On the Bias in Simulated ENSO SSTA Meridional Widths of CMIP3 Models

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ABSTRACT

The fidelity of coupled climate models simulating El Niño–Southern Oscillation (ENSO) patterns has been largely overlooked. Utilizing the preindustrial control simulations of 11 coupled climate models from phase 3 of the Coupled Model Intercomparison Project (CMIP3), it was shown that the simulated width of the ENSO SSTA is only about two-thirds of what is observed. Through a heat budget analysis based on simulations and ocean reanalysis datasets, it is demonstrated that the SSTA outside of the equatorial strip is predominantly controlled by the anomalous meridional advection by climatological currents and heat-flux damping. The authors thus propose a simple damped-advective conceptual model to describe ENSO width. The simple model indicates that this width is primarily determined by three factors: meridional current, ENSO period, and thermal damping rate. When the meridional current is weak, it spreads the equatorial SSTA away from the equator less effectively and the ENSO width thus tends to be narrow. A short ENSO period allows less time to transport the equatorial SSTA toward the off-equatorial region, and strong damping prevents expansion of the SSTA away from the equator, both of which lead to the meridional width becoming narrow. The narrow bias of the simulated ENSO width is mainly due to a systematical bias in weak trade winds that lead to weak ocean meridional currents, and partly due to a bias toward short ENSO periods.

1. Introduction

The El Niño–Southern Oscillation (ENSO), generated through ocean and atmosphere interaction over the tropical Pacific, is one of the most important climatic phenomena with profound global impact. Great progress has been made in understanding, simulating and predicting ENSO (e.g., Bjerknes 1969; Wyrtki 1975; Rasmusson and Carpenter 1982; Cane and Zebiak 1985; Schopf and Suarez 1988; Battisti and Hirst 1989; Jin 1997a,b; Neelin et al. 1998; Wallace et al. 1998; Wang and Picaut 2004; Jin et al. 2006; Bejarano and Jin 2008). Over the past two decades, the ability of coupled general circulation models (CGCMs) to simulate the ENSO phenomenon has been evaluated in terms of its amplitude, periodicity, spatial pattern, and warm/cold asymmetry (e.g., Neelin et al. 1992; Delecluse et al. 1998; Latif et al. 2001; AchutaRao and Sperber 2002, 2006; Davey et al. 2002; Capotondi et al. 2006; Guilyardi 2006; Lin 2007; Zhang et al. 2010).

Despite steady progress in modeling ENSO salient features and its global impact, the state-of-the-art CGCMs have serious systematic errors in background climate and interannual variability (Guilyardi et al.
We have chosen to use simulations of 11 coupled models from the World Climate Research Program (WCRP) CMIP3 multimodel data center. Full details about the models can be found on the Intergovernmental Panel on Climate Change (IPCC) website (http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php). These 11 models are CCSM3, CNRM-CM3, ECHAM5/MPI-OM, FGOALS-g1.0, GFDL-CM2.0, GFDL-CM2.1, GISS-EH, INGV-ER, IPSL CM4, MRI-CGCM2.3.2, and PCM. Two reasons are considered to select these 11 models. First, we examine the models with amplitude exceeding a half of the observed. When the simulated ENSO amplitude is too weak, its meridional pattern is more prone to noise contamination. So, the models such as the GISS-AOM and GISS-ER are not considered because of ENSO amplitude being too weak. Second, we examine the models with ENSO variability located over the eastern equatorial Pacific east of 180°. These models with the ENSO variability shifted too much westward (e.g., CSIRO Mk3.5 and INM-CM3.0) are not selected because the models tend to have a large cold bias in climate mean state.

The data variables used in this study are monthly mean fields including SST, zonal wind stress, ocean currents, subsurface sea temperature, net shortwave and longwave radiation at the surface, and surface latent and sensible heat fluxes. Among the 11 models, only seven provide all subsurface variables and eight provide all data of surface heat fluxes. Therefore, seven and eight models’ simulations are used in the oceanic heat transportation and surface heat flux analyses, respectively. We choose the last 50 years’ simulation results from the picntrl scenario to analyze the meridional width of ENSO.

The observation-based data are monthly SST (1950–2007) from the Hadley Center Sea Ice and Sea Surface Temperature (HadISST) data provided by the Met Office Hadley Center (Rayner et al. 2003). The zonal wind stress is taken from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) data (1958–2001) (Simmons and Gibson 2000). The ocean currents and subsurface sea temperature data are an ocean reanalysis from the Simple Ocean Data Assimilation (SODA) dataset (1950–2007) (Carton et al. 2000; Giese and Ray 2011). In generating this dataset, surface boundary conditions from version 2 of the Twentieth-Century Reanalysis (20CRv2) were utilized to force a global ocean model and all hydrographic variables available and SST data were assimilated. Monthly surface heat fluxes are derived from the National Centers for Environmental Prediction.
(NCEP–Department of Energy (DOE) Reanalysis 2 (R2) data (1979–2007; http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html). The observations represent the twentieth-century run (20C3M) rather than the pinctrl scenario. A similar evaluation is also conducted for the CMIP3 20C3M simulations and the results are nearly the same (not shown).

In the observations, a threshold of 0.6 for the standardized SSTA over the eastern equatorial Pacific (5°N–5°S, 180°–90°W) approximately corresponds to 0.5°C SSTA, which is usually used to define the ENSO events. This threshold is also used to qualify the ENSO events in coupled models. It is noted that the results are not sensitive to different threshold values within a reasonable range. The ENSO composites are obtained by regarding the peak month as ENSO mature phase in the coupled models. In the observations, ENSO events are identified based on the definition of the Climate Prediction Center (CPC) and ENSO composites are averaged by calendar months. To take a rough measurement of the meridional pattern of ENSO, we first take a zonal average (180°–90°W) of SSTA and then normalize each ENSO event dividing by the maximum SSTA in the central/eastern equatorial Pacific (3°S–3°N, 180°–90°W) to ensure the measure is independent of ENSO amplitude. We define an $e$-folding meridional width for ENSO as the width by which this normalized meridional profile of ENSO SSTA reaches $1/e$. The values of the meridional width are the mean of the warm and cold ENSO phases and the analyses are focused on the ENSO mature phase [September–February (SONDJF)]. To focus on the interannual variability associated with ENSO, a 2–7-yr bandpass filter is applied to the SSTA using the second-order Butterworth filter designed following Parks and Burrus (1987). Regression analysis is also used to analyze the ENSO SSTA meridional width.

3. Meridional width of ENSO SSTA in coupled models

To depict the basic nature of the observed and model simulated patterns of SSTA of ENSO, we show in Fig. 1 the SSTA patterns regressed upon the equatorial SSTA over the central and eastern Pacific (3°S–3°N, 180°–90°W). The observed SSTA pattern has maximum values at the equator from the coast of South America to the date line, and the values decrease away from the equator to both the north and south. The SSTA field extends to about 7°N and above 10°S based on a 0.4 (roughly $1/e$) contour. All of the models are capable of simulating the observed spatial pattern to a certain degree, but considerable discrepancies can be seen between the models and observation, in terms of both zonal and meridional structures. Compared to the observed pattern, most of the CGCMs have the maximum SSTA away from the coast of South America and the SSTA at the equator extending farther westward, as mentioned in previous studies (e.g., Capotondi et al. 2006). Another discrepancy is that the modeled SSTA is too tightly confined to the equator with respect to the observations. The meridional width of SSTA is systematically narrower in all the models than the observed. The multimodel averaged SSTA spreads only toward about 5°N and 5°S based on a 0.4 contour. Different models exhibit different behaviors in the meridional width of SSTA. Some models, such as the two GFDL models, exhibit a relatively large meridional width, whereas some models such as the CCSM3, FGOALS-g1.0, and GISS-EH have small meridional widths. These results are robust and are almost the same using unfiltered data (not shown).

To illustrate the time evolution of SSTA in the meridional structure, we show the latitude and time-lag section of SSTA averaged over 180°–90°W in Fig. 2. The month 0 on the abscissa denotes the ENSO mature phase at which the maximum SSTA is reached at the equator. Negative (positive) months are before (after) the ENSO peak. In the observation, at about 8 months before the ENSO peak, the SSTA start to develop near the equator and expand toward the off-equatorial region. After the ENSO peak, the off-equatorial SSTA slightly shrinks back to the equator during the decay phase. The observed ENSO event can persist for as long as 16 months. Despite the difference in ENSO durations, almost all models have similar evolutions.

To quantitatively analyze the meridional width of SSTA of ENSO, the $e$-folding scale described in section 2 is used to define the meridional width. The observed meridional widths of ENSO SSTA are about 22 and 16.5 degrees in latitude for the periods 1950–76 and 1977–2007, respectively (Fig. 3). The observed meridional width of ENSO for entire period of 1950–2007 is near 19 degrees of latitude. The meridional widths of ENSO simulated in the models are systematically narrower than those in the observation, with large variation between models (Fig. 3). The ensemble mean of the simulated ENSO meridional width is about 12 degrees of latitude, which is about only two-thirds of the value observed. This serious bias may induce a weak response of convection over the off-equatorial warm water of the eastern Pacific underlying the intertropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ) during ENSO episodes. Further, the unrealistic simulation in the local convection possibly have consequences in simulating ENSO teleconnections and thus ENSO-associated climate impact over remote regions, which is a subject that needs to be investigated in future.
4. Dynamical processes controlling the meridional width of ENSO SSTA

To better understand what controls the meridional width of ENSO SSTA, we here conduct heat budget analyses for mixed layer temperature using both ocean reanalysis dataset and model simulations. This heat budget analysis will allow us to identify the relative importance of different dynamical processes for SSTA anomalies outside of the narrow equatorial upwelling strip during the ENSO cycle. We follow the same approach of heat budget analysis employed in a number of...
FIG. 2. Lag/lead regression of zonal mean (180°–90°W) SSTA upon the SSTA over the central and eastern equatorial Pacific (3°S–3°N, 180°–90°W). The positive (negative) numbers at the x axis indicate the months by which the equatorial eastern Pacific SSTA leads (lags) the anomalous distribution fields.
studies for ENSO (e.g., McPhaden 2002; An and Jin 2004; Zhang et al. 2007; Yu et al. 2010) and utilize the following anomalous budget equation for mixed layer temperature:

\[
\frac{dT_a}{dt} = -U_c \frac{dT_a}{dx} - U_a \frac{dT_a}{dx} - V_c \frac{dT_a}{dy} - V_a \frac{dT_a}{dy} - V_a \frac{dT_c}{dy} - H(W) \left( W_c \frac{dT_a}{dz} + W_a \frac{dT_c}{dz} + W_a \frac{dT_a}{dz} \right) + \frac{Q_a}{\rho_o C_P H} + R.
\]

The subscript \( c \) indicates the climatological monthly mean and the \( a \) denotes monthly anomaly with respect to the climatological mean seasonal cycle; \( T, U, \) and \( V \) respectively represent the oceanic temperature and zonal and meridional current velocities in the mixed layer (top 45 m). Vertical current velocity (\( W \)) is calculated at the bottom of the mixed layer. The function \( H(W) \) is zero for \( W < 0 \) and 1 for \( W > 0 \). We used \( Q_a \) to denote the anomalous net surface heat flux, which is the sum of the shortwave and longwave radiation and sensible and latent heat flux. Also, \( \rho_o \) and \( C_P \) are the density and heat capacity of the seawater, respectively. The last term \( R \) is the residual term that includes contributions associated with the diffusion and submonthly time scales, such as the tropical instability waves (TIWs).

To compute this heat budget in meridional structure associated with ENSO cycle, we first calculate each term on grids based on monthly fields, and then conduct a zonal average over \( 180^\circ - 90^\circ W \). Finally, the lag/lead regression of each term is computed on the equatorial region. This term is very small at the equator because of near-zero mean meridional currents. The meridional advection associated with the anomalous temperature and mean currents plays an important role on expanding SSTA away from the equator but it makes almost no contribution to the ENSO phase transition because the term is largely in phase with the ENSO cycle. The net surface heat flux has a negative feedback for the SSTA not only at the equator but also over the off-equatorial region (Fig. 4i). With respect to the terms as discussed...
Fig. 4. Lag/lead regression of each term of zonal mean (180°–90°W) heat budget upon SSTA over the central and eastern equatorial Pacific (3°S–3°N, 180°–90°W): (a) \(\frac{dT_a}{dt}\), (b) \(-U_c\frac{dT_a}{dx}\), (c) \(-V_c\frac{dT_a}{dy}\), (d) \(-U_a\frac{dT_c}{dx}\), (e) \(-V_a\frac{dT_c}{dy}\), (f) \(-W_c\frac{dT_a}{dz}\), (g) \(-W_a\frac{dT_c}{dz}\), (h) nonlinear term, and (i) net heat flux.
tendency is again dominated by the term \( V_c (dT_a/dy) \) and surface heat flux in models. The simulated \( V_c (dT_a/dy) \) term is in phase with the ENSO cycle, which is large in the off-equatorial region but vanishes near the equator. Therefore, the term \( V_c (dT_a/dy) \) is the dominant term in expanding the SSTA away from the equator in the model simulations.

5. A damped-advective conceptual model for ENSO meridional width

The SODA data and CMIP3 models consistently exhibit the dominance of the meridional advection of the anomalous temperature by the mean currents. On the basis of the heat budget analysis, we propose a simple thermal damped–advective model for SSTA evolution over the off-equatorial region as follows:

\[
\frac{dT_a}{dt} + V_c \frac{dT_a}{dy} + \alpha T_a = 0, \tag{2}
\]

where \( \alpha \) denotes a damping rate associate with negative heat-flux feedback. This type of simple model has been used in earlier studies in a different context (Saravanan and McWilliams 1998; Niiler et al. 2004) and was specifically used to model the meridional SSTA structure by Zhang et al. (2009).

The zonal and vertical advective feedback essential for ENSO growth and phase transition dynamics in the equatorial upwelling strip is intentionally excluded in this simplified model, which is only applicable over the off-equatorial region of a few degrees away from the equator. The ENSO cycle thus will be prescribed as the equatorial boundary condition of this model and for simplicity we will consider a simple sinusoidal ENSO cycle as follows:

\[
T_a(y = 0, t) = Ae^{i\omega t} + cc, \tag{3}
\]

where \( A \) indicates the ENSO amplitude at the equator and can be approximated as a constant because of the normalization of the ENSO amplitude, \( \omega \) is an ENSO frequency, and \( cc \) stands for the complex conjugate of the term in front of it.

With the given simple boundary condition in (3), we find that the SSTA \( T_a \) of Eq. (2) can be expressed as \( T_a = \tilde{T}(y)e^{i\omega t} + cc \). The meridional structure of SSTA pattern \( \tilde{T}(y) \) can be expressed as

\[
\tilde{T}(y) = Ae^{-\int [(\alpha + i\omega)v(y)]dy} + cc \approx Ae^{-[(\alpha + i\omega)V]y} + cc, \tag{4}
\]
Fig. 6. Meridional evolution of regressed SSTA tendency and $-V_c(dT_a/dy)$ in models.
where $V$ is the meridional mean of $V(y)$. According to this simple solution, the meridional width of ENSO SSTA pattern is controlled by the spatial decay scale ($\alpha/V$) and the “wavenumber” ($\omega/V$). The mean meridional current $\overline{V}$, frequency $\omega$, and damping rate $\alpha$ are three key factors that control the ENSO meridional width. Strong (weak) meridional currents tend to favor a wide (narrow) meridional width of ENSO SSTAs because it becomes relatively more (less) effective to transport the SSTAs at the equator toward the off-equatorial region. For ENSO with a long (short) period, there is relatively more (less) time to spread the SSTAs away from the equator by the meridional advection before it changes its phase, and thus the ENSO meridional width becomes wide (narrow). The damping rate tends to limit ENSO meridional width—that is, strong (weak) damping leads to narrow (wide) ENSO meridional width. Thus, a relatively strong (weak) mean meridional current ($\overline{V}$), a relatively long (short) ENSO period ($\omega^{-1}$), and a relatively weak (strong) damping rate ($\alpha$) can give rise to a relatively wide (narrow) meridional width of the ENSO SSTAs pattern.

In solution (4), the damping rate is estimated as $0.75 \times 10^{-7}$ s$^{-1}$ through regression of the net surface heat flux upon the local SST over the off-equatorial central and eastern Pacific. The meridional currents are approximated as $9$ cm s$^{-1}$ based on the climatological surface current of the SODA data. The observed ENSO frequency $\omega$ is specified as $0.25$ yr$^{-1}$ as a rough count. Based on these parameters in Eq. (4), the SSTA meridional structure can be computed and compared to the observed result by using the SSTA amplitude normalized to $1^\circ$C at the equator (Fig. 7). It is clear that the SSTA meridional structure calculated from the simple conceptual model is in good agreement with observations. In the observation, the zonal (180°–90°W) averaged SSTAs are regressed upon the central and eastern equatorial Pacific (3°S–3°N, 180°–90°W), and the meridional pattern is very similar to the composite structure associated with ENSO events. The conceptual model captures the observed meridional structure of the SSTAs very well during ENSO mature phase, in particular south of the equator. This illustrates that the simple conceptual model captures dominant processes that control the meridional structure of ENSO. Small differences between the conceptual model and observation mainly appear north of the equator, 5°N. The observed width is about 18 degrees of latitude whereas the simulated width in the conceptual model is about 20 degrees of latitude. It should be noted that this degree of agreement is adequate for the simple model given that it only considers the main effects for the meridional structure. Other processes may have an impact on SSTA meridional extent. For example, a significantly stronger TIW north of the equator compared to that south of the equator (e.g., Yu and Liu 2003) may contribute to asymmetry in meridional extent of SSTAs, and this more complicated process is not included.

6. Sources for the bias in simulated ENSO width

According to the discussion in section 4 and conceptual model proposed in section 5, the mean meridional currents, ENSO periods (or frequency), and damping rate are the three dominant factors that control the meridional width of ENSO SSTAs. Here, we will investigate how these factors may affect the simulated ENSO width in different models. In the study by Zhang et al. (2009), it was shown that strengthened trade winds can increase the meridional width of ENSO because strengthened trade winds lead to enhanced meridional currents. To depict the relation between the trade strength and the meridional width of ENSO SSTAs in the coupled models, we plot the climatic zonal wind stress over the central to eastern equatorial Pacific (5°S–5°N, 180°–90°W) against the ENSO meridional width (Fig. 8). The observed value is also shown in the diagram as the reference. Comparing the composites for the two episodes before and after 1976, we find that a weakened trade wind indeed corresponds to a reduced ENSO meridional width during the second episode. Moreover, the modeled ENSO width has a significantly negative correlation ($-0.65$) with the intensity of the zonal wind stress. The significant negative relation in the models indicates that the stronger zonal wind stress favors an occurrence of the wider ENSO SSTAs, and vice versa, which is consistent with the theoretical prediction of the simple thermal damped–advective model that we have
proposed in section 5. In most models, the modeled trade winds are smaller than that is observed over the central and eastern equatorial Pacific. Of the 11 models, 8 models have smaller trade wind stress in this particular region compared to observations over the period 1950–2007. The weakened trade winds and thus weakened Ekman currents in models are less effective to spread the SSTA away from the equator. Therefore, the weakened trade winds constitute one main reason for the systematically narrow bias in the simulated meridional width of ENSO SSTA.

We also examine how the ENSO period influences the meridional width of ENSO SSTA in the models. Figure 9 displays the scatterplot of the ENSO period and meridional width in models. The ENSO period is estimated from the power spectrum of the SSTA over $5^\circ$S–$5^\circ$N, $180^\circ$–$90^\circ$W, which is the time scale corresponding to the maximum power. Stevenson et al. (2010) suggested that a minimum of 250 model years is needed to robustly assess ENSO characteristics. Here, the rough evaluation based on a short period is used to qualitatively analyze the relation of ENSO period and meridional width. There is a positive correlation (0.50) between the simulated periods and the meridional widths of ENSO across the models (Fig. 9). The simulated meridional width tends to increase as the ENSO period increases. The simulated ENSO periods in most models are shorter than the observed data. The spectra peak at about 4 years in the observation, whereas the average modeled period is only 3 years. Therefore, the short ENSO period in models could be another factor in the systematical narrowness of the ENSO meridional width. However, we are aware of the studies (e.g., Capotondi et al. 2006) indicating that ENSO period depends on the meridional width of the zonal wind stress over the central equatorial Pacific as a response to ENSO SSTA. ENSO theory, such as recharge oscillator theory (Jin 1997b, 2001), predicts that a wide zonal wind stress response to ENSO SSTA will involves discharging/recharging the heat content in a wide equatorial basin, and thus lead to a slow turn around or longer period for ENSO. Our advective conceptual model in section 5 suggests that this longer period in turn will lead to a wider width for ENSO SSTA. A wide SSTA may contribute to a wider zonal wind response, and therefore the relation between ENSO width and period shown in Fig. 9 may be not entirely due to the process captured by the conceptual model.

The relation of the damping rate and ENSO meridional width is displayed in Fig. 10. The method used for evaluating the damping rate is the same as that used in Fig. 7. The scatterplot does not show a relation between the damping rate and ENSO meridional width in eight of the models available. The damping rate in models is weaker compared to the observed data, which is similar to the study by Yu et al. (2011) based on SST–heat flux covariability. According to Eq. (4) and Fig. 10, the weaker damping favors relatively wider meridional width of ENSO. However, the simulated meridional width of ENSO is narrower than observed, which suggests that the weak damping in models may not be the reason for the narrow bias of ENSO SSTA.

To identify the importance of different factors for the narrow bias of the simulated ENSO width, the meridional structures are computed based on the parameters.
estimated from the coupled models using Eq. (4). In Fig. 11, the solid black line is based on the observed parameters \( V = 9 \text{ cm s}^{-1}, \omega^{-1} = 4 \text{ yr}, \) and \( \alpha = 0.75 \times 10^{-7} \text{ s}^{-1} \), as is the case in Fig. 7. The solid red line is calculated based on the modeled parameters \( (V = 5 \text{ cm s}^{-1}, \omega^{-1} = 3 \text{ yr}, \) and \( \alpha = 0.5 \times 10^{-7} \text{ s}^{-1} \). According to the e-folding definition, the modeled ENSO meridional width is about 13 degrees of latitude, similar to the models’ ensemble in Fig. 3. The modeled meridional width is 7 degrees of latitude narrower than the observed, which is in agreement with the difference between the models and observations. We then used simulated meridional currents, ENSO period, and damping rate to replace the three observed parameters. If only using the modeled meridional currents (dashed green), the meridional width obtained by the simple conceptual model is close to the actual width simulated in models, which indicates that the discrepancy in the meridional currents is primarily responsible for the systematical bias in the models. Taking the modeled ENSO periods (dashed yellow) into consideration adds little change, suggesting that it plays a less important role in controlling the ENSO meridional width than the mean meridional current. Based on the modeled damping rate (dashed blue), the meridional width should be larger than the observed, which suggests that the weak damping rate in the model is not responsible for the narrow bias of ENSO width.

7. Concluding remarks

This study assesses the meridional width of ENSO SSTA simulated in the 11 CMIP3 coupled models. The meridional widths of ENSO SSTA in the models are systematically narrower than observational data. Using the SODA and coupled models’ data, the heat budget analyses of the mixed layer temperature indicate that the meridional advection of the anomalous temperature by the climatological currents \( (V_c, dT_a/dy) \) is the dominant term that controls the meridional width of ENSO SSTA. We proposed a simple thermal damped–advective conceptual model for SSTA outside the equatorial strip to describe the meridional structure of ENSO SSTA. This model only includes the meridional advection of the anomalous temperature by the climatological currents and negative feedback from surface net heat flux. It has a build in ENSO cycle that is specified as the model’s boundary condition at the equator. The simple conceptual model captures the observed and model simulated meridional width of ENSO SSTA. Based on the simple model, three factors (i.e., the meridional current \( V_c \), ENSO period \( \omega^{-1} \), and damping rate \( \alpha \)) have been identified as essential in controlling the meridional width of ENSO SSTA. A stronger meridional current, a longer ENSO period, and a weaker damping rate all favor a wider meridional width of ENSO SSTA.

The weak climatic zonal wind stress in the eastern equatorial Pacific in most models is the major reason for the narrow bias of the simulated ENSO meridional width. Another contributing factor for the narrow bias is that the ENSO periods simulated in most models are shorter than the observation. The thermal damping rate due to negative heat-flux feedback in the models is generally weaker than in the observations, which should
have favored a wider meridional width of ENSO SSTA and therefore is unlikely to be the cause of the narrow bias. Other physical processes in addition to the factors mentioned above, such as the eddy mixing due to high-frequency variability (e.g., TIW), may also contribute to the narrow bias in ENSO SSTA meridional width but are beyond the scope of this study.

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