Tropical Pacific Decadal Variability Induced by Nonlinear Rectification of El Niño–Southern Oscillation

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ABSTRACT

On the basis of 32 long-term simulations with state-of-the-art coupled GCMs, we investigate the relationship between tropical Pacific decadal variability (TPDV) and El Niño–Southern Oscillation (ENSO). The first empirical orthogonal function (EOF) mode for the 11-yr moving sea surface temperatures (SSTs) in the coupled models is commonly characterized by El Niño–like decadal variability with Bjerknes air–sea interaction. However, the second EOF mode can be separated into two groups, such that 1) some models have a zonal dipole SST pattern and 2) other models are characterized by a meridional dipole pattern. We found that models with the zonal dipole pattern in the second mode tend to simulate strong ENSO amplitude and asymmetry in comparison with those of the other models. Also, the residual patterns, which are defined as the summation of El Niño and La Niña SST composite anomalies, are very similar to the decadal dipole pattern, which suggests that ENSO residuals can cause the dipole decadal variability. It is found that decadal modulation of ENSO variability in these models strongly depends on the phase of the dipole decadal variability. The decadal changes in ENSO residual correspond well with the decadal changes in the dipole pattern, and the nonlinear dynamic heating terms by ENSO anomalies are well matched with the decadal dipole pattern.

1. Introduction

Sea surface temperatures (SSTs) in the Pacific Ocean region have distinct decadal to interdecadal variability (Mantua et al. 1997; Zhang et al. 1997; Power et al. 1999). Pacific decadal variability is characterized by subtropical gyre spatial patterns throughout the North and South Pacific that are in phase with each other and out of phase with the eastern and central equatorial Pacific (Deser et al. 2004; Han et al. 2014; Newman et al. 2016). Especially, the equatorial Pacific is the region with the largest decadal variability (Zhang et al. 1997) and plays an important role in forcing and synchronizing the decadal variability in both hemispheres (Newman et al. 2016). Therefore, understanding tropical Pacific decadal variability (TPDV) and its mechanisms is essential in understanding long-term variations in global climate.

TPDV is a complex phenomenon that includes multiple origins and interactions. Previous studies suggested that extratropical SSTs affect TPDV via equatorward ventilation (Gu and Philander 1997). Although the equatorward ventilation appears to not reach the equator (Schneider et al. 1999), the Gu and Philander hypothesis is still valid in Southern Hemisphere (Wang and Liu 2000; Luo and Yamagata 2001). Other studies suggested that the subtropical–tropical cells (STCs) modulate tropical SST anomalies on decadal time scale (McPhaden and Zhang 2002; Capotondi et al. 2005; Graffino et al. 2019). Weakening of the STCs induces the decrease in upwelling and surface warming over the tropics. The change in STCs intensity is adjusted by the low-frequency oceanic Rossby waves on decadal time scales (Capotondi et al. 2003), leading to changes in upwelling and SST over the tropics. The Rossby waves induced by tropical Pacific SST anomalies are reflected into the equatorial Kelvin waves at the western boundary and lead to thermocline depth and SST anomalies of the opposite sign (Meehl and Hu 2006).

El Niño–Southern Oscillation (ENSO), the largest interannual variability, may also induce the TPDV with its decadal modulation. Observational records show that the amplitude of the ENSO substantially changes on interdecadal time scales (Cobb et al. 2003; An 2009; Sun and Yu 2009; Li et al. 2011; Capotondi and Sardeshmukh 2017). Li et al. (2011) showed that the amplitude of
ENSO was large between the 1890s and 1900s and between the 1970s and 1990s and comparatively small between these periods and before 1890. Numerous studies have suggested that the decadal modulation of the ENSO depends on the background state over the tropical Pacific (Cobb et al. 2003; Li et al. 2011), suggesting that the decadal modulation is closely related to TPDV. For example, the warmer tropical Pacific favors the thermocline feedback rather than the zonal advection feedback, which results in a larger ENSO amplitude because of a weaker zonal SST gradient and an eastward shift in zonal wind stress (An 2009; Sun and Yu 2009).

Although Pacific decadal variability changes ENSO characteristics, the decadal modulation of the ENSO, in turn, can affect TPDV via a nonlinear rectification effect (Timmermann 2003; Rodgers et al. 2004; Choi et al. 2009; Watanabe and Wittenberg 2012), which suggests that there is a two-way interaction. In other words, TPDV can arise as an ENSO residual, suggesting one of the origins of TPDV. It might be related that the ENSO is characterized by an asymmetry in terms of spatial patterns and its intensity (Burgers and Stephenson 1999; Kang and Kug 2002; An and Jin 2004; Su et al. 2010). For example, El Niño anomalies tend to be stronger than La Niña anomalies (An and Jin 2004) and their spatial patterns are not symmetric (Kang and Kug 2002), especially in the central or eastern tropical Pacific (Capotondi et al. 2015; Timmermann et al. 2018). In addition, spatial pattern diversity among El Niño events is much stronger than that among La Niña events (Kug and Ham 2011). The existence of ENSO asymmetry implies that ENSO can rectify the background states over the tropical Pacific, so that the decadal modulation of ENSO characteristics can lead to TPDV.

Rodgers et al. (2004), for example, suggested that decadal variability of SST and isotherm depth showed a dominantly dipole pattern, resembling the residual induced by asymmetry of ENSO even if the numbers of El Niño and La Niña events are the same based on their model results. They showed that residual energy of SST rectifies the mean state due to strong asymmetries during periods of larger ENSO amplitude, consistent with previous studies using ocean general circulation model (Sun and Zhang 2006). Choi et al. (2009) proposed that the large-amplitude ENSO residuals induce surface warming over the eastern Pacific, which plays a role in amplifying ENSO variability through a positive feedback. By contrast, deepening of the mean state of the thermocline due to the surface warming causes reducing of ENSO growth rate through weakened thermocline feedback (i.e., negative feedback).

However, most previous studies have limitations because their results are based on a single model or the observational data, which are too short to clearly identify decadal variability. To overcome these limitations, the relationship between TPDV and the variability of ENSO was investigated in interactive ensemble model analysis and multimodel analysis (Yeh and Kirtman 2004; Choi et al. 2013). Choi et al. (2013) showed that two types of TPDV were associated with ENSO using GCGMs that participated in phase 3 of the Coupled Model Intercomparison Project (CMIP3). One is related to the rectification effect of ENSO with the east–west dipole structure in the tropic, and the other has spatial structure similar to ENSO. The dominant periods of both are quite similar and are interrelated, although their growing mechanisms are different.

Previous literature focused on the relationship between TPDV and ENSO variability mostly used ENSO anomalies, which also contain decadal anomalies, for calculating residuals, so we cannot precisely say whether the residual induces dipole decadal variability or decadal anomalies are reflected to the residual. In addition, the CMIP5 versions show a clear improvement in the simulation of ENSO and TPDV compared with CMIP3 versions (Polade et al. 2013) but a comprehensive analysis of the relationship between ENSO and TPDV in the CMIP5 archive has not yet been performed. Accordingly, the purpose of this study is to perform comprehensive analyses to understand the relationships between TPDV and ENSO using the multiple models that participated in CMIP5. We especially focus on the point that ENSO asymmetry is one of strong drivers of TPDV.

This paper is organized as follows. In section 2, the observation and model data used in the analysis are described. In section 3, we present TPDV and ENSO simulated by the CMIP5 models. We show that the rectification of ENSO may induce TPDV. A summary and discussion are given in section 4.

2. Data

We analyzed preindustrial simulations using the 31 climate models that participated in CMIP5. In addition to the CMIP5 models, we also included CESM1 Large Ensemble (CESM-LE) model simulations (Kay et al. 2015), which have long-term simulations (1801 years). Since we are focusing on interdecadal variability, we chose models that have an integration period of more than 200 years in the CMIP5 models. Information on the institutions that ran the models and integration periods are listed in Table 1. The Extended Reconstructed SST (ERSSTv5; Huang et al. 2017) and the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST; Rayner et al. 2003) were used to compare with the model simulation.

To define El Niño and La Niña events, we used the Niño-3.4 index (SSTA averaged over 190°E–120°W,
El Niño and La Niña events were defined when the Niño-3.4 SST during winter (November–January) belongs to the upper and lower 20% of the analyzing period, respectively, because different numbers of El Niño and La Niña events over different decadal periods may result in a residual mean state. In this case, numbers of defined El Niño and La Niña events are identical and only depend on the analyzing period. A simple summation of El Niño and La Niña composites denotes the residual, which is reflected in the background state. Prior to the analysis, linear trends were removed because several models have weak linear trends. To illustrate decadal and interdecadal variability, we applied an 11-yr running mean to eliminate interannual variability.

3. Results

a. Tropical Pacific decadal variability and ENSO

First, we conducted empirical orthogonal function (EOF) analysis on the 11-yr running mean of the tropical Pacific SST anomalies (120°E–90°W, 20°S–20°N) to
analyze the dominant decadal variability for each model. The eigenvectors against normalized PC time series of the first and second EOF modes are shown in Figs. 1 and 2, respectively. For GFDL-ESM2M, we switched the first and second modes between Figs. 2 and 1 because of pattern similarities. Interestingly, as the first EOF mode, most models yield patterns similar to the observation (Fig. 1), which is similar to the El Niño–like pattern (Power and Colman 2006), although the meridional extent is slightly broader than that of ENSO. The zonal wind and precipitation patterns associated with the first EOF mode are also similar to the ENSO-related pattern, which suggests that this mode developed via the Bjerknes air–sea interaction (not shown). The first EOF mode explains 38%–75.3% of the total decadal variance, which is also comparable with those in the observation. The first EOF mode amplitudes are model dependent. For example, the GISS-E2-R-CC model has the smallest variability, whereas MIROC has the greatest variability.

Figure 2 shows the second EOF mode for observation and each model, which explains 7%–36.7% of the total variance. The second EOF modes in the models are well separated from the remaining EOFs, based on the criteria of North et al. (1982). Unlike the first EOF mode, the spatial patterns for the second EOF mode are somehow different among models and observations. Nevertheless, we found that several models share similar patterns, as shown in Fig. 2. For instance, some models are characterized by a zonal dipole pattern (i.e., dipole decadal variability), where the equatorial eastern and western Pacific regions have opposite signs. The other models show consistently strong signals in northern off-equatorial regions, which is similar to the Pacific meridional mode (Chang et al. 2007). Previous studies have shown that the zonal dipole pattern is associated with asymmetry and decadal ENSO variability (Rogers et al. 2004; Choi et al. 2012; Atwood et al. 2017). The observational pattern also shows somewhat a zonal dipole pattern, but the negative values of the western Pacific are not very distinct and their center is located in the off-equatorial region. Since the observational data might not be sufficient for detecting decadal variability and include various signals such as the global warming, the discrepancy between the models and observations can be explained.

Note that models that show the equatorial zonal dipole pattern in the second EOF mode have a larger variance when compared with the other models. For GFDL-ESM2M, this mode explains 37.7% of the total variance. On the basis of the power spectrum analysis, both the first and second EOF modes have similar spectral peaks on a decadal-to-interdecadal time scale (not shown), which is consistent with previous study (Choi et al. 2013).

To measure how strongly each model simulates the dipole decadal variability, we defined the dipole index as the difference between the eastern (140°–100°W, 10°S–10°N; blue-outlined box) and western (140°–180°E, 10°S–10°N; red-outlined box) Pacific boxes from the eigenvectors in the second EOF mode normalized PC2. Figure 3 shows the amplitude of the dipole decadal variability for the individual models. We observed that seven models have a distinctly strong dipole index compared with the other models. GFDL-ESM2M has the largest dipole index, and most CESM series models simulate larger dipole indices. However, some GFDL and MIROC models do not necessarily simulate strong dipole indices. Hereinafter, we divided the climate models into two groups based on Fig. 3: 1) models that simulate strong dipole decadal variability (group A; 7 models) and 2) models that simulate weak dipole decadal variability (group B; 25 models).

To understand how dipole patterns in decadal variability develop in the models, we first analyzed how ENSO characteristics differ between the two groups. Figure 4 shows the SST composites for both El Niño and La Niña events. For comparison, the observed patterns are also displayed. Group A shows a larger amplitude for El Niño and La Niña SST anomalies. The center of the El Niño SST is located near 128°W, and the maximum SST anomalies are up to 2.1 K. For the La Niña composite, the center is located near 133°W. However, its amplitude is much weaker than that of El Niño. In addition, we observed that the SST anomalies extend farther into the western Pacific, which is consistent with the observed features (Kang and Kug 2002; Dommenget et al. 2013). This result suggests that there is a strong asymmetry between El Niño and La Niña that exists in these models and is consistent with previous study (Dommenget et al. 2013; Karamperidou et al. 2017).

On the other hand, group B simulates relatively weak El Niño and La Niña SST anomalies. Denoted by dots in Fig. 4, group A SST anomalies are significantly greater than group B anomalies, about 61% for El Niño and 45% for La Niña. Note that both El Niño and La Niña events are defined in the exact same way for individual models, which suggests that group B tends to simulate weak ENSO variability. The centers of the El Niño and La Niña SST anomalies are near 120°W, with similar maximum SST anomalies. This indicates that the asymmetry in group B models is much weaker than the asymmetry in group A models.

Figures 4e and 4f show the ENSO residuals, which are defined as the summation of the El Niño and La Niña composites. The residual of the group A shows a clear dipole pattern (i.e., positive in the eastern Pacific and
negative in the western Pacific), since the El Niño SST is greater in the eastern Pacific, and the La Niña SST extends westward. The dipole pattern of the model is similar to the observed one. The pattern correlation between them is about 0.7. However, the negative anomalies extend to the north and south of the positive anomaly in the observation (Fig. 4i). Interestingly, the dipole pattern is quite similar to the second EOF mode.
pattern for the decadal SST anomalies in group A (the pattern correlation coefficient is about 0.8). This suggests that the ENSO residual can contribute to the dipole decadal variability. These results are consistent with previous studies on the interaction between the ENSO variability and TPDV (Rodgers et al. 2004; Schopf and Burgman 2006; Wittenberg 2009; Watanabe and Wittenberg 2012; Atwood et al. 2017). On the other
hand, group B is also characterized by a dipole pattern, but the magnitude is very weak because ENSO asymmetry is weak (Fig. 4f).

Figure 5 shows how individual models in group A simulate El Niño and La Niña. All models in group A simulate the El Niño SST anomalies are greater than 1 K and greater for La Niña SST anomalies in the eastern Pacific. In addition, the La Niña SST anomalies are usually greater than the El Niño SST anomalies west of the international date line. This indicates that all models in group A simulate the strong asymmetry between El Niño and La Niña. Therefore, residuals are positive in the eastern Pacific and negative in the western Pacific. This similarity between models in group A supports the idea that the multimodel ensemble (MME) dipole residual is robust.

b. Rectification of ENSO on tropical Pacific decadal variability

In the previous section, we showed that the residual ENSO pattern is quite similar to the decadal dipole pattern. This suggests that the decadal modulation in the ENSO amplitude and asymmetry may lead to decadal variability over the tropical Pacific. If the residual changes on interdecadal time scales, it will generate interdecadal changes in the background state. To check this possibility, we conducted separate composite analyses of El Niño and La Niña events depending on the phase of the second EOF mode. A positive (negative) phase is defined when the PC of the second EOF mode is greater than 0.8 of its standard deviation (i.e., lower than −0.8 of the standard deviation). It should be noted that the El Niño and La Niña anomalies in positive and negative phases are calculated by removing time mean of each period, respectively. In this case, the decadal anomalies cannot affect the El Niño and La Niña anomalies, and their residuals.

Figure 6 shows the El Niño and La Niña composites for the positive and negative phases. It is clear that the El Niño and La Niña SST anomalies for the positive phase are greater than those for the negative phase. In particular, the difference in the eastern Pacific between the positive and negative phases is significantly greater for the El Niño composite. The difference between the two periods is also clear in the residual, as shown in Figs. 6c and 6g. In both phases, the residuals have dipole patterns, but the residuals are greater for the positive period. Since these residuals are reflected in the background states, the residual difference between the two phases can induce decadal changes in the background states. This pattern is very similar to skewness patterns. The models in group A simulate strong positive skewness.
in the eastern Pacific and negative skewness in the western Pacific, as expected in the El Niño and La Niña composites. The skewness becomes stronger during the positive period and weaker during the negative period. Of course, there is positive feedback between dipole decadal variability and the residual of ENSO (An 2004; Choi et al. 2009, 2013), but it should be noted that the residual was calculated after the decadal mean is removed. This suggests that these interdecadal changes in the ENSO amplitude and skewness induce the interdecadal changes in the residual, which contribute to the decadal anomalies.

Figure 7 shows the residual changes for the individual models that depend on the phase of the second EOF mode. To show the difference clearly, we defined the residual index as the difference in residuals between the eastern (140°–100°W, 10°S–10°N) and western (140°–180°E, 10°S–10°N) Pacific from Fig. 6. Every model simulates stronger residuals during the positive phase, with a significant difference at the 95% confidence level, except for the CESM1-WACCM. The MME result also shows significant differences for the residual index, which supports the idea that dipole decadal variability is related to the decadal modulation of the interannual ENSO.

The ENSO residual may rectify the background states (Timmermann 2003; Rodgers et al. 2004; Sun and Zhang 2006; Choi et al. 2009; Watanabe and Wittenberg 2012; Atwood et al. 2017); that is, the residuals shown in Fig. 5 are reflected in the mean states of the individual models. Likewise, interdecadal changes in the residual contribute to the background state in each decade, which induces interdecadal changes of the mean state over the tropical Pacific. In other words, the decadal modulation of the ENSO variability contributes to decadal variability over the tropical Pacific, which is known as the “rectification effect.” Since group A models simulate strong decadal modulation of ENSO variability, they have a distinctive dipole decadal variability. On the other hand, group B models simulate weak ENSO variability and decadal modulation such that we scarcely detect the dipole pattern in the decadal variability.
To understand how the ENSO anomalies affect the decadal anomalies, we calculated nonlinear dynamic heating (nonlinear advection terms) of ENSO anomalies (Jin et al. 2003). The nonlinear dynamic heating was defined as follows:

$$\text{Nonlinear dynamic heating} = - \left[ u \frac{dT'}{dx} + v \frac{dT'}{dy} + H(w)w'T' - T'_\text{sub} \right] / 30,$$

where $u'$, $v'$, and $w'$ denote the zonal, meridional, and vertical ocean currents, respectively, and $T'$ and $T'_\text{sub}$ denote the surface and subsurface ocean temperature. The subsurface ocean temperature and vertical velocity are values at 50 m, and other variables are defined as vertical average from the ocean surface to 50 m. The anomalies were calculated after the decadal mean is removed, and $H(x) = \begin{cases} 0, & x < 0 \\ 1, & x \geq 0 \end{cases}$ is the step function to ensure that only the vertical upward motion affects upper ocean temperature.

Here, we show the results of the CESM-LE simulation since sufficient ocean variables are available for the ocean budget analysis. Figure 8 shows the nonlinear dynamical heating depending on the phase of the decadal dipole pattern. It is clear that the nonlinear dynamical heating shows the dipole pattern. This pattern mostly resulted from the nonlinear zonal advection term (not shown). It is evident that the nonlinear dynamical heating is greater for the positive phase of the decadal dipole pattern than that for the negative phase, so that their difference shows the dipole pattern. Since the nonlinear terms are directly rectified into the mean state, the difference of the nonlinear terms between the positive and negative phases lead to the decadal anomalies. Once the nonlinear term generates decadal anomalies, the dipole pattern can be further enhanced via air–sea interaction.

To sum up, we checked the relationship between the strengths of the dipole decadal variability and decadal modulation of ENSO based on the intermodel space. The dipole decadal variability is defined by the difference in the mean SST gradients between two phases. Here, the mean SST gradient is calculated as the difference in the mean SST between the east ($140^\circ$–$100^\circ$W, $10^\circ$S–$10^\circ$N) and west ($140^\circ$–$180^\circ$E, $10^\circ$S–$10^\circ$N). As shown in Fig. 9, it shows a strong linear relationship; that is, the strong residual difference between the positive and negative phases is closely related to strong dipole decadal variability. The correlation coefficient is 0.90, which is significant at the 99% confidence level. In addition, all models in group A have a larger residual difference, with a difference in the mean state gradient. This result strongly supports the hypothesis that the
ENSO rectification effect is responsible for dipole decadal variability over the tropical Pacific.

4. Summary and discussion

In this study, using a total of 32 model simulations, we examined TPDV induced by the decadal modulation of the ENSO. The largest decadal variability in the tropical Pacific, represented by the first EOF mode, is the El Niño–like warming pattern, wherein most models simulate very similar patterns. In addition to this pattern, some models also have strong variability that shows zonal dipole patterns in the second EOF mode. Herein, we have suggested that, to a large extent, this dipole...
Decadal variability originates from the decadal modulation of ENSO amplitude and asymmetry. Accordingly, we classified a total of 32 models into two groups, of which one group is for models that simulate strong dipole patterns (group A; 7 models) and the other simulates weak dipole patterns (group B; 25 models). Dipole decadal variability is more evident for models that have strong ENSO variability. The ENSO residual shows a similar pattern to the dipole decadal pattern, and its decadal changes are consistent with the phase of the dipole decadal pattern. In addition, it is shown that the nonlinear dynamic heating of ENSO anomalies plays a role in rectifying the decadal dipole variability. Although we showed only single model result for the nonlinear dynamic heating, it supports our hypotheses that ENSO residuals can rectify the background states.

Although our arguments are based on model simulations, our results may have important implications on the observed decadal variability. Throughout the historical record, the ENSO amplitude has changed considerably on interdecadal time scales (Cobb et al. 2003; An 2009; Sun and Yu 2009; Li et al. 2011; Capotondi and Sardeshmukh 2017). In addition to the amplitude, ENSO asymmetry has considerably changed (An and Wang 2000). This implies that ENSO decadal modulation can also induce the dipole decadal variability that we suggested here based on the climate models. However, the dipole decadal pattern is indistinct for identical EOF analyses of the observational data. The observational data may be relatively too short to separate the two modes, and various signals, which include global warming, are contaminated by internal decadal variability.

Nevertheless, there is clear evidence that ENSO modulation induces decadal variability over the Pacific. An (2009) observed the zonal dipole pattern of different thermoclines between the pre-1980 and post-1980. Such decadal thermocline variability is associated with changes in the mean state along the equator, which is related to the asymmetry of ENSO variability at the subsurface based on SODA reanalysis data (Dewitte et al. 2009). Sun and Yu (2009) suggested that the decadal modulation of the ENSO amplitude and asymmetry (i.e., the ENSO rectification) could induce the observed variability in the decadal dipole in the tropical Pacific.

To further show that the ENSO asymmetry and its decadal modulation contribute to TPDV, we conducted two composite analyses of the decadal SST (11-yr moving mean SST) depending on the decadal variation of the skewness of Niño-3 SST for the period of 1950–2017. Strong or weak phases are respectively defined as when the 11-yr sliding skewness of Niño-3 SST is greater than 0.8 standard deviation or lower than −0.8.
standard deviation. **Figure 10** shows the difference of mean state SST between two periods (strong − weak). The observation data show that the eastern and western Pacific have opposite signs, whose pattern is related to ENSO asymmetry related to the decadal pattern. We did the same analysis with the model data (Figs. 10c,d), and group A shows a clear dipole pattern, which is similar to the second EOF mode, supporting that it is related to ENSO asymmetry. However, group B shows only a weak signal. It is meaningful that both observation and group A models show the zonal dipole pattern, suggesting that they share a similar ENSO–TPDV relation. However, the difference between the observation and group A is also clear. While the observation has strong signals in the eastern Pacific, group A has strong signals in the western Pacific, possibly due to the model’s common bias in simulating ENSO anomalies too far westward. Nevertheless, it strongly supports that ENSO residuals also contribute to TPDV in the observation, as in group A.

In addition, understating the first EOF mode, which explains the largest decadal variability in the Pacific, needs to be examined first. Although the first mode appears to be associated with the Bjerknes feedback in the tropical Pacific, interbasin interactions between the Indian and Atlantic Oceans can modulate El Niño–like decadal variability. For example, SST warming in the north tropical Atlantic can induce cooling in the equatorial Pacific via an atmospheric teleconnection along the Pacific intertropical convergence zone (Ham et al. 2013). This Atlantic–Pacific connection acts to yield not only interannual but also decadal variability (Li et al. 2016). Warming in the Atlantic drives easterly wind anomalies over the Indo-western Pacific, which intensifies the La Niña–type response in the tropical Pacific via the Bjerknes feedback. Equatorial Pacific surface cooling can explain the recent global hiatus (Kosaka and Xie 2013), which may originate from Atlantic warming (Chikamoto et al. 2016). In addition, the Indian Ocean is connected with the Pacific through an atmosphere and oceanic teleconnection (Latif and Barnett 1995). Cold

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![FIG. 9. Scatter diagram between the residual index difference and differences in the mean SST gradient between two periods in an individual model.](image)

**Fig. 9.** Scatter diagram between the residual index difference and differences in the mean SST gradient between two periods in an individual model.

![FIG. 10. Difference of mean state SST between two periods in (a) ERSST, (b) HadISST, (c) group A, and (d) group B. A strong or weak phase is respectively defined when the 11-yr sliding skewness of Niño-3 SST is greater than 0.8 of its standard deviation or lower than −0.8 of its standard deviation.](image)

**Fig. 10.** Difference of mean state SST between two periods in (a) ERSST, (b) HadISST, (c) group A, and (d) group B. A strong or weak phase is respectively defined when the 11-yr sliding skewness of Niño-3 SST is greater than 0.8 of its standard deviation or lower than −0.8 of its standard deviation.)
anomalies in the eastern Indian Ocean induce anomalous westerly winds in the western Pacific, which contribute to eastern Pacific warming (Annamalai et al. 2010; Luo et al. 2010). Therefore, further study is needed to examine the role of interbasin interaction on tropical Pacific variability.

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