Deciphering the Role of Ocean Dynamics in Equatorial Pacific Decadal Variability

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Abstract

Equatorial Pacific decadal variability (EPDV) modulates global climate. Although EPDV is suggested to be generated by both air-sea thermodynamically coupled slab ocean models (SOM) and fully coupled dynamic ocean models (DOM), the reason of EPDV simulated by the two distinct hierarchies of models remains unclear. This ambiguity arises from a gap in the dynamical framework between SOM and DOM. To fill the gap, we conducted a novel experiment (Clim-tau) that retains only the effects of thermodynamic coupling and mean ocean current on EPDV (without anomalous ocean current). We showed that in Clim-tau, thermodynamic-driven EPDV as in SOM is largely damped by equatorial Pacific mean upwelling; whereas involving anomalous ocean current as in DOM, the damped EPDV will be further amplified. Finally, we discussed the role of ocean dynamics in the observed EPDV. Our study highlights that SOM may misinterpret the physical mechanisms in the regions where ocean dynamics is important.

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Key Points:

- Thermodynamic-driven EPDV is primarily damped by equatorial Pacific mean upwelling.
- The damped EPDV will be further amplified by anomalous ocean current.
- Slab ocean models may misinterpret the physical mechanisms in the regions where ocean dynamics is important.

Abstract

Equatorial Pacific decadal variability (EPDV) modulates global climate. Although EPDV is suggested to be generated by both air-sea thermodynamically coupled slab ocean models (SOM) and fully coupled dynamic ocean models (DOM), the reason of EPDV simulated by the two distinct hierarchies of models remains unclear. This ambiguity arises from a gap in the dynamical framework between SOM and DOM. To fill the gap, we conducted a novel experiment (Clim-τ) that retains only the effects of thermodynamic coupling and mean ocean current on EPDV (without anomalous ocean current). We showed that in Clim-τ, thermodynamic-driven EPDV as in SOM is largely damped by equatorial Pacific mean upwelling; whereas involving anomalous ocean current as in DOM, the damped EPDV will be further amplified. Finally, we discussed the role of ocean dynamics in the observed EPDV. Our study highlights that SOM may misinterpret the physical mechanisms in the regions where ocean dynamics is important.

Plain Language Summary

The tropical Pacific impacts global climate. Decadal variability of tropical Pacific sea surface temperatures (SST) in the equatorial belt features an El Niño/Southern Oscillation-like SST pattern, which is termed equatorial Pacific decadal variability (EPDV) in this study. Previous studies suggested that EPDV can be simulated by both simple air-sea thermodynamic coupled models and more realistic fully coupled models; yet, the reason that it can be simulated by the two different complexities of models remains unclear. To decipher this ambiguity, we conducted an intermediate coupled model experiment, demonstrating that the above ambiguity is attributed to the absence of the negative contribution from mean ocean current and positive contribution from anomalous ocean current in the thermodynamic coupled models. We highlight that anomalous ocean current could be the main driver for EPDV in the real world. Our study cautions that thermodynamic coupled models may mislead the interpretation of real physical mechanism in the regions where ocean dynamics is active.

1 Introduction

In the tropical Pacific, the El Niño-Southern Oscillation (ENSO) is the dominant mode of ocean-atmosphere coupled variability on interannual timescales (Timmermann et al., 2018). Additionally, the tropical Pacific also exhibits prominent ENSO-like variability on decadal timescales, featuring meridionally broad sea surface temperature anomalies (SSTAs) in the central-eastern Pacific (Chen & Wallace, 2015; Zhang et al., 1997). In this study, we focus on the ENSO-like variability in 5°S-5°N equatorial Pacific, which is termed equatorial Pacific decadal variability (EPDV). The EPDV has a profound impact on global climate. Specifically, the EPDV modulates the rate of global mean surface temperature, resulting in the acceleration/slowdown of the global warming rate (England et al., 2014; Kosaka & Xie, 2013, 2016; Yang et al., 2020). Therefore, understanding the dynamical process of the EPDV is crucial for improving the prediction of EPDV and the global climatic effects.

Unlike ENSO that originates from air-sea dynamic coupling (Timmermann et al., 2018), the viewpoint supported by fully coupled dynamic ocean models (DOM), the EPDV can be generated by both DOM (e.g., England et al., 2014; Li et al., 2016) and atmospheric models coupled to motionless slab ocean models (SOM; Clement et al., 2011; Okumura, 2013; Zhang et al., 2014) in which only air-sea thermodynamic coupling processes exist. The presence of EPDV in SOM has been shown to originate in the southeast Pacific (Okumura, 2013; Zhang et al., 2014), the SSTAs therein propagating onto the equator via the wind-evaporation-SST (WES) feedback (Xie & Philander, 1994).

The EPDV simulated in both DOM and SOM motivates us to address the questions: why can it be generated by the two distinct hierarchies of modeling experiments? Does ocean dynamics play a role in EPDV? If does, then what role does ocean dynamics play? These questions, however, are hardly answered, perhaps arising from a gap in the dynamical framework between SOM and DOM (Larson et al., 2018a). Specifically, compared to SOM, DOM includes effects of both mean and anomalous ocean current on SSTAs. Removing either effect would thus fill the dynamical gap between SOM and DOM, benefiting to answer the above questions.

To fill the dynamical gap, we conducted a novel air-sea partial coupling experiment, named Clim-τ, in which climatological wind stresses are prescribed over the tropical Pacific. As a result, the experiment suppresses anomalous ocean current driven by the anomalous wind stress, but retains the effect of mean ocean current as well as air-sea thermodynamic coupling processes on EPDV. Consequently, by comparing SOM to Clim-τ, we explored the role of mean ocean current in EPDV; by comparing Clim-τ to DOM, we investigated the role of anomalous ocean current in EPDV. Our results showed that 1) in SOM, thermodynamic coupling processes without ocean current indeed leads to EPDV; 2) in Clim-τ, equatorial Pacific mean upwelling damps the thermodynamic-driven EPDV; 3) in DOM, anomalous ocean current amplifies or even overcomes the upwelling-damped EPDV. Our study demonstrates that although both SOM and DOM simulate similar EPDV pattern to observations, SOM may misinterpret the physical mechanism in the equatorial Pacific where ocean dynamics is important.

2 Data

2.1 A Hierarchy of Coupled Model Experiments

We investigated the roles of mean and anomalous ocean current in EPDV via a step-by-step comparison among SOM, Clim-τ, and DOM. All the model experiments were based on the

Geophysical Fluid Dynamic Laboratory coupled model version 2.1 (CM2.1; Delworth et al., 2006). The models consist of the atmospheric model version 2.1 (AM2.1) with horizontal resolution of 2.5° longitude × 2° latitude, and the Modular Ocean Model version 4.1 with horizontal resolution of 1° longitude × 1° latitude poleward of 30°. The latitudinal resolution equatorward of 30° in the ocean model gets gradually finer to 1/3° at the equator.

For the SOM, we used a motionless, constant-depth slab ocean coupled with AM2.1, which isolates to only retain thermodynamic coupling processes without ocean dynamics. The length of the SOM experiment was 100 years; mixed layer depth was fixed at 50 m globally.

For the Clim-τ, we prescribed wind stresses over the tropical Pacific with daily climatological values obtained from a 1000-year DOM (described below). The prescribed region is 15°S-15°N with 10° buffer zone north and south where the simulated and prescribed wind stresses are blended, with the weight linearly tapering off (see Figure 1 of Zhang et al., 2021). In order to suppress tiny day-to-day fluctuations that remain in the 1000-year climatology, the prescribed wind stress had been weakly smoothed temporally by removing the annual harmonics higher than 18 (corresponding to a frequency of about 20 days). This Clim-τ experiment is the same as mechanically decoupling the DOM (Larson & Kirtman, 2015; Larson et al., 2018a, 2018b), except that only the tropical Pacific is mechanically decoupled. Outside the tropical Pacific, the ocean and atmosphere are fully coupled and free to evolve. The Clim-τ experiment was integrated for 310 years, and only the last 300 years were analyzed. This experiment was recently used to investigate the Pacific Meridional Modes (Amaya, 2019; Amaya et al., 2019; Chiang & Vimont, 2004) without equatorial Pacific influence by Zhang et al. (2021). They discussed the damped equatorial Pacific variability in the Clim-τ was attributed to the mean equatorial upwelling driven by the mean trade winds. In this study, we will explicitly show how the mean equatorial Pacific upwelling plays a key role in damping EPDV.

Finally, we integrated a 1000-year DOM, which includes both buoyancy (thermodynamic and freshwater flux) and dynamic coupling globally. For the dynamic coupling, DOM contains the effects of both mean and anomalous wind-driven ocean current and their impact on SSTAs. It also contains other ocean processes, such as mixing, diffusion, and entrainment.

2.2 Observational Data

We also used observational data to explore the role of ocean dynamics in EPDV. We used monthly SST datasets from the Hadley Centre Global Sea Ice and Sea Surface Temperature version 1.1 (HadISSTv1.1; Rayner et al., 2003) and the NOAA Extended Reconstructed SST version 5 (ERSSTv5; Huang et al., 2017). The horizontal resolution of the HadISSTv1.1 is 1° × 1° and of the ERSSTv5 is 2° × 2°. We also used monthly surface heat flux variables (including shortwave, longwave, sensible, and latent heat fluxes) of atmospheric reanalysis dataset from the NOAA-CIRES-DOE Twentieth Century Reanalysis version 3 (20CRv3; Slivinski et al., 2019) with 1° × 1° horizontal resolution. All the above data are from 1900 to 2015. Monthly anomaly data are obtained by removing 1900-2015 monthly climatology and linear trend.

3 Results

3.1 EPDV in a Hierarchy of Coupled Model Simulations

We explore the roles of mean and anomalous ocean current in EPDV via a step-by-step comparison among the SOM, Clim-τ, and DOM. The EPDV is defined as the first empirical orthogonal function mode (EOF1) of 20-year low-pass filtered annual-mean SSTAs in 5°S-5°N equatorial Pacific, except for the DOM in which the EPDV emerges as the second EOF mode (EOF1 exhibits a zonal dipole pattern, related to ENSO amplitude decadal modulation; Ogata et al., 2013; Rodgers et al., 2004; Yeh & Kirtman, 2004; Fig. S1). The applied 20-year low-pass filter was to largely remove interannual ENSO variability. Patterns in Figure 1 display the regression maps of SST, surface wind, and surface net heat flux anomalies against the corresponding normalized principal component (PC) of EPDV in each experiment.

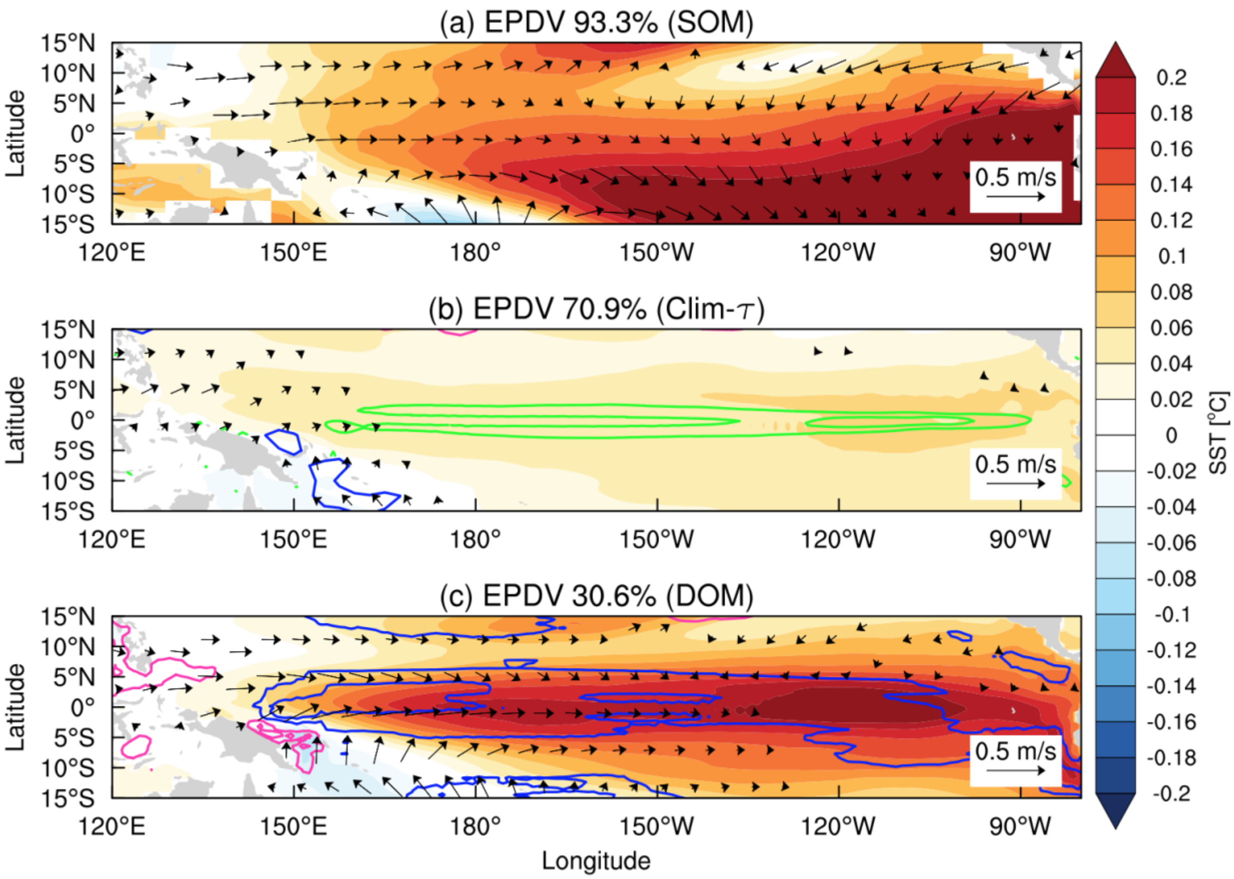

Figure 1. **EPDV patterns in the three experiments.** Regression maps of SST (shading; °C), surface wind (vectors; m s^{-1}), and surface net heat flux anomalies (contour interval: 1 W m^{-2}; purple is positive and blue is negative; downward positive) against the normalized PC time series of

EPDV. (a) SOM, (b) Clim-τ (mean upwelling velocity is green contour), and (c) DOM. The explained variance of EPDV for each experiment is labeled in the title.

The results show that in the SOM (Fig. 1a), EPDV exhibits strong SSTAs in the southeast Pacific and moderate SSTAs in the northeast Pacific. This equatorial asymmetry in the SSTAs mainly results from the distinct intensify of the WES feedbacks in the two hemispheres (Fig. S2). The SSTAs strongly correlate with surface wind anomalies, which are characterized by westerly anomalies over the central Pacific and cross-equatorial northerly anomalies flowing towards the southeast Pacific. The EPDV in the SOM resembles that simulated in other SOMs (Okumura, 2013; Zhang et al., 2014). Previous studies pointed out that EPDV in SOMs originates from the southeast Pacific SSTAs that propagate onto the equator primarily through the WES feedback (Zhang et al., 2014). Note that on decadal timescales, changes in the upper ocean temperature are in a quasi-equilibrium (i.e., all the processes that force SSTAs are balanced with all the damping processes). As a result, net surface heat flux anomaly associated with the EPDV in the SOM is rather weak (no contours in Fig. 1a) because it is the only driver for SSTAs.

Surprisingly, in the Clim-τ (Fig. 1b), EPDV-related SSTAs are markedly damped. Due to the same thermodynamic coupling processes as in the SOM, this damping is only attributed to the effect of mean ocean current. To further investigate which dimension of mean ocean current dominantly damps EPDV, we estimate the damping rate of each dimension of mean ocean current acting on the EPDV-associated SSTAs. The damping rate is computed by the EPDV-associated SSTAs (pattern of Fig. 1a) gradient advected by annual-mean ocean current (obtained from the Clim-τ) divided by the EPDV-associated SSTAs. The result shows that anomalous ocean advections by all three-dimensional mean ocean currents damp the EPDV-related SSTAs off the equatorial Pacific (Fig. 2). The SSTAs on the equatorial Pacific (i.e., the EPDV), in contrast, are predominantly damped by the climatological upwelling (Fig. 2c). The estimated damping rate of the mean upwelling on the equator is about 0.2-0.6 mon^{-1}, indicating its critical role in damping the EPDV.

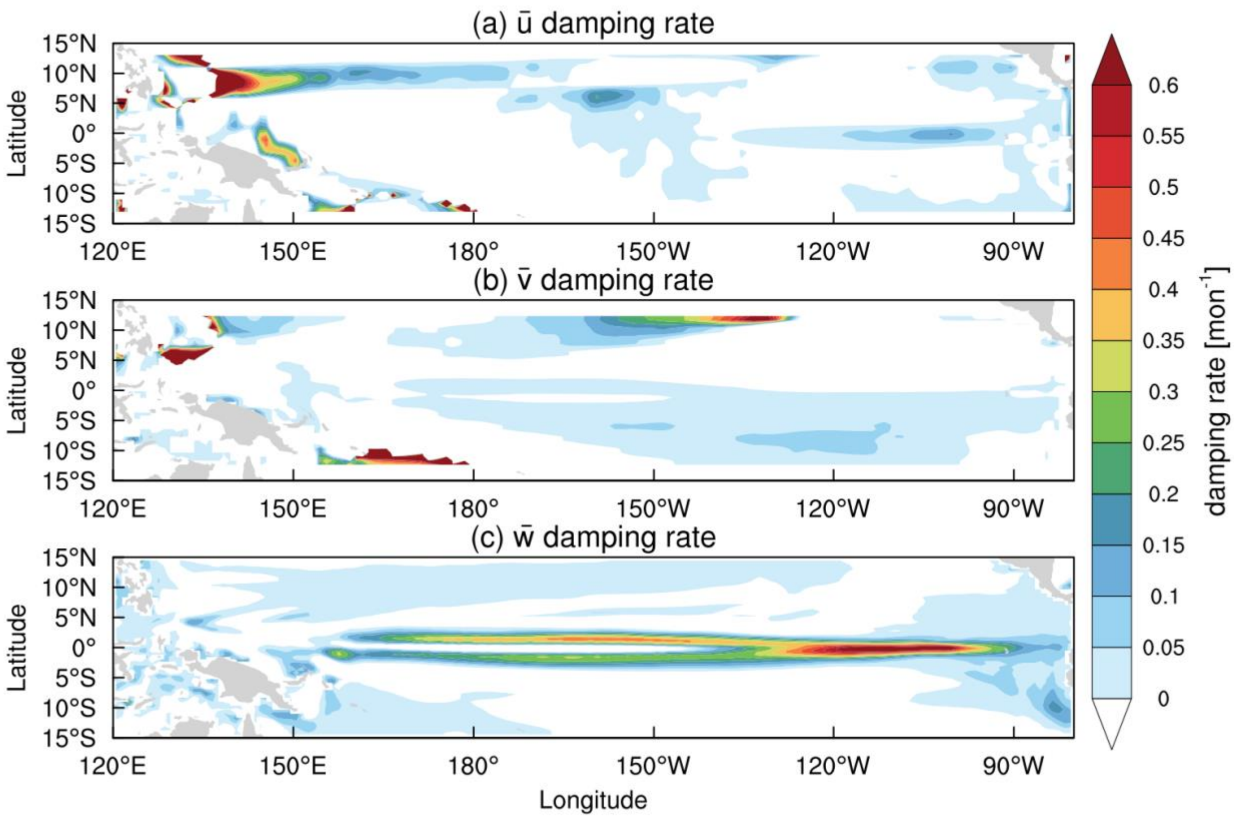

Figure 2. **Estimated EPDV damping rate in the Clim-τ.** (a)-(c) Patterns of the estimated damping rate (see the method in text; unit: mon^{-1}) by annual-mean climatological zonal, meridional, and 50-m vertical current, respectively. All the climatological currents are from the Clim-τ experiment. Negative values (representing forcing rate) are set to white colors.

This dominant damping effect by equatorial Pacific mean upwelling, in fact, acts not only on decadal but also on inter-decadal to multi-decadal timescales. To illustrate this point, we perform power spectrum analysis of annual-mean SSTAs averaged over the Niño-3 plus Niño-4 regions (160°E-90°W, 5°S-5°N) in each experiment. SSTAs averaged over this region will largely remove the signal of zonal dipole mode in the DOM and represent EPDV in all experiments (Fig. S3). The result shows that in the SOM, EPDV variance gradually increases longer than 20-year period and then stabilizes at 0.26 °C^2 after 40-year period (red line in Fig. 3). This relatively stabilized EPDV variance longer than decadal timescales reflects a reddened spectrum generated by integrating atmospheric white noise forcing (Clement et al., 2011; Frankignoul & Hasselmann, 1977; Okumura, 2013). EPDV variance in the Clim-τ, in contrast, decreases by ~80% compared to that in the SOM (blue line in Fig. 3), indicating the prominent role of mean upwelling in damping equatorial Pacific SSTAs on decadal to multi-decadal timescales.

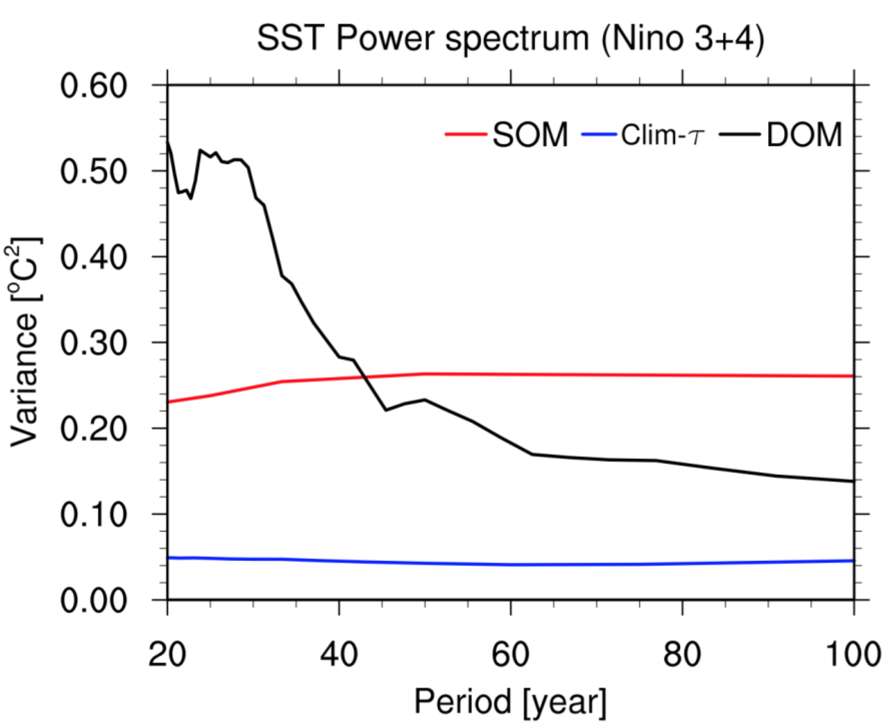

Figure 3. Power spectra of EPDV in the three experiments. The power spectra (unit: °C^2) are performed based on the annual-mean SSTAs averaged over Niño-3 plus Niño-4 regions in each experiment. Spectra with periods no less than 20 years are shown. Red: SOM; blue: Clim-τ; black: DOM.

Compared to the EPDV in the Clim-τ, EPDV is intensified in the DOM (Fig. 1c), suggesting that anomalous ocean current plays a role in amplifying the EPDV. The strength of the amplification, however, is distinct on different timescales (black line in Fig. 3). Specifically, the amplification is strong on inter-decadal (20~40 years) timescales, leading to the EPDV variance in the DOM larger than that in the SOM. In contrast, the strength of the amplification becomes gradually weak on multi-decadal (>40 years) timescales, resulting in the EPDV variance in the DOM smaller than that in the SOM. This timescale-dependent amplification strength seems to be in line with the therotical study by Clarke (2010), which pointed out that longer timescales, weaker interactive ocean dynamics in the eastern equatorial Pacific (i.e., weaker amplification strength).

Further, EPDV in the DOM is damped by net surface heat flux (blue contours in Fig. 1c). Together with the dynamical damping by the equatorial Pacific mean upwelling revealed from the Clim-τ, EPDV is driven by the effect of anomalous ocean current, rather than air-sea thermodynamic coupling as seen in the SOM.

3.2 EPDV in observations

Here we discuss the roles of mean and anomalous ocean current in the observed EPDV. The mean ocean current is supposed to play a damping role, primarily by equatorial Pacific mean upwelling, the result inferred from the Clim-τ. The anomalous ocean current, in contrast, plays a forcing role in most of the equatorial Pacific regions, the result inferred from the negative net surface heat flux anomalies between 180° and 100°W (Fig. 4a). As a caveat, this result may be insignificant as the EPDV obtained from the EOF1 of 20-year low-pass filtered annual-mean SSTAs in the equatorial Pacific does not exceed the 95% confidence level due to the limited degrees of freedom in observations. Thus, alternatively, we extract "EPDV" by performing EOF analysis with 10-year low-pass filtered annual-mean SSTAs. The resulting "EPDV" is significant at the 95% confidence level, with weak negative net surface heat flux anomalies in the central equatorial Pacific (180°-135°W) and strong positive net surface heat flux anomalies in the eastern equatorial Pacific (east of 135°W) (Fig. 4b). The weak negative net surface heat flux anomalies in the central equatorial Pacific implies that anomalous ocean current plays a forcing role, offsetting the damping effects of the weak net heat flux and mean upwelling. The strong positive net surface heat flux anomalies in the eastern equatorial Pacific may largely counteract the strong damping effect by mean upwelling, resulting in a weak role of anomalous ocean current played therein. The above analyses are also seen if based on ERSSTv5 dataset (Fig. S4). To the extent of the role of anomalous ocean current in the observed EPDV needs to be quantified in future studies.

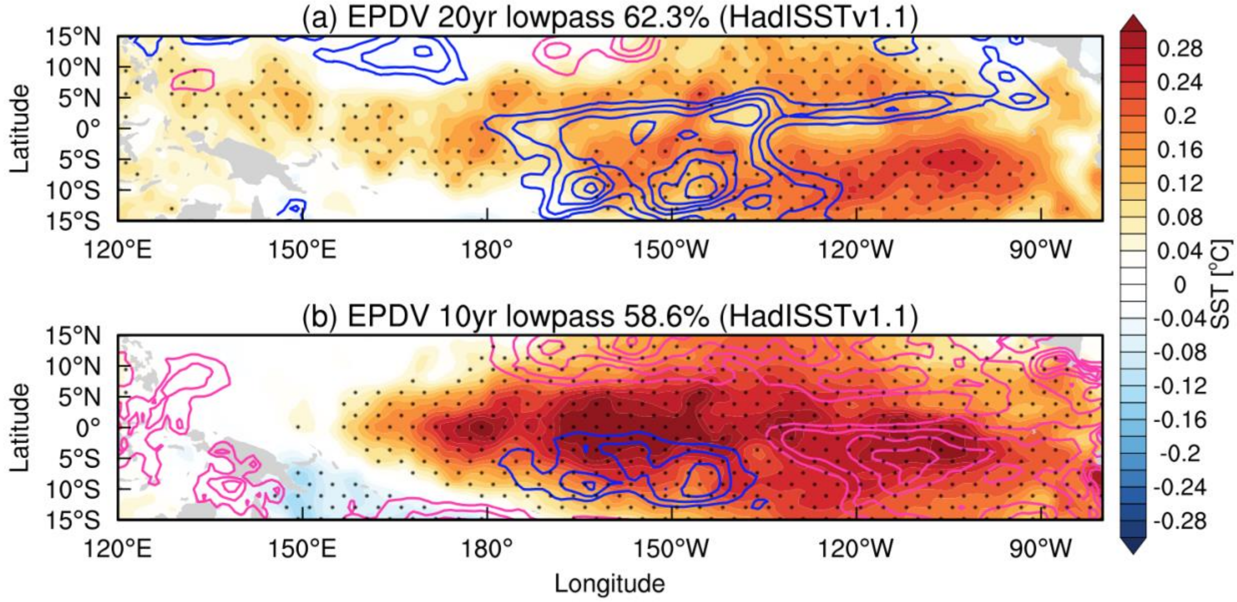

Figure 4. EPDV patterns in observations. The observed EPDV patterns shown are based on the HadISSTv1.1. (a) As in Fig. 1, (b) EPDV is denoted as EOF1 of 10-year low-pass filtered annual-mean SSTAs in the equatorial Pacific. Stippling in (a) and (b) denote the regressed SSTAs (shading) significant at the 95% confidence level. The regressed net surface heat flux anomalies (contours) only significant at the 95% confidence level are shown. Both significance tests are based on the two-tailed *F* test.

4 Summary and Discussion

To fill the gap between the air-sea thermodynamic coupled SOM and fully coupled DOM, we conducted a partial coupling experiment—Clim-τ—which retains the effects of air-sea thermodynamic coupling and mean ocean current driven by mean wind stress on SSTAs. With a step-by-step comparison among the SOM, Clim-τ, and DOM based on the CM2.1, we have investigated the roles of mean and anomalous ocean current in EPDV. We showed that mean ocean current, primarily the equatorial Pacific mean upwelling, plays a key role in damping EPDV. Anomalous ocean current in turn, amplifies the damped EPDV and even overwhelms the damping effect by mean ocean current, leading to a role in forcing EPDV. Finally, we discussed the role of ocean current in the observed EPDV.

Our study demonstrates that SOMs may misinterpret the physical mechanism in the regions where mean upwelling is prominent. Apart from the mean upwelling regions, climate phemomena in others regions with strong ocean dynamics were also simulated by SOMs. For example, in the North Atlantic, the Atlantic Multi-decadal Variability (AMV; Sutton et al., 2018; Zhang et al., 2019), which was thought to be strongly related to the Atlantic Meridional Overturing Circulation (Buckley & Marshall, 2016; Kuhlbrodt et al., 2007), was recently challenged by SOM simulations (Clement et al., 2015). Despite the similarity of the AMV patterns between SOM and DOM on the ocean surface, other AMV-related patterns in the subsurface, such as the temperature anomaly structure, are distinct (Zhang et al., 2019). The examples of the AMV and our EPDV studies caution against the overuse of SOMs in revealing the physical mechanisms of climate phemomena in the regions where ocean dynamics is active.

Acknowledgments

The HadISSTv1.1 data is available at https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html. The ERSSTv5 data is available at https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html. The 20CRv3 data is available at https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html#detail. The SOM data is available at https://nomads.gfdl.noaa.gov/dods-data/gfdl_sm2_1/MLM2.1U_Control-1990_D1/pp/atmos/ts/monthly/; the Clim-τ data is available at https://data.mendeley.com/datasets/ctn5k77ttr/draft?a=c9db68b4-d4af-48a4-b14d-709edc7fa1b7; the DOM data is available at https://data.mendeley.com/datasets/mrg8g4w9zk/draft?a=4d2e535f-7dc6-4f10-b2ad-c1bf565637ce. Y.Z. and X.L. were supported by the National Natural Science Foundation of China (92058203 and 41925025). D.J.A. was funded under a CIRES Postdoctoral Fellowship at CU Boulder. Q.P. was supported by the National Natural Science Foundation of China (42005035) and the Independent Research Project Program of State Key Laboratory of Tropical Oceanography (LTOZZ2102). Y.K. was supported by the Japan Society for the Promotion of Science (JP18H01278, JP18H01291 and JP19H05703), the Japanese Ministry of Education, Culture, Sports, Science and Technology (JPMXD0717935457 and JPMXD1420318865), and the Environtal Restoration and Conservation Agency of Japan (JPMEERF20192004). J.-C.Y. was supported by the project funded by China Postdoctoral Science Foundation (2020M672138) and the Fundamental Research Funds for the Central Universities (202013029). S.M.L. was supported by the National Science Foundation (AGS-1951713). A.J.M. was supported by the National Science Foundation (OCE2022868 and CCE-LTER OCE1637632) and NOAA (MAPP NA17OAR4310106). L.F. was supported by the Natural Science Foundation of China (41975089).

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Geophysical Research Letters

Supporting Information for

Deciphering the Role of Ocean Dynamics in Equatorial Pacific Decadal Variability

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Figures S1 to S4

Additional Supporting Information (Files uploaded separately)

None

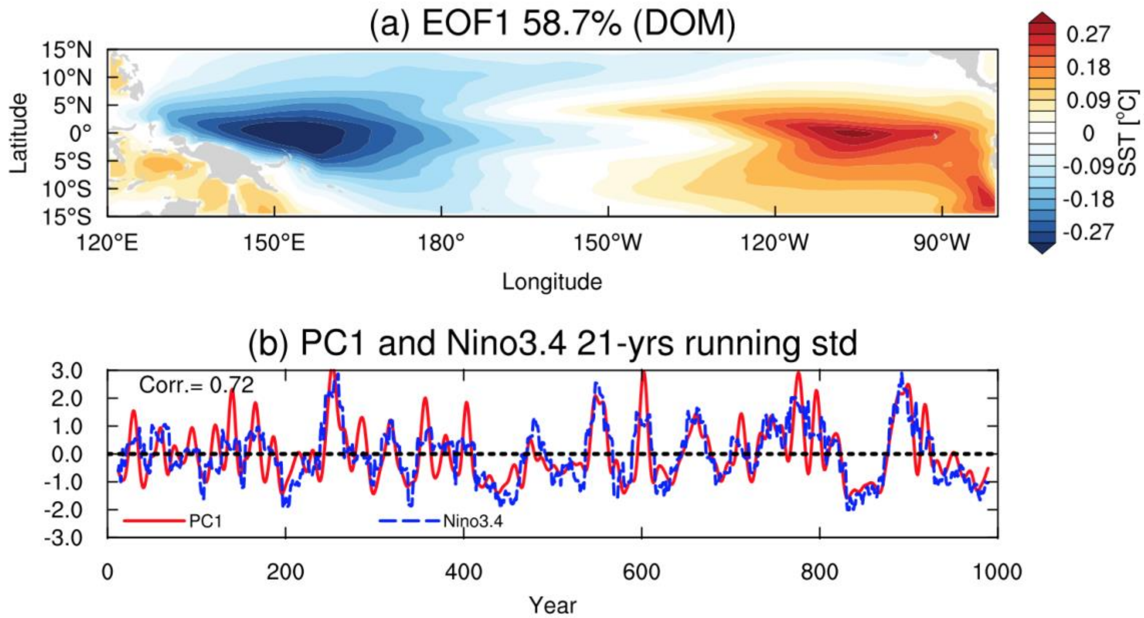

Figure S1. Zonal dipole mode in the DOM. (a) EOF1 of 20-year low-pass filtered annual-mean SSTAs in the equatorial Pacific. (b) The corresponding normalized PC (solid red line) with normalized 21-year running standard deviation of November-January SSTAs averaged over the Niño-3.4 region (170°W-120°W, 5°S-5°N) (dashed blue line). The correlation coefficient between the two time series is labeled in the panel.

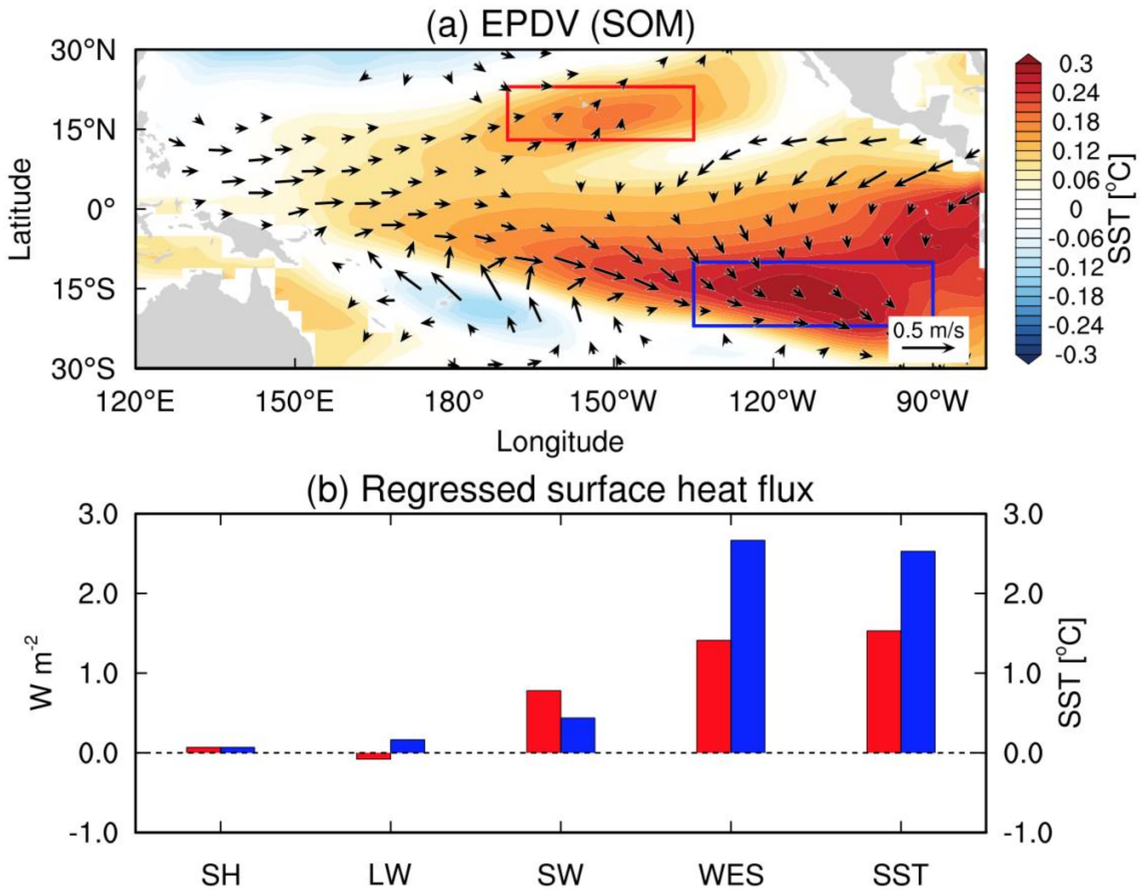

Figure S2. Equatorial asymmetry of EPDV-related SSTAs in the SOM. (a) Regressed tropical Pacific SSTAs (°C) and surface wind anomalies (m s^{-1}) against normalized EPDV PC. Red and blue boxes represent the locations of maximum SSTAs off the equatorial Pacific, respectively. (b) Regressed surface heat flux anomaly (W m^{-2}) against normalized 20-year low-pass filtered SSTAs averaged in the red (red bars) and blue (blue bars) boxes. SH: sensible heat; LW: longwave; SW: shortwave; WES: WES feedback, calculated by $-\bar{Q}_E W'/\bar{W}$, where Q_E is latent heat flux and W is wind speed (overbar denotes climatology and prime denotes anomaly departure from the climatology). The magnitudes of the 20-year low-pass filtered SSTAs averaged in the two boxes are plotted for comparison.

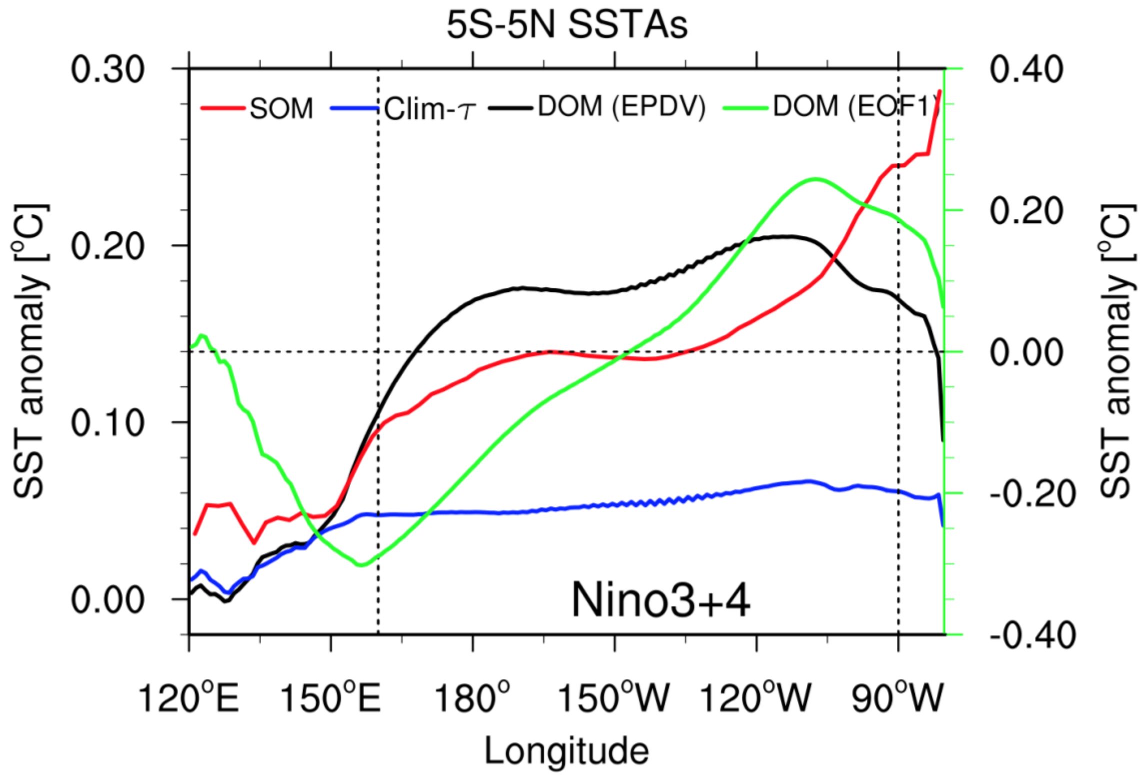

Figure S3. 5°S-5°N meridional mean of EPDV in Fig. 1 and DOM EOF1 in Fig. S1a (green line). Vertical dashed lines denote the longitudinal range of the Niño-3 plus Niño-4 region.

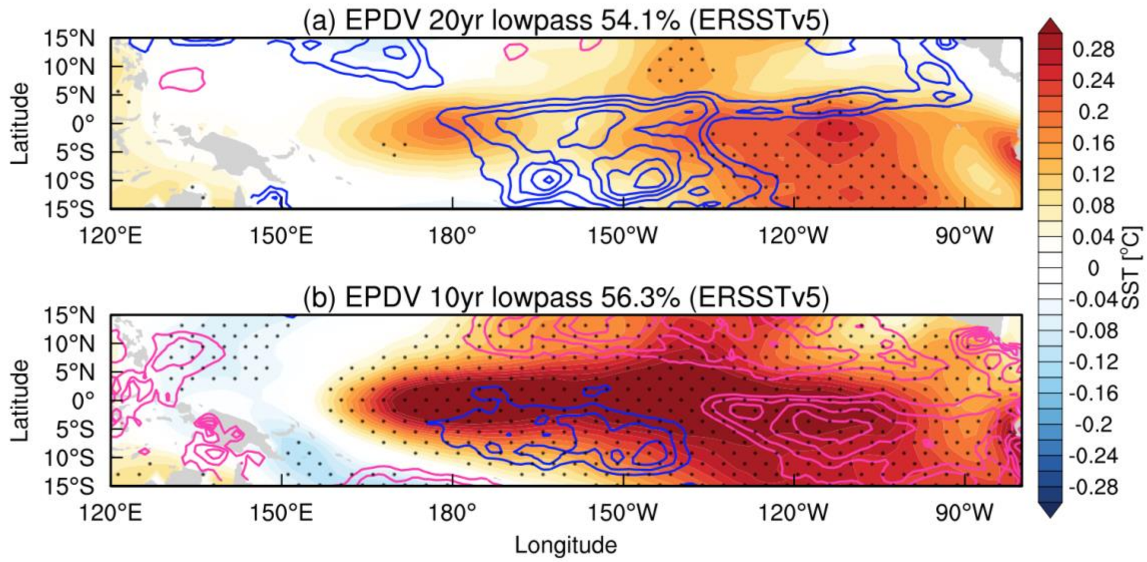

Figure S4. As in Fig. 4, but based on the ERSSTv5.