The Pacific Meridional Mode and ENSO: a Review

Article · September 2019

DOI: 10.1007/s40641-019-00142-x

Dillon J. Amaya
University of Colorado Boulder

Current Climate Change Reports
https://doi.org/10.1007/s40641-019-00142-x

INTERNAL CLIMATE VARIABILITY (S-P XIE, SECTION EDITOR)

Check for updates

The Pacific Meridional Mode and ENSO: a Review

Dillon J. Amaya[1]

Abstract

Purpose of Review This paper reviews recent progress in understanding of the North Pacific Meridional Mode (NPMM) and its influence on the timing, magnitude, flavor, and intensity of the El Niño-Southern Oscillation (ENSO).

Recent Findings The NPMM is a seasonally evolving mode of coupled climate variability and features several distinct opportunities to influence ENSO. They include: (1) A Wind-Evaporation-SST (WES) feedback-driven propagation of surface anomalies onto the equator during boreal spring, (2) Trade Wind Charging (TWC) of equatorial subsurface heat content by NPMM-related surface wind stress curl anomalies in boreal winter and early spring, (3) The reflection of NPMM-forced ocean Rossby waves off the western boundary in boreal summer, and (4) A Gill-like atmospheric response associated with anomalous deep convection in boreal summer and fall. The South Pacific Meridional Mode (SPMM) also significantly modulates ENSO, and its interactions with the NPMM may contribute to ENSO diversity. Together, the NPMM and SPMM are also important components of Tropical Pacific Decadal Variability; however, future research is needed to improve understanding on these timescales.

Summary Since 1950, the boreal spring NPMM skillfully predicts about 15–30% of observed winter ENSO variability. Improving simulated NPMM-ENSO relationships in forecast models may reduce ENSO forecasting error. Recent studies have begun to explore the influence of anthropogenic climate change on the NPMM-ENSO relationship; however, the results are inconclusive.

Keywords Pacific meridional mode · El Niño-southern oscillation · Extratropical-tropical interactions · Teleconnections · ITCZ shifts · Energetics framework · Climate prediction · Climate modeling · Climate variability · Internal variability · Climate dynamics · Pacific variability · Pacific decadal variability · Subseasonal-to-seasonal forecasting · Climate change · Tropics · Paleoclimate

Introduction

Tropical Pacific climate variability is dominated by interannual fluctuations of the El Niño-Southern Oscillation (ENSO). El Niño refers to a warming of the central/eastern equatorial Pacific. This is driven by a reduction in the climatological zonal trade winds, which decreases upwelling by deepening the thermocline along the equator through ocean wave dynamics. The opposite is true of La Niña or cold phase ENSO events. The resulting equatorial sea surface temperature (SST) anomalies (SSTAs) then trigger large-scale atmospheric teleconnections that can significantly impact global weather and climate [1]. As a result, improving our understanding and predictability of ENSO is of great societal relevance.

Historically, the mechanisms that govern the timing and evolution of ENSO events have been thought to be primarily intrinsic to the tropics. For example, the buildup of ocean heat content in the West Pacific Warm Pool have long been leveraged in an effort to extend the skillful predictability of ENSO on seasonal timescales [2–7]. However, while this tropical precursor may point towards the development of an ENSO event, it is not always a successful predictability tool because stochastic Westerly Wind Events (WWEs) are required to trigger the release of built-up heat content [8, 9]. Generally, it is not possible to predict individual WWEs beyond weather timescales. Further, recent evidence suggests that these high-frequency WWEs may play a minor role in ENSO initiation when compared to interannual stochastic forcing driven by interactions with the underlying SST (i.e., multiplicative noise) [10]. This complicated interaction of stochastic

This article is part of the Topical Collection on *Internal Climate Variability*

✉ Dillon J. Amaya
djamaya@ucsd.edu

[1] Scripps Institution of Oceanography, University of California-San Diego, 9500 Gilman Drive #0206, La Jolla, CA 92093-0206, USA

Published online: 04 September 2019

atmospheric forcing with internal tropical states makes it difficult to produce accurate long-lead ENSO forecasts and highlights the competing influences of stochasticity versus ocean memory.

Over the past decade, studies have indicated that Pacific ocean-atmosphere variability outside of the tropics may provide an important deterministic component for the excitation of ENSO events [11–15]. Such external forcing can "push" the aggregated statistics of stochastic tropical noise (e.g., WWEs) towards ENSO-favorable conditions throughout the developing stages of ENSO, potentially increasing long-lead predictability [12, 13, 16, 17]. These extratropical-tropical interactions primarily manifest through the evolution of the so-called North Pacific Meridional Mode (NPMM; Fig. 1a), which represents the second leading mode of North Pacific ocean-atmosphere variability [18].

Since Chiang and Vimont [18] first formalized the NPMM definition, studies have shown significant skill in predicting boreal winter ENSO conditions when considering the state of the NPMM in the preceding spring [11–13, 19–22]. This connection stems from four main physical pathways: (1) A positive feedback between wind-induced latent heat flux anomalies and SSTAs known as Wind-Evaporation-SST (WES) feedback [23], which propagates surface wind anomalies from the subtropics onto the equator during boreal spring and early summer [21, 24–26], (2) Trade Wind Charging (TWC) of equatorial subsurface heat content by NPMM-related surface wind stress curl anomalies in boreal winter and early spring [27, 28], (3) The reflection of NPMM-triggered ocean Rossby waves off the western boundary as equatorial Kelvin waves in boreal summer [21, 29], and (4) A NPMM-forced shift of the mean Intertropical Convergence Zone (ITCZ) in boreal summer and fall, which results in a Gill [30]-like atmospheric response that projects on the equator [11, 22, 31, 32].

Given this progress and the socioeconomic relevance of ENSO, the goal of this paper is to review the current understanding of the evolution of the NPMM, its governing mechanisms, and its relationship to the timing, magnitude, flavor, and predictability of ENSO. More specifically, we will focus on a seasonal decomposition of the NPMM and its interaction with the tropical ocean-atmosphere state during different stages of the ENSO lifecycle. The manuscript is organized as follows. "North Pacific Meridional Mode: Seasonal Connections to ENSO" outlines the seasonal evolution of the NPMM and the various mechanisms by which it influences ENSO. "Role of Mean State" assesses the importance of the tropical mean state in modulating the efficacy of these extratropical-tropical interactions. "NPMM vs. SPMM" and "PMM and Tropical Pacific Decadal Variability" discusses the South Pacific and the PMM's role in contributing to Pacific decadal variability, respectively. Finally, "Summary and Pathways Forward" offers a summary and a perspective on future research questions.

North Pacific Meridional Mode: Seasonal Connections to ENSO

The NPMM is traditionally defined as the first Maximum Covariance Analysis (MCA; [33]) pattern of detrended, 3-month running mean SSTA and 10 m wind anomalies from about 20°S-30°N, 175°E-85°W [18]. In order to isolate extratropical variability that is independent of concurrent ENSO conditions, linear regression is often used to remove an ENSO index from all fields prior to the analysis. Figure 1 shows the results of the calculation using gridded observational products from 1979 to 2018 [34, 35]. Figure 1a depicts the

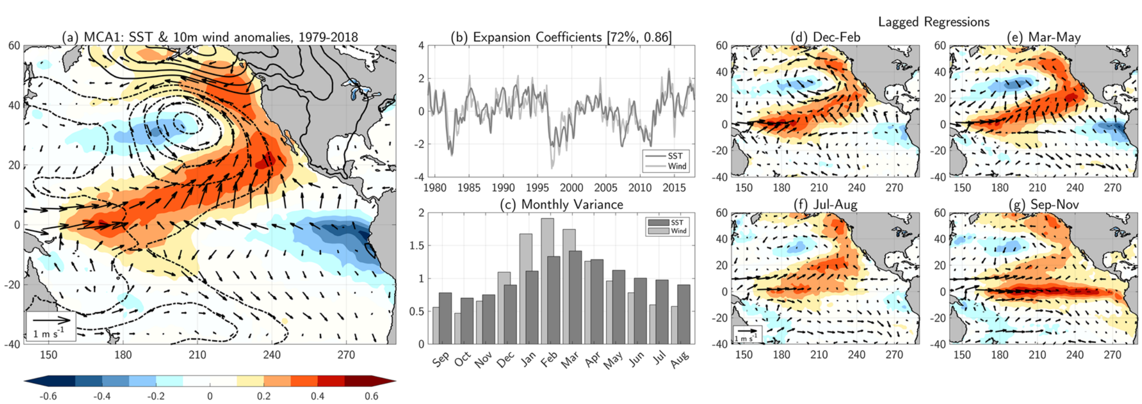

Fig. 1 MCA analysis of SST and 10 m wind anomalies. Calculated for the region 21°S-32°N, 175°E-95°W from 1979 to 2018. For all x/y maps, shading is SSTAs (°C) and arrows are 10 m wind anomalies (m s^{-1}). **(a)** SSTAs and 10 m wind anomalies regressed on normalized SST Expansion Coefficient (EC) in **(b)**. Black contours are SLP anomalies (hPa) regressed on 2-month lagged SST EC (i.e., SLP leads by 2 months). SLP anomaly contour intervals are 2 hPa. **(b)** SST and Wind ECs describing time variability of MCA1. First number in title is the squared covariance fraction for MCA1. Second number in title is the correlation of the two ECs. **(c)** Monthly variance of SST and Wind ECs. **(d)**–**(g)** Seasonally averaged SSTAs and 10 m wind anomalies regressed on March–May averaged SST EC. Note ENSO linearly removed from data prior to taking regressions in **(a)**, but not **(d)**–**(g)**. SST data is from HadISSTv1.1 and atmospheric variables are from ERA5

linear regression of SSTAs and 10 m wind anomalies on the SST Expansion Coefficient (ECs) in Fig. 1b.

The NPMM spatial pattern features warm SSTAs in the subtropical Pacific and cool SSTAs in the eastern equatorial Pacific, producing a characteristic anomalous meridional SST gradient. The positive subtropical SSTAs are maintained by southwesterly surface wind anomalies, which tend to weaken the background trade winds, reduce evaporative cooling at the surface, and warm the upper ocean through a downward latent heat flux [18, 22, 23]. The lead-lag relationship between the surface winds and the upper ocean is more apparent when analyzing the temporal characteristics of the normalized SST (dark gray) and wind (light gray) ECs (Fig. 1b and c). The month-to-month variance of the SST EC peaks in March, while the wind EC peaks a month earlier in February. As a result, while the two ECs are significantly correlated at zero-lag ($R = 0.86$), a cross-correlation analysis shows an asymmetry towards stronger correlations when the wind EC leads the SST EC (see Fig. 2 of Chiang and Vimont [18]).

The original NPMM index was calculated using monthly mean data from all months; however, the physical mechanisms that govern the evolution of the NPMM and its interaction with ENSO strongly vary from season-to-season [11, 16, 21, 22, 26, 27, 36, 37]. This is apparent in the different patterns observed in lagged regressions of seasonally averaged SSTA and 10 m wind anomalies on the March–May (MAM) averaged SST EC (Fig. 1d–g). Therefore, it is important to consider a seasonal decomposition of the NPMM.

NPMM Initiation: Wintertime Stochastic Forcing

The NPMM begins its lifecycle through random fluctuations in the strength of the tropical trade winds during boreal winter [16, 18, 21, 26, 38]. This is primarily accomplished via mid-latitude atmospheric variability associated with the North Pacific Oscillation (NPO), which represents the second Empirical Orthogonal Function (EOF) of wintertime sea-level pressure (SLP) anomalies over the North Pacific [39, 40]. The NPO's importance to the initiation of the NPMM in boreal winter is apparent in Figs. 1a and 2a. The black contours in Fig. 1a depict SLP anomalies regressed onto the 2-month lagged SST EC (Fig. 1a black contours), producing a pattern that strongly resembles the NPO [16, 40]. Figure 2a shows January–March (JFM) averaged latent heat flux (positive upwards) and 10 m wind anomalies regressed onto the following MAM averaged SST EC. Throughout the subtropical North Pacific, westerly wind anomalies associated with the NPO oppose the mean trade winds, producing strong downward latent heat flux anomalies (Fig. 2a shading) that warm the upper ocean (Fig. 2a black contours).

The SSTA "footprint" left by anomalous mid-latitude circulation was first recognized as an integral component of the so-called Seasonal Footprinting Mechanism (SFM) [11, 21, 31, 32], which is an overarching framework that was developed to describe the seasonal evolution of NPO-induced SSTAs, their relationship to the mean Intertropical Convergence Zone (ITCZ), and ultimately their influence on the tropics (see Fig. 15, Amaya et al. [22]). While the NPMM and SFM are intimately related, there are some notable differences that will be expounded upon in "SFM, NPMM, and Summertime ITCZ."

Finally, it is important to reiterate that the fluctuations of the NPO, and by extension the initiation of a NPMM event, is stochastic. However, as discussed below, the physical mechanisms that govern the evolution of these SSTAs and their influence on the atmosphere include a deterministic component [12, 13, 22, 37]. Therefore, while triggering a NPMM event may be random from winter-to-winter, its evolution is more predictable in space, making it a potentially useful tool for improving long-lead ENSO forecasts.

NPMM Growth and Persistence: Importance of Ocean-Atmosphere Coupling

NPO forcing of subtropical North Pacific SSTAs is largely confined to the winter season [16, 40], and in the absence of external forcing, these subtropical SSTAs have an e-folding dampening rate of about 6 months [41]. Further, the NPO's influence on the subtropical upper ocean is a one-way forcing. In contrast, the NPMM is defined as a coupled mode of climate variability [18]. Therefore, a NPMM "event" is not, strictly speaking, said to occur until there is evidence of ocean-atmosphere interactions. For these reasons, both the genesis of the NPMM and its persistence into boreal spring and summer (Figs. 1e–g) relies heavily on coupled ocean-atmosphere feedbacks.

These feedbacks are triggered when NPO-forced SSTAs substantially influence surface winds via deep convection [30] or boundary layer processes [42, 43]. Within the boundary layer, the atmospheric response to an equatorially asymmetric SSTA dipole features cross-equatorial winds from the colder hemisphere to the warmer hemisphere. Due to the Coriolis force, these anomalous winds further weaken the trades in the warmer hemisphere, while strengthening the mean winds in the colder hemisphere. The subsequent latent heat flux response will reinforce the meridional SSTA gradient. As a result, the SST-forced cross-equatorial wind anomalies will similarly strengthen, thereby initiating a positive feedback [25, 44, 45]. This interaction between the SSTAs, surface wind anomalies, and latent heat flux anomalies is known as WES feedback [23] and is integral to the identification and persistence of a NPMM event during boreal spring [18]. Increased downward shortwave radiation at the surface also maintains NPMM SSTAs into boreal spring, particularly in the northwest tropical Pacific [21, 26].

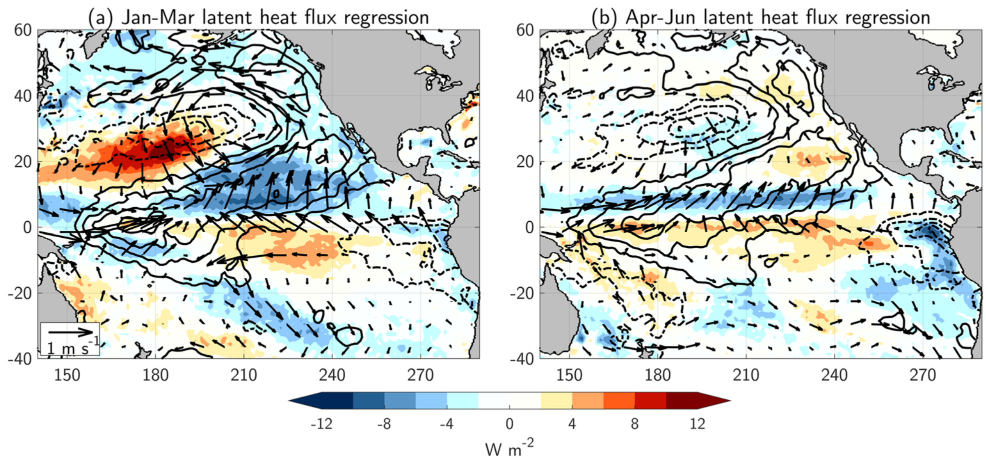

Fig. 2 **(a)** January–March averaged SSTAs (°C; black contours), 10 m wind anomalies (m s^{-1}; arrows), and latent heat flux anomalies (W m^{-2}; shading) regressed on March–May averaged SST EC from Fig. 1b. **(b)** Same as Fig. 2a, but for April–June averaged variables. In order to be consistent with Fig. 1 d-g, ENSO not linearly removed from data prior to taking regressions. SST data is from HadISSTv1.1 and atmospheric variables are from ERA5

Evidence for WES feedback is seen in Fig. 2b, which shows the April–June (AMJ) regression of SSTAs, latent heat flux anomalies, and 10 m wind anomalies onto the preceding MAM SST EC. Around 20°N, upward latent heat flux anomalies indicate a boundary layer atmospheric response, and suggest the underlying SSTAs are dampening [25, 26]. East of the dateline, cross-equatorial 10 m wind anomalies turn according to the Coriolis force, producing the classic C-shape bend that is characteristic of WES feedback [23]. As a result, there is a zonal band of downward (upward) latent heat flux anomalies in the northern (southern) deep tropics where the anomalous winds are further weakening (strengthening) the background trades.

Within the northern subtropics, the combination of upward (downward) latent heat flux anomalies to the northeast (southwest) of the SSTA maximum initiates a southwestward propagation of the SSTA and surface wind anomalies [24, 25, 37, 45]. This WES-driven propagation produces zonal wind stress anomalies along the equator that can excite ocean Kelvin waves, marking the first opportunity for a NPMM event to significantly influence the development of ENSO [16, 21, 22]. These WES interactions are most pronounced in late boreal spring into early summer [26] and have been identified in observations [22, 25, 46] and across a hierarchy of model simulations [16, 21, 22, 26, 37, 45, 47–49]. Therefore, they are a robust feature of the NPMM.

Due to mixed-layer coupled interactions like WES feedback, the NPMM does not require ocean dynamics to evolve. However, that does not mean ocean dynamics are unimportant in transmitting NPMM-related signals into the deep tropics [15]. Anderson et al. [27] and Anderson and Perez [28] showed that wind stress curl anomalies associated with the NPO in boreal winter and the NPMM in boreal spring can charge/discharge subsurface ocean heat content along the equatorial Pacific through meridional mass transport anomalies, leading to a mature ENSO event 12 months later. Additionally, Alexander et al. [21] showed that NPMM-driven surface wind changes can excite off-equatorial ocean Rossby waves during boreal spring, which reflect off the western boundary as equatorial Kelvin waves during the summer and modulate the thermocline in the eastern Pacific. These interactions are summarized in Fig. 5 and represent two additional, primarily oceanic, connection between the NPMM and ENSO.

SFM, NPMM, and Summertime ITCZ

The influence of subtropical North Pacific SSTAs on the summertime ITCZ and atmospheric circulation is referred to as the Summer Deep Convection (SDC) response [22] and was first discussed as a key component of the SFM [11, 31, 32]. Within this framework, NPO-forced SSTAs persist into the summer and induce an anomalous meridional shift of the ITCZ. Convective heating anomalies in the mid-troposphere then drive a Gill-like atmospheric circulation pattern that reflects the solution to an off-equatorial heat source [30]. Surface wind anomalies associated with this pattern project onto the equator, where they can drive ocean Kelvin waves and interact with ENSO during boreal summer and fall [11, 21, 22, 32].

As a result of ocean-atmosphere interactions like WES feedback, NPMM-related SSTAs can significantly persist into boreal summer and early boreal fall [26], where they can then excite this SDC response. The seasonality of the SDC response is driven by the timing of the strongest subtropical SSTAs relative to the position of the mean ITCZ during its seasonal migration. During boreal spring when the NPMM peaks, the ITCZ is closest to the equator and is less sensitive to off-equatorial SSTAs. In contrast, during the late summer, the ITCZ is furthest north and is much more sensitive to persistent NPMM-related SSTAs in the subtropical North Pacific [22, 26]. If triggered, the SDC response offers another distinct opportunity for the NPMM to influence ENSO's development.

Figure 3a illustrates the SDC response as a Joint EOF of detrended August–October (ASO) averaged SSTA and precipitation anomalies in gridded observational products. Note that concurrent ENSO was linearly removed prior to the

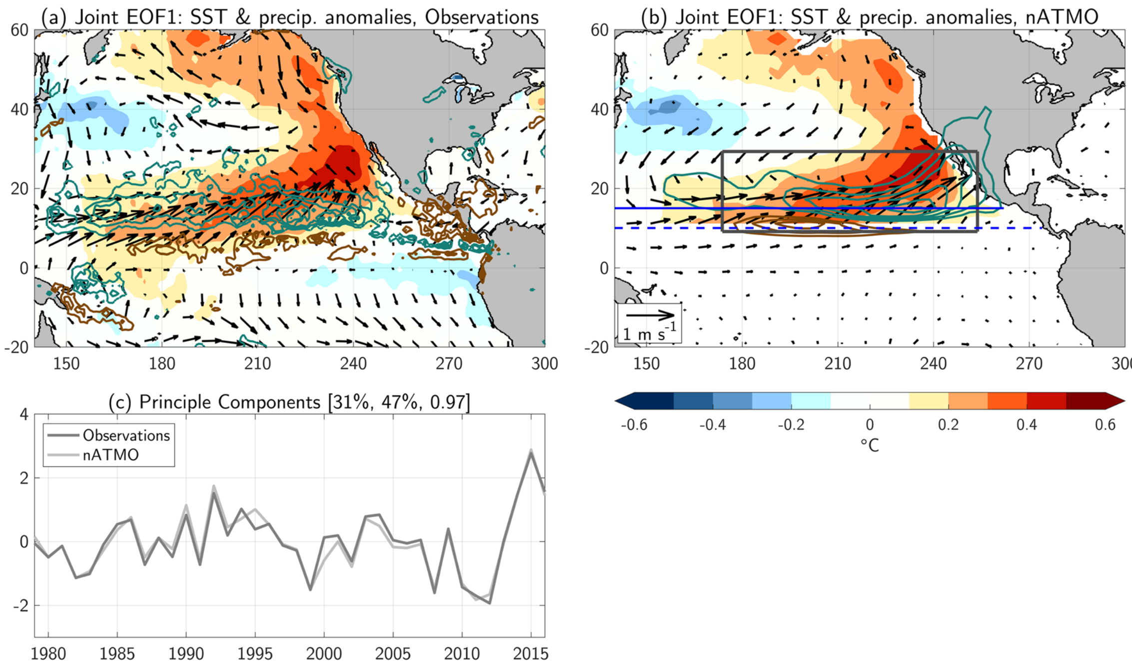

Fig. 3 Joint EOF1 of August–October averaged SSTAs and precipitation anomalies in observations **(a)** and the mean of a 10-member ensemble of boundary-forced atmospheric model simulations (nATMO) **(b)**. nATMO is forced only with observed SSTAs in the North Pacific, north of 15°N (solid blue line). See Amaya et al. [22] for further details. Each Joint EOF is calculated for the region encompassed by the gray box in **(b)** from 1979 to 2016. The x/y maps in **(a)** and **(b)** represent regressions of SSTAs (°C; shading), 10 m wind anomalies (m s^{-1}; arrows), and precipitation anomalies (mm day^{-1}; colored contours, green positive) on their respective normalized PCs depicted in **(c)**. First and second number in title of **(c)** is the variance explained by the observed and nATMO Joint EOF1, respectively. Third number is the correlation between the PCs. Note ENSO linearly removed from data prior to taking regressions. Observed SST data is from HadISSTv1.1 and observed atmospheric variables are from ERA5

analysis. The first Joint EOF is characterized by a NPMM-like SSTA pattern and a zonal band of positive (negative) precipitation anomalies centered on 15°N (5°N) that are consistent with a northward shift of the mean ITCZ. The regression of 10 m wind anomalies shows a broad, Gill-like cyclonic circulation in the subtropics and westerly wind anomalies along the equatorial west Pacific.

Studies have used observations [11] and atmospheric models forced with North Pacific SSTAs [22, 31, 32] to show that these equatorial surface wind anomalies are a direct result of the summertime NPMM-driven ITCZ shift. Further, Amaya et al. [22] used North Pacific SST-forced atmospheric model simulations (nATMO) to show that this SDC response accounts for about 25% of observed zonal wind time variability around the equatorial dateline since 1950. Figure 3b shows the same Joint EOF using their nATMO simulations, which agrees well with observations. While Amaya et al. [22] emphasizes that the North Pacific-forced equatorial wind anomalies are uncoupled from the underlying ocean, Vimont et al. [26] suggests that ocean-atmosphere coupling tends to amplify the downstream wind response and can drive it even closer to the equator. Finally, the presence of developing ENSO conditions along the equator may influence the efficacy of NPMM-related SSTAs in shifting the ITCZ and forcing an atmospheric circulation response. However, the observations and atmospheric model are still similar when repeating the Joint EOF analysis without first linearly regressing out ENSO.

NPMM and ENSO Forecasting

The NPMM offers several distinct opportunities for mid-latitude ocean-atmosphere variability to influence the seasonal development of ENSO. These teleconnective pathways have the potential to inject ENSO-favorable conditions along the equatorial Pacific throughout the year. To what extent can the NPMM and these physical mechanisms be used as a deterministic component in long-lead ENSO forecasting? To demonstrate, Fig. 4 shows the lagged relationship of box-averaged subtropical SSTAs ($NPMM_{box}$; see Fig. 4 caption) with the Niño3.4 index in hindcast simulations from the North American Multimodel Ensemble (NMME; [51]). For each initialization month in Fig. 4a, the model forecast (at 0.5-month lead) of $NPMM_{box}$ is correlated with the observed Niño3.4 index in the following December. Each model is initialized with observations; therefore, the lag-correlation between $NPMM_{box}$ and observed Niño3.4 is expected to be close to the observed value (black dot-dashed line). The spread of the multimodel ensemble at any given month is due to different estimates of the trajectory of $NPMM_{box}$ over half a month.

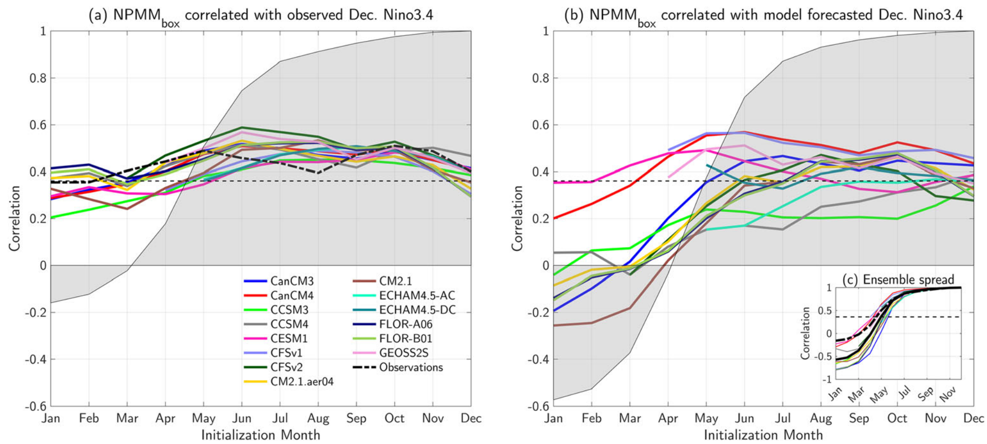

Fig. 4 Lagged correlations of $NPMM_{box}$ index (SSTAs averaged 15°N-25°N, 150°W-120°W) with December Niño3.4 indices from 1982 to 2010. Indices calculated for observations (HadISSTv1.1; **(a)** only) and 14-ensemble mean hindcast simulations from NMME [51]. For each month in **(a)**, the observed value (black dot-dashed) is the correlation of observed $NPMM_{box}$ for that month with the observed December Niño3.4. Individual NMME model (solid colors) values represent the correlation of the model forecasted $NPMM_{box}$ index at 0.5-month lead with observed December Niño3.4. For each month in **(b)**, individual NMME model values represent the correlation of model forecasted $NPMM_{box}$ index at 0.5-month lead with model forecasted December Niño3.4 (i.e., at lead = $12 - (N - 0.5)$, where $N = 1 \ldots 12$ represents the calendar month). Curving thin black lines represent monthly correlations of Niño3.4 with the following December Niño3.4 in **(a)** observations and **(b)** the NMME multimodel mean. Gray shading indicates correlation values smaller than these curves. Niño3.4 persistence curves for each model are shown in **(c)**. Solid (dot-dashed) black line in **(c)** represents the multimodel mean (observations). Black dashed line in all subplots represents 95% significance based on a Student's t test. Models with no reported correlation did not provide forecasts for the given lead time

Based on Fig. 4a, subtropical SSTAs are significantly correlated with observed December Niño3.4 in boreal spring through fall, explaining ~15–30% of the variance, which is consistent with recent observational estimates of the NPMM's influence on ENSO [12, 14, 17, 19, 22, 52]. How do these values compare to the month-to-month persistence of the Niño3.4 index itself? In other words, for a given initialization month, is $NPMM_{box}$ or Niño3.4 a better predictor of the following December Niño3.4 index? One way to measure this is to compare the $NPMM_{box}$ values for each month to the corresponding correlation of observed Niño3.4 with the following observed December Niño3.4 (curving thin black line). If the $NPMM_{box}$ correlation is stronger than the Niño3.4 correlation (i.e., outside the gray shading) and above the 95% significance line (horizontal black dashed), then this provides evidence that the NPMM may extend skillful prediction of Niño3.4 beyond blind persistence. By this measure, observed subtropical North Pacific SSTAs beat Niño3.4 persistence starting in about May, and potentially extend prediction skill to as early as February (Fig. 4a). This is generally consistent with Larson and Kirtman [12] who also used NMME to show that March NPMM is a good predictor of December El Niño events. However, their results indicate that the NPMM most accurately forecasts East Pacific (EP) type El Niño events and does not predict La Niña events with any skill.

How do these relationships compare within the NMME forecasting models? Figure 4b is the same as Fig. 4a, but instead shows the relationship between model forecasted $NPMM_{box}$ and model forecasted December Niño3.4 for different lead times. For example, an April initialization represents the correlation of model forecasted $NPMM_{box}$ at 0.5-month lead with model forecasted Niño3.4 at 8.5-months lead. As before, these values can be compared to the correlation of model forecasted Niño3.4 with the model forecasted December Niño3.4 (colored lines Fig. 4c). However, for brevity we compare the $NPMM_{box}$ correlations for all models to the multimodel mean Niño3.4 persistence curve (heavy black line in Fig. 4c; thin black line and gray shading in Fig. 4b).

When initialized from January to about March, the $NPMM_{box}$ index is not significantly correlated to December Niño3.4 for almost all of the models. However, beginning in boreal spring, this relationship strengthens across the ensemble, and for several models, there are even significant correlations that lie outside of the gray shaded region from April to May. This indicates that subtropical North Pacific SSTAs may increase prediction skill relative to persistence during these months, which could potentially improve ENSO forecasting during the so-called "spring predictability barrier" [53]. Further, these results support past studies who suggest that the NPMM may serve as a source of ENSO forecasting error if it is incorrectly simulated in seasonal climate predictions [12, 17].

Role of Mean State

The previous sections outlined the various physical mechanisms by which the NPMM evolves and interacts with ENSO. An important aspect to consider when discussing these pathways is the influence of the mean state on their efficacy.

For example, consider a simplified tropical atmosphere thermodynamically coupled to a constant-depth slab ocean. Assuming that changes in meridional winds have a negligible impact on surface heat fluxes, the ocean temperature equation is:

$$\frac{\partial T}{\partial t} = \boldsymbol{a}u - \boldsymbol{b}T \tag{1}$$

where u is the zonal wind component and T is SST. Anomalies in T experience a Newtonian damping term, $\boldsymbol{b}$, which has an e-folding timescale of about 6 months. The ocean is thermodynamically coupled to the atmosphere through the WES feedback parameter, $\boldsymbol{a}$, which represents the change in latent heat flux per unit change in the near-surface winds. By assuming a linearized change in latent heat flux (LH) per unit change in wind speed [26, 54] and by substituting the standard bulk formula in which the latent heat flux is linearly proportional to the wind speed $\overline{w} = (u^2 + v^2 + w^2)^{1/2}$, $\boldsymbol{a}$ can be calculated as:

$$\boldsymbol{a} = -\frac{\partial LH}{\partial u} = -LH\frac{u}{\overline{w}^2} \tag{2}$$

See Vimont et al. [45] for the full derivation. Note that the formulation of $\boldsymbol{a}$ also does not consider the contribution of meridional wind variations to WES feedback as the zonal wind component dominates [24].

For mean tropical easterlies, Eq. (2) implies a reduction in the mean upward latent heat flux at the surface per unit westerly zonal wind anomaly, which yields a positive value of $\boldsymbol{a}$ and ocean warming. This equation also suggests that shifts in the mean strength of the trade winds will alter the effectiveness of $\boldsymbol{a}$ in exciting large changes in T. Namely, Eq. (2) implies that larger mean easterlies will induce a larger downward (upward) anomalous heat flux for the same anomalous westerly (easterly) zonal wind speed. As such, Vimont et al. [26] investigated the role of the seasonal cycle in modulating the strength of the WES feedback parameter in the tropical Pacific. They showed that $\boldsymbol{a}$ is uniformly large throughout the tropics during boreal spring and fall, consistent with nearly uniform easterly trade winds. However, during boreal summer and winter, there is a sharp reduction in $\boldsymbol{a}$ in the western summer hemisphere tropics due to a weakening of the mean trade winds, which they attribute to the seasonal migration of the subtropical highs and monsoon troughs.

Aside from seasonal variations in $\boldsymbol{a}$, recent studies have investigated whether shifts in past and/or future climate equilibria significantly impact WES feedback and, by extension, the NPMM-ENSO relationship. Coupled climate models forced with future projections of greenhouse gas emissions show a ~20% increase in the North Pacific WES feedback parameter by 2100, which is beyond the range of internal $\boldsymbol{a}$ variations generated by unforced control simulations [55, 56]. These results point towards a strengthening of WES feedback in warmer world, and perhaps an increasing role for the NPMM in future ENSO variability. However, it is possible that future changes in thermal damping (i.e., $\boldsymbol{b}$ in Eq. (1)), future changes to ENSO itself [57], and/or model sensitivities could affect this conclusion. Thus, future work is needed to investigate the NPMM-ENSO relationship in a changing climate.

NPMM vs. SPMM

The focus of this review is primarily on the variability and impacts of the North Pacific Meridional Mode. However, studies have emphasized the importance of a similar mode of climate variability found in the South Pacific—the South Pacific Meridional Mode (SPMM). The physical interpretation of the SPMM is nearly identical to its northern counterpart, with off-equatorial southeast trade wind variability giving rise to a WES-driven equatorward propagation of SSTAs, surface wind anomalies, and latent heat flux anomalies [58]. The SPMM is also triggered by similar internal atmospheric variability associated with the South Pacific Oscillation [59, 60] during boreal summer. However, due to the seasonality of local mixed-layer depths, the SPMM SST and wind components vary out of phase with one another. Thus, SPMM WES feedback tends to peak in boreal winter [61, 62].

Despite this recent progress, there is still some uncertainty regarding the physical mechanisms that connect the SPMM to ENSO. Several studies argue that, similar to the NPMM, WES feedback propagates surface wind anomalies associated with the SPMM towards the central equatorial Pacific, where they can be important for the generation of ocean Kelvin waves and the overall timing of ENSO [14, 52, 58, 61, 63, 64]. There is also evidence that the SPMM is inherently more effective than the NPMM at propagating surface anomalies onto the equator due to the northward displaced ITCZ, which results in southeasterly mean trade winds that cross the equator in the eastern Pacific [65].

In contrast, a recent study by Larson et al. [62] suggests that the SPMM need not "trigger" ENSO through equatorial ocean dynamics in order to significantly modulate the amplitude of an event. In particular, they show that the SPMM acts as a thermally driven source of eastern Pacific SSTAs that can constructively or deconstructivity interfere with coincident ENSO events by modifying the effectiveness of latent heat flux damping. This interpretation is further supported by the presence of ENSO-like variability in general circulation models that either lack ocean dynamics completely (i.e., slab ocean models) [58, 66] or restrict ocean circulation anomalies by prescribing surface wind stress [62]. Regardless, there is no clear consensus in the literature on how the SPMM and ENSO are physically connected. Therefore, future research is needed on these topics.

Additionally, there is uncertainty regarding the contributions of the NPMM and the SPMM to ENSO diversity. ENSO diversity refers to the observed difference in the magnitude and longitudinal location of equatorial SSTAs from one ENSO event to the next [67]. Generally, the SPMM tends to be associated with the onset of EP ENSO events [58, 60, 64, 68], while the NPMM may favor the development of Central Pacific (CP) ENSO events [17, 22, 38, 68, 69]. Recent research has also emphasized the combined effects of the NPMM and SPMM as being important in determining the timing, intensity, and diversity of ENSO events [61, 70]. However, other studies suggest that SST-based precursors may have a minor influence on ENSO diversity when compared to other factors such as the initial thermocline state along the equator [71]. Further investigation into these relationships may improve predictability of the various impacts generated by different ENSO "flavors" [67, 72].

PMM and Tropical Pacific Decadal Variability

Recent research indicates that the NPMM and SPMM may collectively contribute to Tropical Pacific Decadal Variability (TPDV) [38, 55, 56, 61, 62, 66, 73, 74]. Indeed, You and Furtado [61] show that observed NPMM and SPMM indices exhibit significant periodicities longer than ~5 years and significant squared coherence with ENSO at periods beyond 6 years (see their Fig. 14). These decadal periodicities may arise partly from mid-latitude air-sea coupling that reddens the oceanic response to white-noise atmospheric forcing [18, 75], and partly from tropical Pacific remote forcing [36, 76]. The latter mechanism is essential to the so-called "Pacific climate null hypothesis" [38, 74], which describes a process where extratropical atmospheric variability excites an ENSO event ~12 months later through meridional mode dynamics, and then the resulting ENSO-driven atmospheric teleconnections force ocean anomalies in the extratropics that decay over a period of 6–12 months. These ocean anomalies may then couple back to the tropics by reenergizing the meridional modes, completing a multiyear feedback.

Another hypothesis suggests that the SPMM may be more important than the NPMM in driving TPDV [62, 66, 73]. When artificially suppressing the NPMM in a coupled climate model, Liguori and Di Lorenzo [73] reported a substantially weaker ENSO, but little change in TPDV. However, when they suppressed the SPMM, they found the opposite was true. This study and others [49, 62, 65, 77] support an earlier analysis by Okumura [66], which proposed that thermodynamics air-sea interactions (e.g., WES feedback) originating from the South Pacific more frequently intrude into the equatorial region owing to the eastern Pacific ITCZ being positioned northward throughout most of the year. Nevertheless, even at low-frequencies the meridional modes are only a significant predictor of TPDV at ~1 year lead [61], which suggests limited scope for improving decadal predictability of Pacific climate. Further work investigating the mechanisms that connect the NPMM, SPMM and TPDV may overcome these limitations.

Summary and Pathways Forward

The last two decades have seen exciting advances in our understanding of extratropical ENSO precursors. As a result, the North and South Pacific Meridional Modes are now recognized as important components of the tropical climate system that significantly modulate the timing, amplitude, and/or flavor of ENSO. To a first order, this relationship stems from a series of air-sea interactions that inject ENSO favorable conditions onto the equator by integrating stochastic mid-latitude atmospheric variability into a propagating band of SSTA and surface wind anomalies. Additional studies have shown that the NPMM can also interact with the mean ITCZ and force a Gill-like atmospheric response that projects onto the equator. This offers a second distinct opportunity for the NPMM to influence the development of ENSO. With respect to ocean circulation, off-equatorial NPMM-related wind stress curl anomalies induce meridional mass transport into and out of the equatorial Pacific, which can charge or discharge subsurface heat content along the equator and provide the necessary conditions for an ENSO event. Finally, the propagation and reflection of ocean Rossby waves triggered by the NPMM may also impact the equatorial Pacific. These physical pathways are summarized in the schematic illustration depicted in Fig. 5.

While the initiation of a NPMM event results from largely unpredictable atmospheric forcing, its seasonal evolution is deterministic, and may provide an opportunity to improve ENSO forecasting on seasonal to interannual timescales. The best observational estimates show that boreal spring NPMM can explain about 15–30% of ENSO variability in the following winter. This relationship is largely reproduced in ensembles of model hindcast simulations (Fig. 4 here; [12]); however, improving the simulation of NPMM dynamics may extend the skillful prediction of ENSO during the spring predictability barrier [17].

In spite of these advances, there are a number of outstanding questions that should be addressed. First, what impact does internal tropical noise have on the efficacy of external PMM-related (both North and South Pacific) signals? The surface anomalies associated with the PMMs are small relative to similar perturbations produced within the tropics. Thus, their effectiveness in influencing ENSO is heavily reliant on the timing of tropical noise relative to the timing of the external forcing. Relevant tropical processes include atmospheric

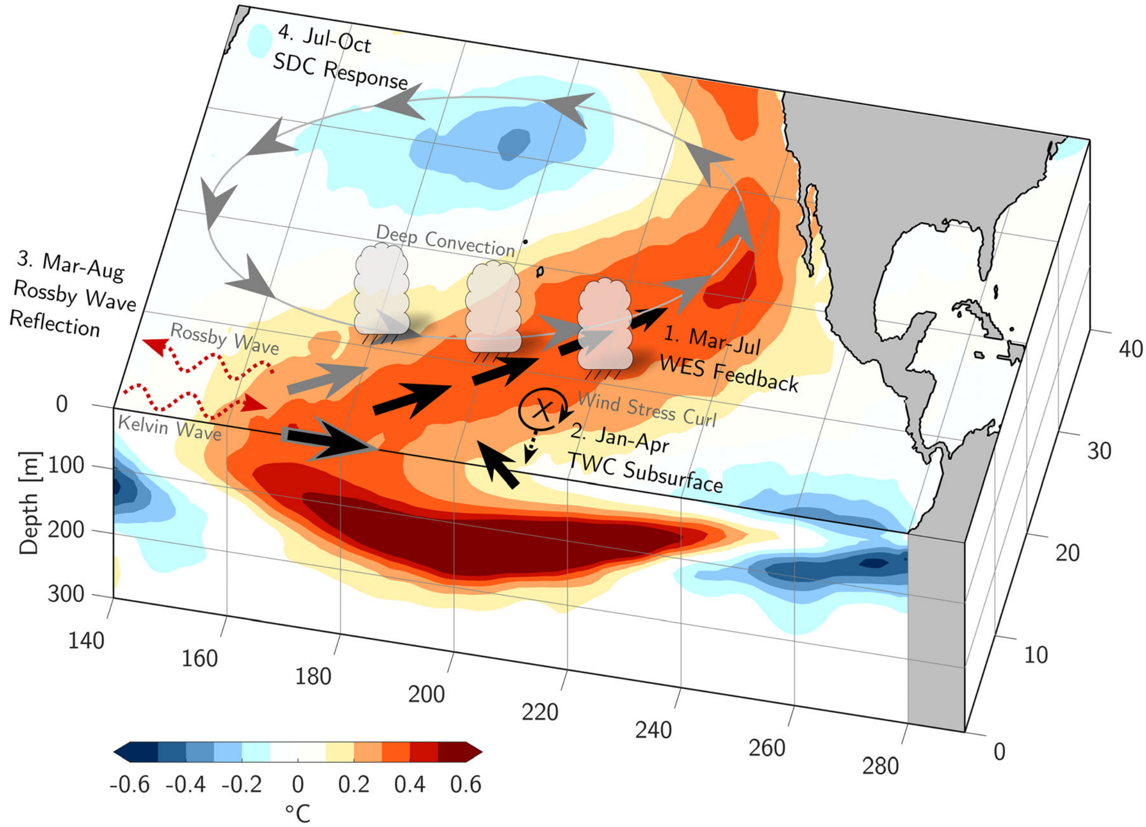

Fig. 5 Schematic illustration of the primary physical pathways linking the NPMM to ENSO. They include: (1) A Wind-Evaporation-SST (WES) feedback driven propagation of surface anomalies onto the equator during boreal spring (solid black arrows), (2) Trade Wind Charging (TWC) of equatorial subsurface heat content by NPMM-related surface wind stress curl anomalies in boreal winter and early spring (black circular/dashed arrows and x/z shading), (3) The reflection of NPMM-forced ocean Rossby waves off the western boundary in boreal summer (red dashed arrows), and (4) A Gill-like atmospheric circulation pattern associated with an anomalous ITCZ shift in boreal summer and fall known as the Summer Deep Convection (SDC) response (clouds and solid gray arrows/lines). Each mechanism provides an opportunity for North Pacific Ocean–atmosphere anomalies to influence ENSO development, either by altering off-equatorial ocean circulation (as in Pathways 2 and 3) or by generating zonal wind stress anomalies along the equator (as in Pathways 1 and 4). Shading in the x/y plane is the same as Fig. 1a. Shading in the x/z plane is the regression of observed subsurface potential temperature anomalies averaged 5°S-5°N on the SSTA EC depicted in Fig. 1b. Subsurface temperature data is from the GODAS ocean reanalysis [50] for the period 1980–2018. Note arrows are not to scale

modulations across the tropics such as the Madden Julian Oscillation [78], the buildup or recent discharge of subsurface ocean heat content [27, 28, 61, 79, 80], and the influence of other basins on the tropical Pacific [81]. Additionally, the primary focus of this paper has been on triggering ENSO; however, PMM-driven teleconnections may also disrupt ENSO development if the subtropical forcing is out of phase with the internal tropical state. Uncovering which internal tropical states are most/least susceptible to PMM forcing will improve the overall simulation and increase predictability of the PMM-ENSO relationship.

Related to this is, how does an altered tropical mean state impact the PMM-ENSO relationship? Early work on this topic indicates that the WES parameter ($\frac{\partial LH}{\partial u}$) is projected to increase as a result of global warming [55, 56], which implies a potential enhanced role for the PMMs in future ENSO variability. However, climate model simulations also suggest that the distribution of ENSO events could fundamentally change in a warmer world [57], which would impact the PMM-ENSO relationship as well. Further, the northward positioned mean ITCZ has been shown to be a limiting factor in the PMMs' interaction with the deep tropics [65]. Paleoclimate proxy-based reconstructions of past hydroclimate change have revealed substantial meridional shifts in the zonal mean ITCZ in response to large-scale climate forcing [82]. Therefore, it is reasonable to hypothesize that the relative impact of the NPMM and SPMM on ENSO has not been constant throughout history. Moving forward, it will become increasingly important to untangle these mean state relationships in past and future climates.

Another interesting question is, what role does the NPMM and SPMM play in TPDV and multiyear ENSO events? There is substantial evidence to suggest that both PMMs can significantly contribute to TPDV (see "PMM and Tropical Pacific Decadal Variability"); however, the importance of these interactions and the extent to which they may improve decadal predictability of tropical Pacific climate remains unclear. Additionally, while most research is focused on the PMMs' impact on ENSO, there has been comparably less work on ENSO's influence on the PMMs [76]. ENSO's projection on the NPO and SPO may reenergize subtropical coupled dynamics during boreal winter [38]. As a result, ENSO-forced PMM may play an important role in multiyear ENSO events [83, 84] and the transition between El Niño and La Niña [79].

Of some concern is the separability of ENSO and the PMMs. It is common to linearly regress out an ENSO index from surface variables before calculating a PMM index via MCA [18]. This is typically done to isolate subtropical climate variability that is linearly independent from concurrent ENSO. However, ENSO is an evolving phenomenon with a diverse array of "flavors" that cannot be accurately captured by a single index [67, 85]. Therefore, it is unclear which ENSO index is most appropriate to remove or whether it is even a necessary step when defining PMM variability. For example, Fig. 1a was obtained by removing the first EOF of detrended tropical Pacific SSTAs (20°S-20°N, 140°E- 60°W), which is highly correlated with the Niño3 index ($R = 0.99$), but less so with Niño4 ($R = 0.83$). Figure 1a is recovered, in full, as the second MCA if this pre-processing step is not taken; however, the MCA results are significantly different if instead the Niño4 index is removed. This may be related to the strong zero-lag relationship between the NPMM and CP ENSO [76], which is apparent from the positive SSTAs found along the equatorial dateline in Fig. 1d. Future research is needed to assess the sensitivity of the PMM definition to different characterizations of ENSO variability.

Finally, the NPMM and SPMM are not only important to tropical Pacific climate; both climate modes have consequential impacts on mid-latitude ocean-atmosphere variability. For example, NPMM variability has been linked to changes in tropical cyclone activity in the Western North Pacific [86], the Northeast Pacific [87], and the North Atlantic [88]. The 2014 NPMM event was a significant component of the 2013–2015 North Pacific marine heatwave [89, 90], which had far reaching impacts on marine ecosystems along the North American coastline [91]. There is evidence that WES feedback and the PMM may play an important role in the so-called "energetics framework," which relates the zonal mean position of the ITCZ to interhemispheric energy imbalances [82, 92]. Additionally, the interaction of the NPMM with the North Pacific subtropical high may alter the frequency of atmospheric ridging events in boreal fall, with implication for subseasonal-to-seasonal predictability of landfalling atmospheric rivers over the Southwestern USA [93]. Further investigation into these topics would improve our understanding of the NPMM and its role in the climate system.

Acknowledgments D.J.A is supported by the National Science Foundation Graduate Research Fellowship (NSF; DGE-1144086). Additional support was provided by NSF (OCE1419306) and NOAA (NA17OAR4310106). Thank you to Amaya et al. [22] for providing access to the atmospheric model simulations used in Fig. 4 of this work. Thank you to Art Miller, Pascal Polonik, Mike DeFlorio, and Shang-Ping Xie for their helpful comments throughout the course of this review. Thank you also to Antonietta Capotondi and one other anonymous reviewer for providing additional insightful comments that greatly improved the clarity and focus of the results. Thank you to the European Centre for Medium-Range Weather Forecasting (ECMWF) for developing the ERA5 reanalysis data used in this study, which is freely available at the Copernicus Climate Change Service (C3S; https://cds.climate.copernicus.eu/cdsapp#!/home). Thank you also to the UK Met Office Hadley Centre for maintaining the HadISST gridded data used in this study, which is available online (https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html). Finally, thank you to the multi-institutional collaborative efforts of NMME, whose data is also readily available online (http://iridl.ldeo.columbia.edu/SOURCES/.Models/.NMME/).

Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Horel JD, Wallace JM. Planetary-scale phenomena associated with the southern oscillation. Mon Weather Rev. 1981;109:813–29.
2. Barnston AG, Tippett MK, Ranganathan M, L'Heureux ML. Deterministic skill of ENSO predictions from the North American multimodel ensemble. Clim Dyn. 2017:1–20. https://doi.org/10.1007/s00382-017-3603-3.
3. Newman M, Sardeshmukh PD. Are we near the predictability limit of tropical Indo-Pacific Sea surface temperatures? Geophys Res Lett. 2017;44:8520–9.
4. Petrova D, Koopman SJ, Ballester J, Rodó X. Improving the long-lead predictability of El Niño using a novel forecasting scheme based on a dynamic components model. Clim Dyn. 2017;48:1249–76.
5. Ramesh N, Murtugudde R. All flavours of El Niño have similar early subsurface origins. Nat Clim Chang. 2013;3:42–6.
6. Meinen CS, McPhaden MJ. Observations of warm water volume changes in the equatorial Pacific and their relationship to El Nino and La Nina. J Clim. 2000;13:3551–9.
7. Timmermann A, An SI, Kug JS, et al. El Niño–southern oscillation complexity. Nature. 2018;559:535–45.
8. Jin FF, Lin L, Timmermann A, Zhao J. Ensemble-mean dynamics of the ENSO recharge oscillator under state-dependent stochastic forcing. Geophys Res Lett. 2007;34. https://doi.org/10.1029/2006GL027372.
9. Fedorov AV, Hu S, Lengaigne M, Guilyardi E. The impact of westerly wind bursts and ocean initial state on the development, and diversity of El Niño events. Clim Dyn. 2015;44:1381–401.
10. Capotondi A, Sardeshmukh PD, Ricciardulli L. The nature of the stochastic wind forcing of ENSO. J Clim. 2018;31:8081–99.
11. Vimont DJ, Wallace JM, Battisti DS. The seasonal footprinting mechanism in the Pacific: implications for ENSO. J Clim. 2003;16:2668–75.
12. Larson SM, Kirtman BP. The pacific meridional mode as an ENSO precursor and predictor in the North American multimodel ensemble. J Clim. 2014;27:7018–32.

13. Larson SM, Kirtman BP. An alternate approach to ensemble ENSO forecast spread: application to the 2014 forecast. Geophys Res Lett. 2015;42:9411–5.
14. Lu F, Liu Z, Liu Y, Zhang S, Jacob R. Understanding the control of extratropical atmospheric variability on ENSO using a coupled data assimilation approach. Clim Dyn. 2017;48:3139–60.
15. Pegion KV, Selman C. Extratropical precursors of the El Niño–southern oscillation. Climate extremes: patterns and mechanisms, geophysical monograph series 226, American geophysical union and John Wiley and Sons. 2017;299–314.
16. Thomas EE, Vimont DJ. Modeling the mechanisms of linear and nonlinear ENSO responses to the pacific meridional mode. J Clim. 2016;29:8745–61.
17. Ma J, Xie SP, Xu H. Contributions of the North Pacific meridional mode to ensemble spread of ENSO prediction. J Clim. 2017;30:9167–81.
18. Chiang JCH, Vimont DJ. Analogous Pacific and Atlantic meridional modes of tropical atmosphere-ocean variability. J Clim. 2004;17:4143–58.
19. Chang P, Zhang L, Saravanan R, Vimont DJ, Chiang JCH, Ji L, et al. Pacific meridional mode and El Niño - southern oscillation. Geophys Res Lett. 2007;34:1–5.
20. Larson S, Kirtman B. The Pacific meridional mode as a trigger for ENSO in a high-resolution coupled model. Geophys Res Lett. 2013;40:3189–94.
21. Alexander MA, Vimont DJ, Chang P, Scott JD. The impact of extratropical atmospheric variability on ENSO: testing the seasonal footprinting mechanism using coupled model experiments. J Clim. 2010;23:2885–901.
22. Amaya DJ, Kosaka Y, Zhou W, Zhang Y, Xie SP, Miller AJ. The North Pacific pacemaker effect on historical ENSO and its mechanisms. J Clim. 2019. https://doi.org/10.1175/JCLI-D-19-0040.1.
23. Xie S-P, Philander SGH. A coupled ocean-atmosphere model of relevance to the ITCZ in the eastern Pacific. Tellus A. 1994;46:340–50.
24. Liu Z, Xie S. Equatorward propagation of coupled air–sea disturbances with application to the annual cycle of the Eastern Tropical Pacific. J Atmos Sci. 1994;51:3807–22.
25. Amaya DJ, DeFlorio MJ, Miller AJ, Xie SP. WES feedback and the Atlantic meridional mode: observations and CMIP5 comparisons. Clim Dyn. 2017;49:1665–79.
26. Vimont DJ, Alexander MA, Fontaine A. Midlatitude excitation of tropical variability in the pacific: the role of thermodynamic coupling and seasonality. J Clim. 2009;22:518–34.
27. Anderson BT, Perez RC, Karspeck A. Triggering of El Niño onset through trade wind-induced charging of the equatorial Pacific. Geophys Res Lett. 2013;40:1212–6.
28. Anderson BT, Perez RC. ENSO and non-ENSO induced charging and discharging of the equatorial Pacific. Clim Dyn. 2015;45:2309–27.
29. Solomon A, Shin SI, Alexander MA, McCreary JP. The relative importance of tropical variability forced from the North Pacific through ocean pathways. Clim Dyn. 2008;31:315–31.
30. Gill AE. Some simple solutions for heat-induced tropical circulation. Q J R Meteorol Soc. 1980;106:447–62.
31. Vimont DJ, Battisti DS, Hirst AC. Footprinting: a seasonal connection between the tropics and mid-latitudes. Geophys Res Lett. 2001;28:3923–6.
32. Vimont DJ, Battisti DS, Hirst AC. The seasonal footprinting mechanism in the CSIRO general circulation models. J Clim. 2003;16:2653–67. https://doi.org/10.1175/1520-0442(2003)016<2653:TSFMIT>2.0.CO;2.
33. Bretherton CS, Smith C, Wallace JM. An Intercomparison of methods for finding coupled patterns in climate data. J Clim. 1992;5:541–60.
34. Copernicus Climate Change Service (C3S) (2017) ERA5: fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS) https://cds.climate.copernicus.eu/cdsapp#!/home
35. Rayner NA. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J Geophys Res. 2003;108. https://doi.org/10.1029/2002JD002670.
36. Furtado JC, Di Lorenzo E, Anderson BT, Schneider N. Linkages between the North Pacific oscillation and central tropical Pacific SSTs at low frequencies. Clim Dyn. 2012;39:2833–46.
37. Martinez-Villalobos C, Vimont DJ. An analytical framework for understanding tropical meridional modes. J Clim. 2017;30:3303–23.
38. Di Lorenzo E, Liguori G, Schneider N, Furtado JC, Anderson BT, Alexander MA. ENSO and meridional modes: a null hypothesis for Pacific climate variability. Geophys Res Lett. 2015;42:9440–8.
39. Rogers JC. The North Pacific oscillation. J Climatol. 1981;1:39–57. https://doi.org/10.1002/joc.3370010106.
40. Linkin ME, Nigam S. The North Pacific oscillation-West Pacific teleconnection pattern: mature-phase structure and winter impacts. J Clim. 2008;21:1979–97.
41. Frankignoul C, Reynolds RW. Testing a dynamical model for midlatitude sea surface temperature anomalies. J Phys Oceanogr. 1983;13:1131–45.
42. Battisti DS, Sarachik ES, Hirst AC. A consistent model for the large-scale steady surface atmospheric circulation in the tropics. J Clim. 1999;12:2956–64.
43. Lindzen RS, Nigam S. On the role of sea surface temperature gradients in forcing low-level winds and convergence in the tropics. J Atmos Sci. 2002;44:2418–36.
44. Chang P, Ji L, Li H. A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions. [letter]. Nature. 1997;385:516–8.
45. Vimont DJ. Transient growth of thermodynamically coupled variations in the tropics under an equatorially symmetric mean state. J Clim. 2010;23:5771–89.
46. Chang P, Ji L, Saravanan R. A hybrid coupled model study of tropical Atlantic variability. J Clim. 2001;14:361–90.
47. Wu S, Wu L, Liu Q, Xie S-P. Development processes of the tropical pacific meridional mode. Adv Atmos Sci. 2010;27:95–9.
48. Martinez-Villalobos C, Vimont DJ. The role of the mean state in meridional mode structure and growth. J Clim. 2016;29:3907–21.
49. Wang F. Thermodynamic coupled modes in the tropical atmosphere–ocean: an analytical solution. J Atmos Sci. 2010;67:1667–77.
50. Behringer, DW, Xue Y (2004) Evaluation of the global ocean data assimilation system at NCEP: the Pacific Ocean. Eighth symposium on integrated observing and assimilation systems for atmosphere, oceans, and land surface, AMS 84th Annual Meeting, Washington State Convention and Trade Center, Seattle, Washington, 11–15.
51. Kirtman BP, Min D, Infanti JM, Kinter JL III, Paolino DA, Zhang Q, et al. The north American multimodel ensemble: Phase-1 seasonal-to-interannual prediction; phase-2 toward developing intraseasonal prediction. Bull Am Meteorol Soc. 2014;95:585–601.
52. Lu F, Liu Z. Assessing extratropical influence on observed El Niño-southern oscillation events using regional coupled data assimilation. J Clim. 2018;31:8961–9.
53. Lai AWC, Herzog M, Graf HF. ENSO forecasts near the spring predictability barrier and possible reasons for the recently reduced predictability. J Clim. 2018;31:815–38.
54. Czaja A, van der Vaart P, Marshall J. A diagnostic study of the role of remote forcing in tropical Atlantic variability. J Clim. 2002;15:3280–90.
55. Liguori G, Di Lorenzo E. Meridional modes and increasing Pacific decadal variability under anthropogenic forcing. Geophys Res Lett. 2018;45:983–91.

56. Sanchez SC, Amaya DJ, Miller AJ, Xie S-P, Charles CD. The Pacific meridional mode over the last millennium. Clim Dyn. 2019. https://doi.org/10.1007/s00382-019-04740-1.
57. Cai W, Santoso A, Wang G, et al. ENSO and greenhouse warming. Nat Clim Chang. 2015;5:849–59.
58. Zhang H, Clement A, DiNezio PN. The south pacific meridional mode: a mechanism for ENSO-like variability. J Clim. 2014;27: 769–83.
59. Jin D, Kirtman BP. Why the southern hemisphere ENSO responses lead ENSO. J Geophys Res Atmos. 2009;114. https://doi.org/10.1029/2009JD012657.
60. You Y, Furtado JC. The role of South Pacific atmospheric variability in the development of different types of ENSO. Geophys Res Lett. 2017;44:7438–46.
61. You Y, Furtado JC. The South Pacific meridional mode and its role in tropical Pacific climate variability. J Clim. 2018;31:10141–63.
62. Larson SM, Pegion KV, Kirtman BP. The South Pacific meridional mode as a thermally driven source of ENSO amplitude modulation and uncertainty. J Clim. 2018;31:5127–45.
63. Ding R, Li J, Tseng YH. The impact of South Pacific extratropical forcing on ENSO and comparisons with the North Pacific. Clim Dyn. 2015;44:2017–34.
64. Min Q, Su J, Zhang R. Impact of the south and north pacific meridional modes on the El Niño-southern oscillation: observational analysis and comparison. J Clim. 2017;30:1705–20.
65. Zhang H, Deser C, Clement A, Tomas R. Equatorial signatures of the Pacific meridional modes: dependence on mean climate state. Geophys Res Lett. 2014;41:568–74.
66. Okumura YM. Origins of tropical pacific decadal variability: role of stochastic atmospheric forcing from the South Pacific. J Clim. 2013;26:9791–6.
67. Capotondi A, Wittenberg AT, Newman M, di Lorenzo E, Yu JY, Braconnot P, et al. Understanding ENSO diversity. Bull Am Meteorol Soc. 2015;96:921–38.
68. Vimont DJ, Alexander MA, Newman M. Optimal growth of central and East Pacific ENSO events. Geophys Res Lett. 2014;41:4027–34.
69. Yu JY, Kim ST. Relationships between extratropical sea level pressure variations and the Central Pacific and eastern Pacific types of ENSO. J Clim. 2011;24:708–20.
70. Ding R, Li J, Tseng YH, Sun C, Xie F. Joint impact of North and South Pacific extratropical atmospheric variability on the onset of ENSO events. J Geophys Res. 2017;122:279–98.
71. Capotondi A, Sardeshmukh PD. Optimal precursors of different types of ENSO events. Geophys Res Lett. 2015;42:9952–60.
72. Amaya DJ, Foltz GR. Impacts of canonical and Modoki El Niño on tropical Atlantic SST. J Geophys Res Ocean. 2014;119:777–89.
73. Liguori G, Di Lorenzo E. Separating the north and South Pacific meridional modes contributions to ENSO and tropical decadal variability. Geophys Res Lett. 2019;46:906–15.
74. Liu Z, Di Lorenzo E. Mechanisms and predictability of Pacific decadal variability. Curr Clim Chang Rep. 2018;4:128–44.
75. Barsugli JJ, Battisti DS. The basic effects of Atmosphere–Ocean thermal coupling on midlatitude variability*. J Atmos Sci. 1998;55: 477–93.
76. Stuecker MF. Revisiting the Pacific meridional mode. Sci Rep. 2018;8:3216. https://doi.org/10.1038/s41598-018-21537-0.
77. Sun T, Okumura YM. Role of stochastic atmospheric forcing from the South and North Pacific in tropical Pacific decadal variability. J Clim. 2019;32:4013–38.
78. Kim H, Vitart F, Waliser DE. Prediction of the Madden–Julian oscillation: a review. J Clim. 2018;31:9425–43.
79. Park JY, Yeh SW, Kug JS, Yoon J. Favorable connections between seasonal footprinting mechanism and El Niño. Clim Dyn. 2013;40: 1169–81.
80. Anderson BT. On the joint role of subtropical atmospheric variability and equatorial subsurface heat content anomalies in initiating the onset of ENSO events. J Clim. 2007;20:1593–9.
81. Martín-Rey M, Rodríguez-Fonseca B, Polo I. Atlantic opportunities for ENSO prediction. Geophys Res Lett. 2015;42:6802–10.
82. Schneider T, Bischoff T, Haug GH. Migrations and dynamics of the intertropical convergence zone. Nature. 2014;513:45–53.
83. Yu JY, Fang SW. The distinct contributions of the seasonal footprinting and charged-discharged mechanisms to ENSO complexity. Geophys Res Lett. 2018;45:6611–8.
84. DiNezio PN, Deser C, Okumura Y, Karspeck A. Predictability of 2-year La Niña events in a coupled general circulation model. Clim Dyn. 2017;49:4237–61.
85. Compo GP, Sardeshmukh PD. Removing ENSO-related variations from the climate record. J Clim. 2010;23:1957–78.
86. Gao S, Zhu L, Zhang W, Chen Z. Strong modulation of the pacific meridional mode on the occurrence of intense tropical cyclones over the western North Pacific. J Clim. 2018;31:7739–49.
87. Murakami H, Vecchi GA, Delworth TL, Wittenberg AT, Underwood S, Gudgel R, et al. Dominant role of subtropical Pacific warming in extreme Eastern Pacific hurricane seasons: 2015 and the future. J Clim. 2017;30:243–64.
88. Zhang W, Villarini G, Vecchi GA, Murakami H. Impacts of the Pacific meridional mode on Landfalling North Atlantic tropical cyclones. Clim Dyn. 2018;50:991–1006.
89. Di Lorenzo E, Mantua N. Multi-year persistence of the 2014/15 North Pacific marine heatwave. Nat Clim Chang. 2016;6:1042–7.
90. Amaya DJ, Bond NE, Miller AJ, Deflorio MJ. The evolution and known atmospheric forcing mechanisms behind the 2013-2015 North Pacific warm anomalies. US CLIVAR Var. 2016;14:1–6.
91. Siedlecki S, Bjorkstedt E, Feely R, Sutton A, Cross J, Newton J. Impact of the Blob on the Northeast Pacific Ocean biogeochemistry and ecosystems. US CLIVAR Var. 2016;14:7–12.
92. Chiang JCH, Bitz CM. Influence of high latitude ice cover on the marine intertropical convergence zone. Clim Dyn. 2005;25:477–96.
93. Gibson PB, Waliser DE, Guan B, DeFlorio MJ, Ralph FM, Swain DL. Ridging associated with drought in the Western and Southwestern United States: characteristics, trends, and predictability sources. J Clim. 2019; in revision.