Contributions of the North Pacific Meridional Mode to Ensemble Spread of ENSO Prediction

JING MA

Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters/KLME/ILCEC, Nanjing University of Information Science and Technology, Nanjing, China, and Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California

SHANG-PING XIE

Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, and Physical Oceanography Laboratory/CIMST, Ocean University of China, and Qingdao National Laboratory for Marine Science and Technology, Qingdao, China

HAIMING XU

Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters/KLME/ILCEC, Nanjing University of Information Science and Technology, Nanjing, China

(Manuscript received 21 March 2017, in final form 14 August 2017)

ABSTRACT

Seasonal prediction of El Niño–Southern Oscillation (ENSO) employs the ensemble method, which samples the uncertainty in initial conditions. While much attention has been given to the ensemble mean, the ensemble spread limits the reliability of the forecast. Spatiotemporal coevolution of intermember anomalies of sea surface temperature (SST) and low-level winds over the Pacific is examined in ensemble hindcasts. Two types of evolution of intermember SST anomalies in the equatorial Pacific are identified. The first features an apparent southwestward propagation of the SST spread from the subtropical northeastern Pacific southeast of Hawaii to the central equatorial Pacific in boreal winter–spring, indicative of the precursor effect of the North Pacific meridional mode (NPMM) on ENSO variability. Extratropical atmospheric variability generates ensemble spread in ENSO through wind–evaporation–SST (WES) in the subtropical northeastern Pacific and then Bjerknes feedback on the equator. In the second type, ensemble spread grows in the equatorial Pacific with a weak contribution from the subtropical southeastern Pacific in summer. Thus, the extratropical influence on ENSO evolution is much stronger in the Northern Hemisphere than in the Southern Hemisphere. The growth of Niño-4 SST ensemble spread shows a strong seasonality. In hindcasts initialized in September–March, the Niño-4 SST spread grows rapidly in January–April, stabilizes in May–June, and grows again in July–September. The rapid growth of the Niño-4 SST spread in January–April is due to the arrival of NPMM, while the slowdown in May–June and rapid growth in July–September are attributable primarily to the seasonality of equatorial ocean–atmosphere interaction. NPMM contributes to the ensemble spread in equatorial Pacific SST, limiting the reliability of ENSO prediction.

1. Introduction

El Niño–Southern Oscillation (ENSO) is the dominant mode of interannual variability in the tropical Pacific, providing predictability on a global scale with significant influences on North America (Cayan et al. 1999), the northwestern Pacific, and East Asia (Huang and Wu 1989; Zhang et al. 1996; Du et al. 2011; Xie et al. 2016). Therefore, ENSO is the primary focus in the seasonal–interannual prediction. Coupled instabilities are considered necessary for the growth of sea surface temperature (SST) perturbations associated with ENSO (Bjerknes 1969; McCreary 1983, 1985; Philander et al. 1984; Gill 1985; Yamagata 1985; Battisti 1988). Equatorial ocean waves become destabilized when the ocean–atmosphere coupling is sufficiently strong. In the equatorial Pacific, anomalous westerlies weaken the zonal gradient of the thermocline.
depth and reduce the zonal SST contrast, while SST anomalies in turn increase the westerly anomalies. This constitutes a positive feedback, first proposed by Bjerknes (1969). The coupled instabilities associated with ENSO have only recently been isolated and modeled using fully coupled climate models (Larson and Kirtman 2015a). Stochastic zonal wind stress perturbations near the equatorial date line activate the coupled instability by driving local SST and anomalous zonal current changes that induce upwelling anomalies and thermocline responses (Larson and Kirtman 2017).

Alternatively, ENSO is also viewed as a stable (or weakly damped) mode triggered by stochastic forcing (Lau 1985; Penland and Sardeshmukh 1995; Kessler 2002). This hypothesis is referred to as the optimal perturbation mechanism. Initial perturbations that grow into ENSO events within a given time interval are called optimal growth modes and can be derived statistically from observations or models.

Recent studies have identified ENSO precursors defined as phenomena that tend to occur prior to ENSO events, including the Indian summer monsoon (Kirtman and Shukla 2000), the Madden–Julian oscillation (MJO; McPhaden et al. 2006), and westerly wind bursts over the western equatorial Pacific (McPhaden 1999; Kug et al. 2008). The North Pacific meridional mode (NPMM; Chiang and Vimont 2004) refers to a subtropical SST warming (or cooling) coupled with the weakened (or strengthened) trade winds in the subtropical northeastern Pacific (NEP). The coupled pattern propagates southward and influences ENSO variability via a seasonal footprinting mechanism (SFM; Vimont et al. 2001, 2002, 2003): the northeast trade wind anomalies in winter can leave a footprint on SST over the NEP by modifying the latent heat flux, known as wind–evaporation–SST (WES; Liu and Xie 1994; Xie and Philander 1994; Xie 1999; Vimont et al. 2009) feedback. Chang et al. (2007) found that over 70% of El Niño events are preceded by a positive NPMM (SST warming in the NEP) in observations for the period of 1958–2000.

In addition to the NPMM, the South Pacific meridional mode (SPMM) is also suggested to act as a conduit through which extratropical atmospheric variability can impact equatorial Pacific climate (Okumura 2013; Zhang et al. 2014). The physical process is nearly identical to that of the NPMM, but with SST and wind anomalies in the subtropical southeastern Pacific (SEP) region.

The robust relationship between the NPMM and ENSO is also found in the multimodel ensemble retrospective forecasts. Using the North American Multimodel Ensemble (NMME; Kirtman et al. 2014) system, Larson and Kirtman (2014) found that the multimodel ensemble mean well captures NPMM variability at both 1- and 3-month lead times and that NPMM often acts as a precursor to ENSO events. In the seasonal–interannual prediction, an ensemble forecast with different initial conditions is usually conducted to account for the chaotic nature of the atmosphere. In predictability and prediction skill studies, the ensemble mean is often used to approximate the forecast, while the ensemble spread is an important measure of the prediction uncertainty. A large spread indicates that the ensemble mean forecast suffers large uncertainties or the phenomenon of interest inherently has low predictability. The intermember anomalies (defined as deviations from the ensemble mean) arising from different initial conditions can provide useful insights into the intrinsic variability of the ocean and atmosphere (Kosaka et al. 2013). Specifically, Ma et al. (2017) identified the NPMM in boreal spring in the ensemble spread of multimodel hindcasts.

The present study further investigates the covariability of intermember anomalies of SST and wind over the Pacific in ensemble hindcasts. We show that the NPMM develops over the NEP during boreal winter–spring and contributes to the subsequent growth of intermember variability in central equatorial Pacific SST. In contrast, such an extratropical influence is weak from the Southern Hemisphere. Equatorial Bjerknes feedback also contributes to pronounced seasonal variations in the ensemble spread in equatorial Pacific SST.

The rest of this paper is organized as follows. Section 2 introduces the data and methods. Section 3 investigates the intermember covariability of the SST and low-level winds in the Pacific and shows the temporal evolution characteristics of the Niño-4 SST spread. Section 4 uses another set of hindcasts to further confirm and complement the results in section 3. Section 5 provides the summary and discussion.

2. Data and methods

The NMME is a multimodel seasonal forecasting system composed of coupled models from the modeling centers of the United States and Canada. The NMME hindcasts can reasonably capture the interannual variability of the NPMM and ENSO (Larson and Kirtman 2014). The Fourth Generation Canadian Coupled Global Climate Model (CanCM4) from NMME phase 1 (http://iridl.ldeo.columbia.edu/SOURCES/.Models/.NMME/) is one of the models that are fairly skilled in predicting Pacific meridional mode (PMM) at 6-month lead and well reproduce the amplitude and persistence of the negative PMM event during the period from the late 1990s through the early 2000s (Larson and Kirtman 2014). In addition, the CanCM4 provides more variables
available on the website for NMME phase 1 than other models. Therefore, we use its hindcast data including SST and 850-hPa horizontal winds for the period of 1981–2010. The hindcasts are initialized from the first day of each month of each year. Each hindcast encompasses an ensemble of 10 members with different initial conditions and is run for 12 months (lead time is 0.5–11.5 months). Initial conditions for the ensemble members are obtained from an ensemble of coupled assimilation runs. These runs assimilate gridded atmospheric analyses through a procedure that resembles the incremental analysis update technique but introduces only a fraction of the analysis increment in order that differences among ensemble members represent the observational uncertainties (Merryfield et al. 2013). In this study, we refer to October, November, December, January, February, and March (April, May, June, July, August, and September) as winter (summer) months for simplicity.

Singular value decomposition (SVD) is used to find covarying patterns in two different fields and provides an objective method for assessing the strength of covariability (Wallace et al. 1992; Deser and Timlin 1997). For the CanCM4 hindcasts, SVD analyses are performed between SST and wind velocity on the concatenated 10 members by 30-yr records. For instance, the SST matrix is (Nx, Ny, Nens, yr), where Nx and Ny are the zonal and meridional grid numbers, respectively, Nens is the ensemble number, and yr denotes the number of years. We focus on the intermember variability by subtracting the ensemble mean (Nx, Ny, yr) from the matrix (Nx, Ny, Nens, yr). Then the matrix \( \text{Nx \times Ny, Nens \times yr} \) is used for the SVD analysis. Hence, the conventional time dimension is enlarged by the ensemble size.

To examine the temporal evolution in the covariability between intermember anomalies, we conduct month-reliant SVD analyses (Ma et al. 2017). We investigate the SST and wind anomalies in a monthly sequence with 12 months. For instance, the monthly sequence starts from January (February) to December (next January) when hindcasts initialized from January (February) are used. A covariance matrix is constructed by treating the SST or wind anomalies in the monthly sequence as one step. Thus, we can obtain the heterogeneous fields consisting of 12 sequential patterns representing monthly evolution of the intermember anomalies for each mode. As these patterns share the same principal component (PC) of Nens \( \times yr \), the heterogeneous fields reflect the temporal evolution characteristics. In this study, multivariate SVD analyses are conducted for covariability between two (zonal and meridional winds) atmospheric variables and SST, as the northeasterly trade winds prevail in the NEP region.

To confirm and complement the results based on the CanCM4 hindcasts, this study also uses the ENSEMBLES hindcasts (van der Linden and Mitchell 2009), which include five fully coupled atmosphere–ocean–land models from the European Centre for Medium-Range Weather Forecasts (ECMWF), the Leibniz Institute of Marine Sciences at Kiel University (IFM-GEOMAR), Météo-France (MF), the Met Office (UKMO), and the Centro Euro-Mediterraneo per I Cambiamenti Climatici–Istituto Nazionale di Geofisica e Vulcanologia (CMCC-INGV). The ENSEMBLES hindcasts successfully reproduce the interannual variability of ENSO including its different phases (Li et al. 2014). The SST, 850-hPa horizontal winds, and latent heat flux (LHF) in the hindcasts of all the five models for the period of 1980–2005 are used. The seasonal forecasts are initialized on the 1 February, 1 May, 1 August, and 1 November for each year, each containing an ensemble of nine members with different initial conditions. Hindcasts starting from February, May, and August are run for seven months, and the hindcasts with the November initialization from all models except for CMCC-INGV are run for 14 months.

For the ENSEMBLES hindcasts, SVD analyses are conducted on the concatenated five models by nine members by 26-yr records of SST and wind fields. Using hindcasts with the start date of February (August), we obtain seven sequential patterns showing temporal evolution of the intermember anomalies from February to August (from August to next February).

We also calculate the correlation coefficients between winds, LHF, and the SST PC of the first SVD mode to present a clear picture of the relationship between winds, LHF, and the coupled modes. The Student’s \( t \) test is used to determine the significance of correlations.

3. Results

a. Coevolution of intermember SST and wind anomalies

Figure 1 shows the ensemble spread in SST (measured as standard deviation of intermember SST anomalies) in the tropical and subtropical Pacific. With February initialization, the SST spread in March (color shading in Fig. 1a) features large values poleward of 20° and in the eastern equatorial Pacific. The spread in the eastern equatorial Pacific may be due to differences among the ensemble members in predicting the decay phase of ENSO. In addition, a relatively large spread is located in the NEP. In the following August (color shading in Fig. 1b), SST spread grows near the equator significantly with the increase in lead time, which may arise from differences among the ensemble members in predicting...
the developing phase of ENSO. In the hindcasts initialized from August, the September SST spread in the subtropics is small, with large spread in the eastern equatorial Pacific (color shading in Fig. 1c). In the following February (color shading in Fig. 1d), the spatial pattern of SST spread is similar to the spread in March shown in Fig. 1a, but with much larger values as a result of the longer lead time. Specifically, large spread is located poleward of 20° and in the NEP southeast of Hawaii. We have examined ensemble spread distributions in hindcasts initialized in all 12 months. Generally, wintertime SST spread features large values in the NEP, extratropical regions poleward of 20°, and the eastern equatorial Pacific, related to the differences among the ensemble members in predicting the subtropical SST and peak or decay phase of ENSO, while large spread is mainly confined near the equator in boreal summer, mainly due to differences in predicting the developing ENSO amplitude.

Figure 1 also illustrates the spatial pattern of the ensemble spread in 850-hPa zonal wind. For the hindcasts initialized from February, the zonal wind spread in March (contours in Fig. 1a) is large in the subtropics and western equatorial Pacific with the largest spread in the northern subtropics. In August (contours in Fig. 1b), the largest spread is located in the southern subtropics and also in the western equatorial Pacific. The spatial pattern of the zonal wind spread in September (February) in the hindcasts with August initialization in Fig. 1c (Fig. 1d) is reminiscent of the August (March) spread in Fig. 1b (Fig. 1a). Therefore, the largest wind spread in winter (summer) occurs in the northern (southern) subtropics. Additionally, in summer, large spread is also located over the western equatorial Pacific.

Next, we investigate the covariability characteristics between the intermember anomalies of SST and low-level winds. Figure 2 shows the first month-reliant SVD mode (explained covariance: 64.58%) of the intermember wind and SST anomalies from February to next January using the hindcasts initialized from February. The monthly wind and SST anomalies in the region of 30°S–30°N, 150°E–90°W are used as the left and right fields, respectively. The coupled pattern of the intermember anomalies of SST and winds evolves with time. The anomalies from February to April show the strongest coupling in the NEP, featuring positive SST and southwesterly anomalies. This is reminiscent of the NPMM, which primarily arises as a result of the WES feedback (section 4). In May, large anomalies appear in the western equatorial Pacific. On the equator, the westerly wind anomalies are closely tied to the positive SST anomalies, indicative of the Bjerknes (1969) feedback. From June to November, coupled positive SST and westerly anomalies in the equatorial Pacific grow. In January, SST anomalies in the equatorial Pacific decrease markedly as the northwesterly anomalies displace south of the equator (Harrison and Vecchi 1999; Vecchi and Harrison 2003; McGregor et al. 2012; Xie...
and Zhou 2017). The deceleration of the equatorial westerlies weakens the activity of the oceanic equatorial waves, causing equatorial Pacific SST anomalies to decay. This is rooted in the Bjerknes feedback.

The SVD results using hindcasts initialized in January, March, October, November, and December are similar (not shown). The coupled SST–wind anomalies over the NEP in winter–spring are indicative of the precursor role of the NPMM in the early growth of equatorial SST anomalies. In studying initial perturbations that subsequently develop into El Niño patterns, Penland and Sardeshmukh (1995) also identified extratropical processes as important in triggering ENSO events. Based on 51-yr observations, Vimont et al. (2014) showed that the optimal initial conditions for central Pacific (CP) ENSO events resemble the NPMM. Here, we show that the NPMM is an important source of ensemble spread in equatorial SST prediction. The use of the initial-condition ensemble increases the sample size by one order of magnitude (10 members × 12 hindcasts each year), enabling a detailed study of NPMM’s seasonal evolution (e.g., Fig. 2).

Figure 3 shows the first SVD mode of intermember wind and SST anomalies (explained covariance: 46.12%) in the hindcasts initialized in April. Distinct from Fig. 2, the anomalies in the first few months mainly occur in the SEP and equatorial Pacific, with the maxima located south of the equator, which is related to the SPMM. However, the anomalies in the SEP are nearly concurrent with those in the equatorial Pacific. Thus, it seems that the effect of the SPMM on the ENSO variability is not as strong as that of the NPMM. In April and the following few months, the ensemble spread of SST in the NEP is small as atmospheric internal variability weakens rapidly (Fig. 1), rendering the SST spread in the equatorial Pacific larger than that in the NEP. In addition, SST spread in the SEP also starts to increase after April (not shown). This explains why the SVD analysis using hindcasts initialized from April finds the equatorial ocean–atmosphere coupled pattern and SPMM
rather than the NPMM pattern. The hindcasts initialized in May, June, and July show similar SVD results as Fig. 3 (not shown).

The first month-reliant SVD mode (explained covariance: 36.94%) based on the hindcasts initialized from August (Fig. 4) shows that the anomalies of SST and winds first appear in the SEP and the equatorial Pacific, similar to Fig. 3. Differently, large anomalies start to occur in the NEP starting from November and increase rapidly until the following July. The SVD results in the hindcasts with September initialization are similar to Fig. 4 (not shown).

Figure 5 shows the latitude–month cross sections of SST anomalies averaged along 150°E–90°W in the heterogeneous fields of the first month-reliant SVD mode using the hindcasts with initializations from February, April, June, August, October, and December. Hindcasts initialized in winter months show the equatorward propagation of SST anomalies from the NEP in the first few months. Even in the hindcasts initialized in August, NEP SST anomalies develop and migrate southward to the equator during winter–spring. Hence, the southward migration of the NEP SST anomalies is phase-locked to winter–spring when atmospheric internal variability in the northeast trade winds is high. In addition, LHF is sensitive to the seasonal cycle of low-level winds in the NEP region (Vimont et al. 2009). The hindcasts initialized from summer months primarily exhibit a growth in the equatorial Pacific. The SPMM contributes a little to the SST variability near the equator. Here, we conclude that the NPMM is important for the SST anomaly development in the central equatorial Pacific, while Zhang et al. (2014) found that the SPMM is important for the SST anomaly development mainly in the eastern equatorial Pacific. Note that SST spread in the NEP is large during July–September. This may be related to the expansion of ENSO variability, as ocean–atmosphere feedback in the equatorial Pacific is strongest in this period. This will become clear later.

The above results identify two types of evolution of intermember SST anomalies. The first exhibits a southward propagation of SST spread from the NEP to the central equatorial Pacific, which occurs in the hindcasts initialized in winter months, when the North Pacific

![Figure 3](https://example.com/fig3.png)
oscillation (NPO) is most energetic (Vimont et al. 2003). The second type is characterized by a growth in the equatorial Pacific. This is seen in the hindcasts with initializations of summer months. The first type reflects the precursor effect of the NPMM on the ENSO variability, while the second type is a manifestation of the ocean–atmospheric coupling in the equatorial Pacific.

b. Temporal evolution of SST spread

Section 3a shows that NPMM contributes to the ENSO variability with an evident southward migration of the SST spread from the NEP to the central equatorial Pacific. Here, we focus on the SST spread in the central equatorial Pacific by calculating the intermember Niño-4 SST spread (measured as standard deviation of intermember SST anomalies). Figure 6a shows temporal variations of the Niño-4 SST spread in the hindcasts with initializations from January to December. The Niño-4 SST spread growth has a strong seasonality. In the hindcasts initialized in winter months, a slowdown or even stagnation of the SST spread growth stands out in May–June. From July to September, SST spread increases abruptly in these hindcasts. In the hindcasts with April and May initializations, a slowdown in May–June and an abrupt increase in July–September are also discernible.

Ensemble spread is expected to grow in time. We define a “reference” growth of spread in Niño-4 SST by averaging the spread for all 12 initialization months (dotted lines in Fig. 6a). We then calculate the differences between the original and reference spread (dashed lines in Fig. 6a and color shading in Fig. 6b). A rapid growth of ensemble spread occurs in January–April, followed by a marked slowdown in May–June. A second rapid growth appears in July–September.

The thick black curve in Fig. 6a shows the ensemble mean annual cycle of the standard deviation of interannual anomalies of Niño-4 SST. The interannual variability of Niño-4 SST is generally larger than the ensemble spread at 12-month lead, indicating that Niño-4 SST is predictable. The interannual variability of Niño-4 SST also has a strong seasonality, with the smallest from May to July and largest around March and September. This corresponds, respectively, to the slowdown
or even stagnation of the SST ensemble spread growth in May–June and the abrupt increase in January–April and July–September in the hindcasts with winter initializations. The temporal evolution feature of the standard deviation of interannual anomalies of Niño-4 SST is similar to that indicated by the difference between the original and reference Niño-4 SST ensemble spread in Fig. 6a. This agrees with Karspeck et al. (2006). They found that the seasons of greatest anomaly variance correspond to the seasons of greatest spread. The seasonal dependence can be attributed to the background state stability, with large spread in spring and summer. This is consistent with Chen et al. (1997) and Xue et al. (1997).

The rapid growth of Niño-4 SST spread in January–April results from the NPMM effect, in agreement with the southward migration of NEP SST anomalies into the equatorial Pacific that is phase locked to winter–spring (section 3a). Note that the slowdown in Niño-4 SST spread in May–June can also be found in the hindcasts with April and May initializations. In these hindcasts, the NPMM is weak and has little impact on the ENSO variability. This indicates that the slowdown is a manifestation of the seasonal variation in the local ocean–atmosphere coupling in the central equatorial Pacific. DiNezio and Deser (2014) found negative feedback from air–sea fluxes and the delayed thermocline feedback in the Niño-3.4 region during boreal spring. We speculate that the slowdown of the Niño-4 SST spread growth in May–June may be also related to the net air–sea fluxes and the delayed thermocline feedback. This requires further investigation.

The rapid spread growth in July–September is evident in all the hindcasts, which reflects the seasonality of the local ocean–atmosphere interaction in the equatorial Pacific. This originates from the unstable background favorable for the Bjerknes feedback in summer (Larson and Kirtman 2015a).

The growth of SST spread also depends on the initialization month. Table 1 summarizes the Niño-4 SST spread increase in the first three months of the hindcasts. The growth is larger in the hindcasts initialized in January, February, June, July, August, and December than those initialized in March, April, May, September, October, and November. The rapid growth of the spread with January, February, and December initializations is associated with the precursor effect of the NPMM. The large growth in the June, July, and August initialized hindcasts result from the seasonality of local ocean–atmosphere

![Figure 5](https://example.com/figure5.png)

**Fig. 5.** Latitude–month cross sections of SST anomalies averaged along 150°E–90°W in the heterogeneous fields of the first SVD mode using the hindcasts with initializations from (a) February, (b) April, (c) June, (d) August, (e) October, and (f) December.
interaction in the equatorial Pacific. In the hindcasts with April and May initializations, the spread increase in the first three months is smallest at 0.12 K, significantly smaller than the other initializations. This is indicative of the slowdown of the spread growth, because the NPMM and equatorial ocean–atmosphere coupling are both weak in May–June.

It is noteworthy that the increases from July to September in the hindcasts with February and March initializations are larger than those initialized in June and July (Table 1), indicating that the NPMM tends to amplify the summertime growth of the Niño-4 SST spread.

In addition, the SST spreads at the 12-month lead time with initializations of April, May, June, and July are smaller than those with January, February, March, September, October, November, and December initializations, indicating that ENSO prediction uncertainty tends to be larger if the forecasts are initialized before and through spring. This implies the amplification role of the NPMM in the ENSO variability or the multiplicative effect of the relatively low background stability in summer on existing SST anomalies. It seems that, in spite of the precursor role of the NPMM in the ENSO variability, the NPMM increases SST spread in the equatorial Pacific, thus making the ENSO prediction unreliable. In this sense, the NPMM may not be a reliable predictor for ENSO.

Based on a coupled model framework, Larson and Kirtman (2015b) found that noise-driven coupled instabilities overshadow the NPMM’s precursor effect for ENSO prediction. While they focused on Niño-3 SST, the NPMM effect is larger on Niño-4 SST. We show that the NPMM induces marked SST spread in the central equatorial Pacific in January–April when an evident southwestward propagation of SST anomalies from the NEP to the central equatorial Pacific, which is clearly seen in the hindcasts initialized in winter months, and may arise from the WES feedback.

### Table 1. Increases in the Niño-4 SST spread in the first three months and from July to September in the hindcasts with initializations from January to December.

<table>
<thead>
<tr>
<th>Initialization month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>First 3 months</td>
<td>0.18</td>
<td>0.19</td>
<td>0.15</td>
<td>0.12</td>
<td>0.12</td>
<td>0.17</td>
<td>0.19</td>
<td>0.17</td>
<td>0.15</td>
<td>0.15</td>
<td>0.16</td>
<td>0.18</td>
</tr>
<tr>
<td>July–September</td>
<td>0.19</td>
<td>0.24</td>
<td>0.23</td>
<td>0.16</td>
<td>0.21</td>
<td>0.19</td>
<td>0.19</td>
<td>—</td>
<td>—</td>
<td>0.17</td>
<td>0.18</td>
<td>0.17</td>
</tr>
</tbody>
</table>

FIG. 6. (a) Temporal evolution in Niño-4 SST ensemble spread (solid; K), reference Niño-4 SST ensemble spread (obtained by averaging the spread of all 12 initialization months; dotted lines, identical and shifted to fit the initial months; K), and the difference between the original and reference Niño-4 SST ensemble spread (dashed lines; K) using the hindcasts with initializations from January to December. The thick black curve shows the ensemble mean annual cycle of the standard deviation of interannual anomalies of Niño-4 SST. (b) Differences (color shading; K) between the original and reference Niño-4 SST spread at each lead time (y axis) for each initialization from each month (x axis).
Section 4, limiting the skill in ENSO prediction, primarily the CP ENSO.

4. ENSEMBLES results

To further confirm the above results, we use the ENSEMBLES hindcasts to conduct the month-reliant SVD analyses. Figure 7 shows the first month-reliant SVD mode (explained covariance: 30.66%) of the intermember anomalies of 850-hPa winds and SST in the tropical and subtropical Pacific region from February to August using the ENSEMBLES hindcasts initialized from February. The temporal evolution characteristics of SST and wind anomalies are generally similar to those in Fig. 2, featuring the NPMM anomalies in the beginning months and the subsequent increases of anomalies in the equatorial Pacific.

Section 3a shows that the coevolution of the SST and wind anomalies in the early months reflects the NPMM and SPMM. To evaluate the WES feedback, we show the correlation map between LHF (positive downward) and the PC of the first SVD mode using the hindcasts with February initialization for individual month from February to August (Fig. 8). In February (Fig. 8a), southwesterly anomalies appear in the NEP region, without significant SST correlations. In March (Fig. 8b), positive SST correlations occur in the
This implies that the SST variation is induced by the wind changes. In addition, significantly positive correlations between the LHF and the PC are located in the NEP region, slightly shifted to the northeast of the maximum SST correlation area.

In April (Fig. 8c), the positive LHF correlations shrink markedly, located to the northern edge of the positive SST correlation region. Negative LHF correlations appear on the equator. Notably, significant wind correlations start to appear on the equator, which results from the southwestward shift of wind anomalies induced by the WES feedback. From May to August (Figs. 8d–g), positive and negative LHF correlations sit in the western and eastern part of the equatorial Pacific, respectively. This suggests that LHF contributes to the SST warming in the western equatorial Pacific, while it damps the SST warming in the eastern equatorial Pacific. The warming in the east is associated with the Bjerknes feedback and caused by the ocean heat transport including the eastward warm advection and downwelling.

The above results show that, in spring, the coupled pattern between SST anomalies and the reduced northeast trades generates WES feedback, and the pattern extends southwestward to trigger the equatorial Bjerknes mode, which grows in summer. This evolution from the subtropical WES into equatorial Bjerknes mode is seen in both the observations (Vimont et al. 2001; Yu and Kim 2011) and coupled models (Alexander et al. 2010;
Wu et al. 2010; Lin et al. 2015). We demonstrate that the extratropical atmospheric variability can generate intermember variability of ENSO through the mode transition from WES to Bjerknes feedback.

The first month-reliant SVD mode with August initialization accounts for 38.63% of the total covariance. The heterogeneous fields are shown in Fig. 9. Similar to Fig. 4, the anomalies first appear in the SEP and the equatorial Pacific. However, different from Fig. 4, the anomalies that appear over the NEP in November do not increase with lead time. Nevertheless, the SVD results based on the ENSEMBLES hindcasts share much consistency with those from CanCM4 hindcasts.

Figure 10 shows the correlation maps for the hindcasts with the August initialization. In September (Fig. 10b), positive LHF correlations mainly occur in the SEP region, a manifestation of the SPMM. Meanwhile, negative correlations appear in the eastern equatorial Pacific, which indicates that the SST anomalies in the equatorial Pacific start to develop in September. This implies that the SPMM does not necessarily contribute to the ENSO variability. From September to next February (Figs. 10b–g), negative correlation area expands westward.

To summarize, the results based on the ENSEMBLES hindcasts lend support to those in section 3 and show the effect of the mode transition from the WES to Bjerknes feedback on the ENSO variability.
5. Summary and discussion

This study investigates spatiotemporal coevolution in intermember anomalies of SST and low-level winds over the Pacific in ensemble hindcasts. Two types of evolution of intermember SST anomalies in the equatorial Pacific are identified. The first type features an evident southwestward propagation of SST anomalies from the NEP to the central equatorial Pacific, which is readily seen in the hindcasts initialized in winter months. The second type displays the growth in the equatorial Pacific with a weak northward propagation from the SEP. This occurs in the hindcasts initialized in summer months. These results highlight the north–south asymmetry in extratropical influences, with the strong precursor effect of the NPMM on ensemble spread of central Pacific SST prediction.

The southwestward migration of the NPMM onto the equator is phase locked onto winter–spring. This phase locking is due to large atmospheric variability in the North Pacific trade winds and to the more efficient LHF response to the low-level winds in the NEP region during winter–spring (Vimont et al. 2009). The ENSEMBLES hindcasts confirm that the coupled pattern between the positive SST anomalies and the reduced northeast trades generates positive WES feedback in spring. The coupled pattern extends southwestward to trigger the summertime equatorial Bjerknes mode, thus influencing ENSO variability.

The Niño-4 SST spread increases rapidly in January–April, stabilizes in May–June, and grows again in July–September in hindcasts initialized in winter months. The rapid growth of the Niño-4 SST spread in January–April is attributed to the arrival of NPMM perturbations from the
NEP, while the slowdown in May–June and rapid growth in July–September arise mainly from the seasonality of the ocean–atmosphere interaction in the equatorial Pacific.

Previous studies (Chiang and Vimont 2004; Larson and Kirtman 2013) suggested NPM as a precursor for ENSO prediction based on the correlation between the two. Here, we show that NPM perturbations contribute to the rapid growth of intermember uncertainty in predicting equatorial Pacific SST in winter–spring, which limits the reliability of ENSO prediction. In studying phenomena of climate variability, the degree of freedom is limited by the length of observations. Our study shows that, although the models used for forecasts are not perfect, ensemble hindcasts offer an alternative way to study climate variability, with the advantage of increased degrees of freedom from the ensemble size and frequent initialization.

Acknowledgments. We acknowledge the agencies that support the NMME system and thank Environment Canada climate modeling group for producing and making available the model output. This work is jointly supported by the U.S. National Science Foundation (1637450), the Natural Science Foundation of China (41575077 and 41490643), the China Scholarship Council (201508320298), and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

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