Origins of Tropical Pacific Decadal Variability: Role of Stochastic Atmospheric Forcing from the South Pacific*

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ABSTRACT

Based on the analysis of multicentury–millennium integrations of an atmospheric model coupled to the ocean with varying degrees, it is argued that ENSO-like decadal variability is primarily driven by stochastic atmospheric forcing. In particular, the leading mode of internal atmospheric variability over the South Pacific, which projects onto the Pacific–South American (PSA) pattern, plays an important role in modulating the trade winds and sea surface temperature (SST) in the southeast tropical Pacific. Subsequent ocean–atmosphere interactions organize a basinwide SST anomaly pattern in the tropics, which in turn forces atmospheric Rossby waves into the extratropics, reinforcing the PSA pattern and inducing coherent decadal changes in the North Pacific. In the absence of ocean dynamics, equatorial SST variability is reduced and the North Pacific exhibits decadal variability independent of the tropical–South Pacific. The strong tropical–South Pacific linkage may be attributed to the equatorially asymmetric nature of tropical Pacific climate.

1. Introduction

Decadal variability of Pacific climate has widespread impacts on atmospheric circulation, hydrological cycle, and marine and terrestrial ecosystems (Mantua and Hare 2002). Decadal variations in the tropical Pacific are strongly linked to decadal variations in the North and South Pacific, with ocean–atmosphere anomaly patterns similar to those associated with El Niño–Southern Oscillation (ENSO) (Garreaud and Battisti 1999; Deser et al. 2004). In analogy to ENSO, some earlier studies suggest that Pacific decadal variability originates in the tropics while atmospheric teleconnections induce coherent changes in the extratropics (see Liu 2012 for a review). Different mechanisms of tropical Pacific decadal variability (TPDV) have been proposed, including slow propagation of off-equatorial Rossby waves (Knutson and Manabe 1998; Jin 2001), decadal changes in ENSO activity (Rodgers et al. 2004; Vimont 2005), and delayed

negative feedback from the extratropics via a subsurface oceanic pathway (Gu and Philander 1997; Luo and Yamagata 2001). Note that ocean dynamics plays an active role in all these mechanisms.

Other studies, on the contrary, propose that decadal variability can be generated within the extratropical North Pacific through oceanic integration of stochastic atmospheric forcing and Rossby wave adjustments (Schneider et al. 2002; Kwon and Deser 2007). The associated changes in the atmospheric circulation may affect surface winds in the tropics, inducing TPDV and changes in ENSO activity (Barnett et al. 1999; Pierce et al. 2000). Indeed, ENSO-like decadal variability weakens when stochastic atmospheric variability is suppressed in a climate model (Yeh and Kirtman 2004). By analyzing multiple atmospheric models coupled to the ocean with varying degrees, Clement et al. (2011) argue that TPDV is consistent with stochastically forced process and does not require interactive ocean dynamics. It is, however, unclear what is the nature of stochastic atmospheric forcing important for TPDV. The stochastic climate model proposed by Frankignoul and Hasselmann (1977) is the leading paradigm of extratropical ocean–atmosphere variability, but this mechanism is overlooked in the tropical Pacific because of the predominant role of air–sea interactions and dynamical oceanic adjustment in ENSO (Bjerknes feedback).

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Despite a number of studies over the past two decades, many important questions remain regarding the origins of TPDV. What is the most fundamental process in generating TPDV? Does ocean dynamics play an important role? Is TPDV forced from the extratropics? What part of stochastic atmospheric variability is important? What causes the coherent variability over the North and South Pacific? The present study revisits these questions by comparing two long control simulations of coupled ocean–atmosphere models with and without interactive ocean dynamics.

2. Model experiments

Two long control simulations of coupled ocean–atmosphere models are analyzed in this study: a 1300-yr run of the Community Climate System Model, version 4 (CCSM4; Gent et al. 2011), and a 500-yr run of its atmospheric component, the Community Atmosphere Model, version 4, coupled to a slab ocean model (CAM4-SOM). The ocean and atmosphere are fully coupled in CCSM4, whereas they are only thermodynamically coupled through surface heat flux in CAM4-SOM. The Bjerknes feedback and oceanic Rossby wave adjustments are therefore absent in CAM4-SOM. In this model, sea surface temperature (SST) is computed from surface heat flux and “ Q flux” that represents the effect of climatological ocean heat transport. The mixed layer depth and Q flux are based on the climatology of the CCSM4 control simulation. The CCSM4 and CAM4-SOM also include the same land and sea ice models. Both control simulations are conducted at nominal 1° horizontal resolution under preindustrial atmospheric greenhouse gas concentrations.

Tropical Pacific mean climate is very similar between CCSM4 and CAM4-SOM and compares well with observations although SST has a warm bias off the coast of Peru and the South Pacific convergence zone extends too far east (Fig. S1 in the supplemental material). The CCSM4 simulates many important features of Pacific climate variability on interannual–decadal time scales (Deser et al. 2012). In particular, the period of ENSO ranges 3–6 yr (Fig. S2 in the supplemental material) and El Niño and La Niña events exhibit asymmetry in both the spatial pattern and duration as in observations. Importantly, North Pacific decadal variability shows significant associations with the tropics as well as with the South Pacific, although the linkages are somewhat weaker than in observations. The similarity of mean climate in CCSM4 and CAM4-SOM helps to isolate the role of interactive ocean dynamics in TPDV while the long integrations provide robust statistics of TPDV and linkages to the extratropics. Note that in the multimodel

FIG. 1. Patterns of TPDV and associated global anomalies in (top) CAM4-SOM and (bottom) CCSM4. Maps show regressions of surface temperature ($^{\circ}\text{C}$; shading), SLP (black contours at intervals of 0.1 hPa; zero contours thickened), and precipitation [negative (positive) contours in brown (green) at intervals of 0.2 mm day^{-1}] anomalies upon the leading PC of 10-yr low-pass filtered annual SST anomalies in the tropical Pacific (20°S – 20°N , 120°E – 80°W). The leading EOF modes explain 38% and 47% of the total filtered variance in CAM4-SOM and CCSM4, respectively. Note that large temperature anomalies in polar regions reflect the surface temperature over sea ice.

study by Clement et al. (2011) the slab ocean models are forced with Q flux based on observations and the length of simulations is 81 yr on average.

3. Results

Figure 1 shows the dominant patterns of TPDV and associated global anomalies in CCSM4 and CAM4-SOM obtained by regressing ocean–atmosphere fields onto the leading principal component (PC) of 10-yr low-pass filtered annual SST in the tropical Pacific (20°S – 20°N , 120°E – 80°W). The associated leading empirical orthogonal function (EOF) explains 47% of the total filtered variance in CCSM4 and 38% in CAM4-SOM. Despite the different ocean representations, Pacific basin anomaly patterns are strikingly similar between these simulations and resemble the observed patterns of decadal variability. In the tropical Pacific, SST warming is associated with an increase in precipitation and a westward gradient of sea level pressure (SLP)

FIG. 2. Patterns of internal atmospheric variability and associated surface temperature changes in (top),(middle) CAM4-SOM and (bottom) CCSM4. Maps show correlations of SLP (contours at intervals of 0.2; zero contours thickened) and surface temperature (shading) anomalies with the leading PC of monthly SLP variability in the extratropical (left) North (15° – 70° N, 130° E– 110° W) and (right) South (15° – 70° S, 170° E– 70° W) Pacific. In CAM4-SOM (CCSM4), the North and South Pacific EOF modes explain 34% and 31% (36% and 32%) of the total variance, respectively. In (middle),(bottom), the monthly PCs and surface temperature/SLP data are smoothed with a 10-yr low-pass filter prior to the correlation analysis. See Fig. S4 in the supplemental material for the correlation maps based on unfiltered monthly data for CCSM4.

anomalies. Wave train patterns of SLP anomalies and related SST changes extend over the North and South Pacific. The similarity of CCSM4 and CAM4-SOM suggests that interactive ocean dynamics are not required to produce ENSO-like decadal variability. Notable differences are, however, found in some regions. Compared to CCSM4, SST and precipitation anomalies are smaller in the equatorial Pacific in CAM4-SOM. Equatorial ocean dynamics thus contributes to decadal SST variability, although the power spectra of SST in the Niño-3.4 region (5° S– 5° N, 170° – 120° W) are not significantly different between these models on time scales longer than 15 yr (Fig. S2). Intriguingly, SST and SLP anomalies show comparable magnitude between CCSM4

and CAM4-SOM over the South Pacific but are considerably smaller in CAM4-SOM than in CCSM4 over the North Pacific. In association with the strong linkage to the South Pacific, the SST warming is centered in the southeast tropical Pacific in CAM4-SOM. These results are consistent with Clement et al. (2011).

What causes TPDV in the CAM4-SOM control simulation? In CAM4-SOM, the ocean and atmosphere are coupled through local surface heat flux and therefore the spatial structure of tropical SST variability may be influenced by patterns of internal atmospheric variability, which is prominent in the extratropics but extends into the tropics. Indeed, SLP anomalies associated with the leading mode of TPDV project onto the Pacific–North

American (PNA) and Pacific–South American (PSA) patterns (Fig. 1), which arise from internal atmospheric dynamics as well as tropical SST forcing (Lau 1997; Cai and Watterson 2002). In CAM4-SOM, the PNA and PSA patterns appear as the leading EOF mode of monthly SLP variability in the extratropical North and South Pacific, respectively (Fig. 2, top). Note that the South Pacific pattern also shows some signatures of the southern annular mode, the leading mode of hemispheric variability. On month-to-month time scales, the PNA and PSA modes are not significantly correlated with underlying SSTs, confirming that they are modes of internal atmospheric variability. On decadal time scales, both the PNA and PSA modes become strongly correlated with underlying SST as the ocean mixed layer integrates stochastic atmospheric variability (Fig. 2, middle). Surprisingly, the PSA mode is significantly correlated with tropical Pacific SST ($r \sim 0.6$) while the SST correlations with the PNA mode are limited to the extratropical North Pacific. The linkage between the PSA mode and tropical SST is effectuated via the South Pacific high, which drives the southeasterly trade winds over the southeast tropical Pacific. In fact, monthly–decadal variability of the southeasterly trade winds is associated with a large-scale atmospheric circulation anomaly pattern similar to the PSA mode (Fig. S3 in the supplemental material). The SST and SLP correlation patterns associated with the PSA mode bear a strong resemblance to the leading mode of TPDV in CAM4-SOM. This result suggests that the PSA mode plays an important role in driving TPDV by modulating surface winds and heat flux over the southeast tropical Pacific.

Does the addition of interactive ocean dynamics change the linkages between the PNA/PSA modes and TPDV? The same correlation analysis of SLP modes is conducted for the CCSM4 control simulation. The leading EOFs of monthly SLP variability in the extratropical Pacific are very similar to those in CAM4-SOM, except the PNA mode has slightly higher correlations with equatorial SST and subtropical SLP due to ENSO forcing during winter (Fig. S4). On decadal time scales, the PSA mode exhibits significant correlations with tropical Pacific SST (Fig. 2, bottom right). Compared to CAM4-SOM, the tropical SST correlations are centered more at the equator and the region of negative SLP correlations extends into the North Pacific. The tropical SST correlations are weaker in CCSM4 compared to CAM4-SOM because of the existence of a second prominent mode of TPDV in CCSM4 that is nearly absent in CAM4-SOM (not shown). Nonetheless, the standard deviation of 10-yr low-pass filtered SST in the Niño-3.4 region increases by 82% in CCSM4 compared to CAM4-SOM (cf. Figs. 1 and S2). In contrast to CAM4-SOM, the

FIG. 3. Relationships between the modes of internal atmospheric variability and TPDV in (top) CAM4-SOM and (bottom) CCSM4. Blue (red) curves show lead-lag cross correlations between the leading PCs of extratropical SLP variability in the North (South) Pacific and tropical Pacific SST variability. The leading PCs of monthly SLP variability are averaged for each calendar year and smoothed with a 10-yr low-pass filter prior to the cross-correlation analysis. Negative (positive) lags indicate that SLP modes lead (lag) TPDV.

PNA mode in CCSM4 shows significant correlations with tropical Pacific SST on decadal time scales (Fig. 2, bottom left). The tropical SST correlations are pronounced near the equator, suggesting that these equatorial SST variations enhanced by interactive ocean dynamics force part of PNA variability through changes in atmospheric deep convection. Associated weak SLP correlations extend to the South Pacific, resembling the PSA pattern.

To further examine the causality of the PNA/PSA modes and TPDV in CCSM4 and CAM4-SOM, a lead-lag cross-correlation analysis is conducted with the leading PCs of extratropical SLP and tropical SST variability obtained earlier (Fig. 3). In both simulations, the PSA mode is significantly correlated with the leading mode of TPDV for both positive and negative lags with the maximum correlation at lag 0. The correlations tend to be larger for negative lags when the PSA mode leads

TPDV. These results suggest that the PSA mode plays an important role in driving TPDV but that the resultant tropical SST changes may in turn force the PSA pattern as suggested by previous studies (e.g., Cai and Watterson 2002; Okumura et al. 2012). The PNA mode is not significantly correlated with the leading mode of TPDV in CAM4-SOM, but the correlations become comparable to those for the PSA mode in CCSM4. The symmetrical structure of the lead-lag cross-correlation curve is suggestive of a positive feedback between the PNA mode and TPDV. A lack of apparent lag indicates that their linkage is brought about by atmospheric, rather than oceanic teleconnections. The correlations are slightly larger for positive lags when TPDV leads the PNA mode, in support of the idea that the enhanced equatorial variability mediates their linkage. The PNA mode may, in turn, contribute to SST changes in the northeast tropical Pacific by affecting the northeasterly trade winds and low-level clouds (Figs. 1 and 2).

The mechanism of Pacific decadal variability proposed here is analogous to the “hyper climate mode” conjectured by Dommenget and Latif (2008). Based on the analysis of long climate model simulations, the present study robustly shows that the leading mode of internal atmospheric variability over the South Pacific plays an important role in driving TPDV through changes in the southeasterly trade winds. It is further suggested that the associated equatorial SST changes are enhanced by interactive ocean dynamics and force coherent decadal variability in the North Pacific, which is otherwise confined in the extratropics.

4. Discussion

The strong linkage of TPDV to the South Pacific in CCSM4 and CAM4-SOM is consistent with other model studies (Matei et al. 2008; Clement et al. 2011) and observational analyses that show pronounced tropical ocean-atmosphere anomalies south of the equator (Garreaud and Battisti 1999; Deser et al. 2004). On interannual time scales, Zhang et al. (2013) show that in both models and observations the onsets of ENSO events are more strongly influenced by atmospheric variability in the South Pacific than in the North Pacific through a so-called seasonal footprinting mechanism (Vimont et al. 2001; Chang et al. 2007; Alexander et al. 2010). In fact, an early observational study by Trenberth and Shea (1987) envisioned the role of South Pacific atmospheric variability in triggering ENSO events. On decadal time scales, paleoclimate proxy records may be helpful to assess the relative role of South and North Pacific atmospheric variability in TPDV (Villalba et al. 2011; Okumura et al. 2012).

The leading role of South Pacific atmospheric variability in TPDV is surprising, given that previous studies of Pacific decadal variability focused on the North Pacific partly because of relatively abundant data (Garreaud and Battisti 1999). Why is the tropical Pacific connected more strongly to atmospheric variability in the South Pacific than in the North Pacific? The equatorially asymmetric nature of tropical Pacific mean climate is a likely factor. In the eastern tropical Pacific, the intertropical convergence zone is displaced north of the equator and the southeasterly trade winds extend into the equatorial region during most of the year (Fig. S1). These southeasterly trade winds are affected by the strength and position of the South Pacific high, which is in turn modulated by internal atmospheric variability over the South Pacific (Fig. S3). Thus, the PSA mode can directly force SST changes in the southeast equatorial Pacific through wind-induced changes in surface heat flux. Subsequent thermodynamic air-sea interactions within the tropics may further organize this regional SST response into a broader, equatorially symmetric pattern (Liu and Xie 1994; Zhou and Carton 1998; Dommenget 2010).

While ocean dynamics are not fundamental to TPDV, they may play an important role in setting the time scale of decadal variability, therefore providing some predictability. Interestingly, previous studies suggest that the subduction mechanism proposed by Gu and Philander (1997) may work more efficiently in the South Pacific than in the North Pacific because of the presence of a potential vorticity barrier in the North Equatorial Countercurrent region (Schneider et al. 1999; Wang and Liu 2000; Chang et al. 2001; Luo and Yamagata 2001). Tatebe et al. (2013) show that ENSO-like decadal variability weakens in a coupled model when subsurface ocean temperature and salinity are restored to their climatological values between 8° and 12°S. Therefore, the tropical-South Pacific linkages may have two pathways, one via the atmosphere and one via the ocean. The present study also suggests that ocean dynamics plays a pivotal role in increasing the interhemispheric coherency of Pacific decadal variability by enhancing equatorial SST variability and resultant atmospheric teleconnections. The relative role of ocean dynamics may, however, be model dependent (Clement et al. 2011), and it is unclear how the enhanced decadal variability in the equatorial Pacific is associated with interannual ENSO events. More analyses of TPDV and its interactions with ENSO are underway and will be reported in a separate paper.

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