Introduction

The preference of peaking during boreal winter and rapidly decaying in spring, referred to as the seasonal synchronization or phase-locking phenomenon, is one of the fundamental features of El Niño-Southern Oscillation (ENSO) (Rasmusson and Carpenter 1982, Philander 1983, Tziperman et al 1998, McPhaden et al 2006). Many studies have discussed the possible mechanisms of this significant behavior, which can be majorly summarized into two arguments (Hirst 1986, Chang et al 1994, Tziperman et al 1994, Jin et al 1996, Neelin et al 2000). One argument conceptually explains the phase-locking phenomenon as a result of nonlinear interaction between the ENSO inherent cycle without phase-locking feature and an annual cycle with locking tendency (Chang et al 1994, Tziperman et al 1994), where a series of subharmonics locking in both frequency and phase derives (Jin et al 1994, Stuecker et al 2015). Another argument attributes the phase-locking behavior to the seasonal variation of ENSO’s coupled instabilities induced by the seasonal cycle of tropical climate background, or named as the seasonal modulation of ENSO’s instabilities. Specifically, several factors in the tropics featuring seasonality, such as the Pacific intertropical convergence zone, the sea surface temperature (SST) gradient, and the equatorial thermocline depth, could be responsible for this seasonal modulation (Tziperman et al 1997, Yan and Wu 2007, Zhang et al 2015, Dommenget and Yu 2016, Abellan et al 2017). These factors would together contribute to a variation of ENSO growth rate that peaks in the boreal summer and autumn via a series of dynamic and thermodynamic processes (e.g., Kim et al 2014, Rashid and Hirst 2016). ENSO tends to peak a few months later than the ENSO growth rate, thus locked in the boreal winter (Li 1997, An and Wang 2001, Stein et al 2010). The stochastic wind forcing over the equatorial Pacific can also affect the phase-locking phenomenon.
ENSO phase-locking behavior is of importance to ENSO prediction. The ENSO forecast skill shows a substantial seasonal variation that has been suggested to be influenced by the ENSO phase-locking to the annual cycle (Jin and Kinter 2009). The growth phase of ENSO events (generally boreal summer and autumn) is more predictable than the decay phase (boreal winter and spring) or neutral state. Thus, the strength of the so-called spring barrier of ENSO prediction is shown to depend on the degree of phase-locking behavior (Balmaseda et al 1995, Torrence and Webster 1998, Tian et al 2019). However, the simulation of ENSO phase-locking phenomenon in climate models is still far from satisfying; many models tend to simulate ENSO events peaking in summer, and this problem persists during the Coupled Model Intercomparison Project (CMIP) phase 3 and 5 (Ham et al 2013, Bellenger et al 2014, Ham and Kug 2014). Commonly, the shifted locking-time of ENSO was linked to the bias in the tropical climate background and its seasonal cycle (Yan and Wu 2007, Rashid and Hirs 2016, Wengel et al 2018). Moreover, previous studies mostly focus on when the locking behavior occurs while ignoring its sharpness (Chen and Jin 2020), namely, the strength of this locking behavior in the system.

The output of CMIP6 models was newly released with original CMIP5 members updated and several fresh members joining based on a series of the progress of ENSO dynamics and model development (Freund et al 2020, Song et al 2020). Has the ENSO phase-locking simulation in these state-of-the-art climate models improved compared to the last phase, and what leads to this improvement? An assessment of the simulations of ENSO phase-locking in models from CMIP5 to CMIP6 and the possible affecting factors of simulation performance is presented in this study.

2. Data and methods

The HadISST1.1 dataset from the Met Office Hadley Center is analyzed as the observational sea surface temperature, ranging from January 1900 to December 2019, with a 1.0° × 1.0° horizontal grid (Rayner et al 2003). The observational zonal wind stress is from the ECMWF Ocean Reanalysis System 5, ranging from January 1960 to December 2018, with a 1.0° × 1.0° horizontal grid. Monthly outputs from the pre-industrial control experiment of 30 CMIP5 models (Taylor et al 2012) and 30 CMIP6 models (Eyring et al 2016) are used to evaluate the simulation of ENSO peak phase-locking in models (table 1). For each model, the output of the last 300 years is taken from the first ensemble member (r1i1p1 of CMIP5 models and r1i1p1f1 of CMIP6 models) interpolated into the same grid as the observational SST data in advance.

In this study, ENSO event in both observations and models is identified when the 3-month running mean of Niño3.4 index, i.e., averaged SST anomalies (SSTA) in the Niño3.4 region (5°S–5°N, 170°W–120°W), exceeds ±0.5 standard deviations for at least five consecutive months (Ren et al 2018, Wengel et al 2018). All anomalies are calculated as a departure from the long-term climatology with a linear trend removed in advance. This study only focuses on the phase-locking behavior of the ENSO peak. We examine the probability histogram of ENSO peak time accounting to the calendar-month and define the time when the histogram peaks as the locking-month (Tziperman et al 1998, Abellan et al 2017). Additionally, a distance variance, i.e., mean square of the relative distance between each ENSO event’s peak time to the histogram locking-month, is defined to measure the phase-locking sharpness. The smaller the distance variance, the stronger the phase-locking behavior. Our assessment of the phase-locking simulation among models will be majorly in terms of the above two features, i.e., the locking-month and its sharpness.

3. Results

As shown in figure 1, the ENSO phase-locking behavior is pronounced in observations. Evolution of the Niño3.4 index in most historical El Niño (figure 1(a)) and La Niña (figure 1(b)) events peaks during boreal winter, suggesting a qualitatively consistent peak–phase-locking behavior in both ENSO warm and cold episodes. Based on HadISST from January 1900 to December 2019, the frequency of ENSO events peaking during boreal winter is much higher than that outside of winter (figure 1(c)), shaping a very sharp histogram distribution with a probability of 75% concentrated in three months (November–January). Thus, we recognize December as the preferred locking-month in observations, and the calculated distance variance of observed phase-locking sharpness is 3.5. We also check the monthly SSTA variance evolution, which is another traditional measure to indicate the locking-month but hard to describe its sharpness (Chen and Jin 2020). The locking-months indicated by the two methods are consistent.

Each CMIP model’s output could form an ENSO peak time probability histogram (figures S1 and S2 (available online at stacks.iop.org/ERC/3/031004/mmedia)) with the ENSO occurrence frequency roughly per 1.5 years to 2.5 years, which is reasonable compared to the observation (per 2.0 years). We also calculate a multi-
From the perspective of MME, CMIP5 models have succeeded in capturing the real locking-month of ENSO observations. Besides, the CMIP5 MME features a much gentler histogram distribution compared to the model ensemble (MME) by accumulating ENSO events in all CMIP5 models into one histogram (figure 2(a)). From the perspective of MME, CMIP5 models have succeeded in capturing the real locking-month of ENSO peak in December. However, from the individuals, there are still many (10 out of 30) CMIP5 models simulating a shifted locking-month, i.e., these models prefer to simulate an ENSO peak outside November-January remarkably varies by CMIP5 members, and only three models approach the level of observation with a distance variance of 8.3 versus 3.5. The specific performance of sharpness simulation remarkably varies by CMIP5 members, and only three models approach the level of observation (with a distance variance lower than 4.0). Stein et al. (2014) also suggested a similar conclusion that the simulated 2:1 phase synchronization of ENSO to the annual cycle in most CMIP5 models is weak. We define a relatively good performance as a simulated phase-locking behavior displaying a locking-month in November-January and the distance variance of its sharpness lower than 8.0.

The CMIP6 MME histogram (figure 2(b)) displays a realistic locking-month of ENSO peak in December but features a sharper distribution compared to CMIP5, with a distance variance reducing from 8.3 to 7.2 (passed the 99% confidence level of F-test). The improvement between the two CMIP phases can be more clearly seen from the perspective of individual models. The count of CMIP6 members simulating a realistic locking-month (24 versus 20) and that reproduce a close-to-real sharpness (8 versus 3) both increase (figure 2(d)).

Comprehensively, the ratio of models displaying relatively good performance rises significantly from 12 out of 30 to 20 out of 30. Thus, simulations of ENSO phase-locking in CMIP6 models robustly improve over CMIP5 in terms of the peak locking-month and its sharpness.

| CMIP5 Model No. | Model Abbreviated | Modeling Center | CMIP6 Model No. | Model Abbreviated | Modeling Center |
|-----------------|-------------------|-----------------|-----------------|-------------------|-----------------|
| 1               | ACCESS1-0         | CSIRO-BOM       | 1               | ACCESS-CM2        | CSIRO-BOM       |
| 2               | ACCESS1-3         | CSIRO-BOM       | 2               | BCC-CSM2-MR       | BCC (China)     |
| 3               | bcc-csm1-1        | BCC (China)     | 3               | BCC-ESM1          | BCC (China)     |
| 4               | bcc-csm1-1-m      | BCC (China)     | 4               | CAMS-CSM1-0       | CAMS (China)    |
| 5               | CanESM2           | CCCMA (Canada)  | 5               | CanESM5           | CCCMA (Canada)  |
| 6               | CSM4              | NCAR (USA)      | 6               | CESM2             | NCAR (USA)      |
| 7               | CESM1-BGC         | NCAR (USA)      | 7               | CESM2-FV2         | NCAR (USA)      |
| 8               | CESM1-CAM5        | NCAR (USA)      | 8               | CESM2-WACCM       | NCAR (USA)      |
| 9               | CMCC-CM           | CMCC (Italy)    | 9               | CMCC-ESM2-WACCM-FV| NCAR (USA)      |
| 10              | CMCC-CM5          | CMCC (Italy)    | 10              | CIESM             | THU (China)     |
| 11              | CNRM-CM5-2        | Météo-France    | 11              | CMCC-CM2-SR5      | CMCC (Italy)    |
| 12              | CNRM-CM5          | Météo-France    | 12              | ESM-1-0           | ESM-Project (USA)|
| 13              | CSIRO-Mk3-6-0     | CSIRO-QCCCE     | 13              | EC-Earth3-Veg-LR  | EC-Earth (Europe)|
| 14              | EC-EARTH          | EC-Earth (Europe)| 14              | FGOALS-g3        | LASG (China)    |
| 15              | FGOALS-s2         | LASG (China)    | 15              | FIO-ESM-2-0       | FIO (China)     |
| 16              | FIO-ESM           | FIO (China)     | 16              | GFDFL-CM4         | GFDFL (USA)     |
| 17              | GFDFL-ESM2G       | GFDFL (USA)     | 17              | GFDFL-ESM4        | GFDFL (USA)     |
| 18              | GISS-E2-H         | NASA (USA)      | 18              | GISS-E2-1-G       | NASA (USA)      |
| 19              | GISS-E2-R         | NASA (USA)      | 19              | GISS-E2-1-H       | NASA (USA)      |
| 20              | inmcm4            | INM (Russia)    | 20              | HadGEM3-GC31-LIL | Hadley Center (UK)|
| 21              | IPSL-CM5A-LR      | IPSL (France)   | 21              | HadGEM3           | Hadley Center (UK)|
| 22              | IPSL-CM5A-MR      | IPSL (France)   | 22              | IPSL-CM6a-LR      | IPSL (France)   |
| 23              | IPSL-CM5B-LR      | IPSL (France)   | 23              | MCM-UA-1-0        | UA (USA)        |
| 24              | MIROC3            | CCSR (Japan)    | 24              | MIROC6            | CCSR (Japan)    |
| 25              | MIROC-ESM         | CCSR (Japan)    | 25              | MPI-ESM-1-2-HAM   | MPI (Germany)   |
| 26              | MIROC-ESM-CHEM    | CCSR (Japan)    | 26              | MPI-ESM1-2-HR     | MPI (Germany)   |
| 27              | MPI-ESM-LR        | MPI (Germany)   | 27              | MPI-ESM1-2-LR     | MPI (Germany)   |
| 28              | MPI-ESM-P         | MPI (Germany)   | 28              | MRI-ESM2-0        | MRI (Japan)     |
| 29              | MRI-CCGCM3        | MRI (Japan)     | 29              | NESM3             | NUIST (China)   |
| 30              | NorESM1-M         | NCC (Norway)    | 30              | SAM0-UNICON       | SNU (KOR)       |
As mentioned in section 1, some studies have argued that the phase-locking behavior comes from the seasonal modulation of ENSO’s instabilities, which is a dynamics concept and hard to be simply described in a complex model. However, it can be indirectly indicated by the seasonal variation of SSTA amplitude (standard deviations of the Niño3.4 index for 12 calendar-months) with a phase shift (Stein et al. 2010, An and Jin 2011, Stein et al. 2014). As shown in figure 3, the locking-month of the ENSO peak and the peak-month of the seasonal variation of SSTA amplitude are highly correlated in CMIP models (with a correlation coefficient of 0.82, passed the 99% confidence level of T-test). This synchronization implies that the lag-correlation of ENSO peak with the maximum growth rate is still robust in CMIP models. Compared to CMIP5, more CMIP6 models simulate a seasonal variation of SSTA amplitude peaking in November-January (24 versus 20); that is, more CMIP6 models truly reproduce the phase of ENSO’s instabilities. In this case, the amount of CMIP6 models simulating a realistic locking-month of ENSO peak increases. Moreover, we noticed seven CMIP5 models and seven CMIP6 models have two peaks in the seasonal variation of SSTA amplitude (the additional peaks are marked with purple hollow circles and oblique-crosses in figure 3); in other words, these models display an exaggerated semi-annual variation of ENSO’s instabilities. That may come from the bias of upwelling in the eastern equatorial Pacific (Song et al. 2014, Wang and Yu 2019). In corresponding, the ENSO events they simulated also show two preferred peak times. Around half of these models finally simulate a locking-month of ENSO peak shifted to the boreal spring or summer, though their ENSO events still have a secondary peaking tendency in the boreal winter. If removing these models, the correlation coefficient between the locking-month of ENSO peak and the peak-month of seasonal variation of SSTA amplitude could reach 0.90. In summary, an exaggerated semi-annual variation of SSTA amplitude is very likely to result in a shifted locking-month of ENSO, and from CMIP5 to CMIP6, models with this characteristic have not been fundamentally reduced.

The correct phase of seasonal variation of ENSO’s instabilities could only ensure a correct locking-month but cannot control the sharpness of the simulated phase-locking behavior. For instance, model CMCC-CMS (CMIP5-model No.10) reproduces a seasonal variation of SSTA amplitude peaking in January, and the ENSO it simulated also prefers to peak in January (figure 3). However, this phase-locking phenomenon is much weaker than observations (with a distance variance three times of observations, seen in figure 2(c)). Chen and Jin (2020) suggested that the phase-locking sharpness is sensitive to the intensity of seasonal modulation of ENSO’s instabilities rather than its phase. In a complex model, this intensity can be indirectly indicated by the extreme difference of seasonal variation of SSTA amplitude (Tian et al. 2019). For those models showing an apparent semi-annual variation of SSTA amplitude, the extreme difference is calculated between the means of two maxima and two minima. For each model and observations, the calculated intensity of seasonal modulation of ENSO’s instabilities is normalized by the mean of SSTA standard deviations for 12 calendar-months to compare across.

Figure 1. Evolutions of the 3-month running averaged Niño3.4 index (units: °C, colored thin curves) and their composites (red thick curve) for historical (a) El Niño and (b) La Niña events. Evolution starts from January of the event-developing year to December of next year (marked with +). (c) Probability histogram of ENSO peaking time (red bars, units: 1) and monthly variance of the Niño3.4 index evolution (green curve, units: °C²), both based on data from January 1900 to December 2019 (in (a) and (b), only events after the 1950s are shown). Red text on the upper-right indicates the count of events.
The intensity of seasonal modulation of ENSO’s instabilities reproduced in CMIP models varies broadly, and most of them are weaker than the reality (figure 4(a)). As previous works suggested, the phase-locking sharpness is highly correlated with the intensity of seasonal modulation of ENSO’s instabilities among models (with a correlation coefficient of $-0.81$, passed the 99% confidence level of T-test). The stronger this seasonal modulation, the sharper the phase-locking tendency. Overall, CMIP6 models reproduce a more realistic
intensity of seasonal modulation of ENSO’s instabilities than CMIP5, no matter from the perspective of their MMEs or counts of stronger individuals. Thus, the phase-locking sharpness they simulated improves correspondingly. Besides, models featuring an exaggerated semi-annual variation of SSTA amplitude (marked with hollow circles in figure 4) generally exhibit a much weak seasonal variation of ENSO’s instabilities and poorly sharpness simulation. The better simulation of SST and its annual cycle in the eastern equatorial Pacific (figure S5) may be a major factor responsible for improving the seasonal modulation of ENSO’s instabilities (Yan and Wu 2007). Though there is a cold bias over that region in most models, the cold bias has been decreased from CMIP5 to CMIP6 (Song et al 2020), which would improve the regional thermodynamic feedback (Ham and Kug 2014, Kim et al 2014). Meanwhile, the simulated SST annual cycle is also improved (mean of correlation coefficients rise from 0.77 to 0.82), which may favor a better seasonal variation of the Ekman feedback and thermocline feedback (Yan and Wu 2007, Wengel et al 2018).

Figure 4(b) shows the correspondence between the phase-locking sharpness and the relative intensity of noise (with a correlation coefficient of 0.56, passed the 99% confidence level of F-test); the latter is defined as the standard deviation ratio of high-frequency (the remaining after removing a 3-month running average) and total zonal wind stress over western and central equatorial Pacific (2°S–2°N, 130°E–150°W). Here, models featuring an exaggerated semi-annual variation of SSTA amplitude and model FIO-ESM (CMIP5-No.16, displays a strong semi-annual cycle in the negative SSTA amplitude; see figure S3) are removed to avoid interference (The correspondence including all models is shown in figure S4). As the atmospheric noise strengthens, ENSO peak phase-locking sharpness tends to degrade due to the stronger irregularity occurring randomly. Meanwhile, the simulated noise intensity is improved from CMIP5 to CMIP6, whether compared by their MMEs or amounts of models with close-to-real intensity, though most CMIP models still overrate it. Therefore, it is also reasonable to interpret that CMIP6 models reproduce a better phase-locking sharpness due to less flattening impact from the noise.

4. Summary and discussions

In this study, we assessed the ENSO phase-locking behavior in an equal amount of CMIP5 and CMIP6 models in terms of the locking-month of ENSO peak and the sharpness of locking tendency. Overall, a robust improvement exists in CMIP6. From the perspective of MME, both CMIP5 and CMIP6 models reproduce a realistic locking-month of ENSO peak, but the proportion of models simulating the realistic locking-month further increases in CMIP6. Meanwhile, the sharpness of ENSO phase-locking in CMIP6 models also improves, though most of them are still far from the observations. We verified that the seasonal modulation of ENSO’s coupled instabilities and the relative intensity of noise are vital for the ENSO phase-locking in CMIP models. The locking-month highly corresponds to the phase of seasonal modulation of ENSO’s instabilities. The sharpness of phase-locking is mainly controlled by the intensity of this seasonal modulation, and the relative intensity of noise also negatively impacts it. Compared to CMIP5, CMIP6 models simulate these affecting factors.
closer to the observations, thus reproducing the ENSO phase-locking better. Moreover, the improvement of mean SST and its seasonal cycle in the eastern equatorial Pacific in CMIP6 models may be responsible for the better simulation of seasonally varying ENSO’s instabilities. Our results also suggest that models displaying an exaggerated semi-annual variation of ENSO’s instabilities simulate the ENSO phase-locking relative-poorly, and these models show no reduction from CMIP5 to CMIP6.

This study has emphasized that the tropical seasonal cycle is vital for the ENSO phase-locking behavior. Besides the SST in the eastern equatorial Pacific, other factors, such as the seasonal-migrated warm-pool, the mean wind divergence, and the equatorial thermocline depth, can seasonally modulate the ENSO’s instabilities (e.g., Kim et al 2014, Rashid and Hirst 2016). Further dynamics analyses on the seasonal variation of ENSO’s instabilities, and how the climatological background and seasonal cycle been improved in CMIP6 models are essential for the model design and development. The better performance of CMIP6 models in reproducing the ENSO phase-locking may also come from the relatively higher model resolutions, the improved data assimilation methods, and numerical solution methods (e.g., Eyring et al 2016, Wan et al 2018, Roberts et al 2019). In our analysis, we calculated the noise amplitude using monthly wind stress due to the limit of data resolution, and as suggested, only the low-frequency component of noise is important to the ENSO variability (Hayashi and Watanabe 2017, Capotondi et al 2018). We did not further diagnose the effect of the seasonal cycle from a perspective of nonlinear frequency interaction as reviewed in section 1 (e.g., Stein et al 2014). It is unnecessary and impractical under the aim of evaluating the phase-locking behavior in CMIP models. Moreover, the ENSO phase-locking behavior may be different between ENSO episodes and types. Current climate models are still limited in accurately presenting the ENSO asymmetry and diversity (e.g., Kim and Yu 2012, Zhang and Sun 2014, Feng et al 2019); it is more practical to leave the examination of these secondary features for future research.

Acknowledgments

The authors gratefully acknowledge Prof Fei-Fei Jin for his valuable comments and suggestions to the paper. This work was jointly supported by the China National Science Foundation under Grant 41975094 and the China National Key Research and Development Program on Monitoring, Early Warning and Prevention of Major Natural Disaster (2018YFC1506000). Sarah Ineson was supported by the UK-China Research & Innovation Partnership Fund through the Met Office Climate Science for Service Partnership (CSSP) China as part of the Newton Fund.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI:https://doi.org/https://esgf-node.llnl.gov/projects/cimip6/.

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