A Theory of the Spring Persistence Barrier on ENSO. Part I: The Role of ENSO Period

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ABSTRACT: In this paper, we investigate the role of the period of El Niño–Southern Oscillation (ENSO) in the spring persistence barrier (SPB), mainly using the neutral recharge oscillator (NRO) model both analytically and numerically. It is suggested that a shorter ENSO period strengthens the SPB. Moreover, in contrast to the strict phase locking of the SPB in the Langevin equation, the phase of the SPB is no longer locked exactly to a particular time of the calendar year in the NRO model. Instead, the phases of the SPB for different initial months shift earlier with lag months of maximum persistence decline. In particular, the phase of the SPB will be shifted from the early summer to early spring, corresponding to the initial months of the early half year and later half year. This feature demonstrates that for the later half year, ENSO predictability decreases as the presence of ENSO period. For realistic parameters, the range of the phase change is modest, smaller than 2–3 months. A similar phase shift is also identified for the SPB in the damped ENSO regime, unstable ENSO regime, and observations. Our theory provides a null hypothesis for the role of ENSO period with regard to the SPB.

KEYWORDS: ENSO; Climate prediction; Forecast verification/skill; Seasonal forecasting; Tropical variability

1. Introduction

The spring persistence barrier (SPB) and the associated spring predictability barrier have received considerable attention in El Niño–Southern Oscillation (ENSO) prediction studies. It has long been noticed in the observations of the tropical Pacific Ocean sea surface temperature (SST) anomaly (e.g., Niño-3.4; 5°S–5°N, 170°–120°W; Ren et al. 2016) variability and the variability in sea level pressure (Troup 1965; Webster and Yang 1992) and rainfall (Walker and Bliss 1932; Wright 1979). The major feature of this SPB is that a band of maximum decline of monthly autocorrelation occurs at a fixed phase (or month), as seen from the monthly autocorrelation of SST anomaly variability and its lag gradient (e.g., Liu et al. 2019). This maximum decline of persistence of fixed phase shows that, regardless of the initial months, a damped persistence forecast loses its predictability most rapidly in the following May or June, forming the SPB of ENSO. Recent studies also suggested that there are distinct features of persistence barrier in the two types of ENSO, the eastern Pacific (EP) and central Pacific (CP) types (Ren et al. 2016). By using a statistical model, Ren et al. (2019) found that the summer barrier in the ENSO persistence for the CP type is closely related to the summer predictability barrier.

Despite intensive studies of the SPB of ENSO, the nature of the SPB has not been fully understood. Some studies suggested

that the spring predictability barrier is related to systematic errors of the forecasting scheme and therefore is not an intrinsic feature of ENSO (Chen et al. 2004; Johnson et al. 2000; Yu et al. 2012), whereas some other studies demonstrated that the SPB or spring predictability barrier is an intrinsic feature in the real climate system related to the seasonally varying initial error growth or ENSO growth rate of SST anomaly, which is in turn related to the background of the tropical Pacific (Blumenthal 1991; Moore and Kleeman 1996; Torrence and Webster 1998; Mu et al. 2007; Levine and McPhaden 2015). Zhu et al. (2015) indicated that, over the eastern equatorial Pacific, the connection between the thermocline and SST is the weakest during boreal spring, which may be one of causes for ENSO SPB. Recently, Liu et al. (2019, hereinafter LJ19) derived a simple analytical solution for the SPB as an asymptotic solution of the damped persistence model with seasonal growth rate and noise forcing—that is, a Langevin equation of seasonally varying coefficients. This solution demonstrated explicitly that once the amplitude of the seasonal growth rate exceeds a threshold, the seasonal persistence barrier occurs. It showed theoretically that the persistence barrier is an intrinsic feature in a seasonal forcing system, at least in a system described by the Langevin equation. By linking the seasonal growth rate in this equation with the seasonally varying Bjerknes instability index (Jin et al. 2006), Jin et al. (2019) indicated that seasonal thermodynamic damping and thermocline positive feedback play an important role in determining the ENSO SPB. The role of ENSO growth rate in SPB strength (i.e., a weaker ENSO growth rate strengthens SPB) is further identified in two different ENSO regimes (Jin et al. 2020). Overall, the role of ENSO growth rate in SPB has been discussed by recent studies.

One major deficiency of the theory of LJ19 and Jin et al. (2019, 2020), however, is the lack of the effect of the natural ENSO period on SPB, because the Langevin equation does not

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include an ENSO period. Because the ENSO period has been suggested to be important for its predictability (Chen et al. 1997; Chen and van den Dool 1997), it is interesting to examine the role of an inherent ENSO period in SPB. More specifically, we are interested in the following question: How does the ENSO period influence the strength and phase of the SPB?

This paper is an attempt to understand the modulation of ENSO period on SPB mainly in the context of the neutral recharge oscillator (NRO) model (Stein et al. 2014). Both analytical and numerical solutions of the autocorrelation function (ACF) and SPB are derived in the NRO model. The features of SPB caused by ENSO period are also observed and interpreted in the damped regime, self-exciting regime, and ENSO observations.

The paper is arranged as follows. The recharge oscillator model, the definition of ENSO SPB strength and timing, and the reanalysis data will be presented in section 2. In sections 3 and 4, we will explore the effect of ENSO period on SPB in the NRO model in analytical and numerical solutions, respectively. Section 5 will further examine the SPB for ENSO in the damped and self-exciting regime as well as in the observations. A summary and discussion will be given in section 6.

2. Model, method, and data

a. The parametric recharge oscillator model

Our ENSO model is based upon the recharge oscillator model (Jin 1997a,b). It contains cubic nonlinearity, quadratic nonlinearity, and stochastic noise forcing. This recharge oscillator captures the dynamic relationship between the western equatorial Pacific thermocline anomaly H and eastern SST anomaly T and can be written as follows (Chen and Jin 2020):

$$\frac{dT}{dt} = -\lambda(t)T + \omega_0 H + \sigma\xi - cT^3 + bT^2, \quad (2.1)$$

$$\frac{dH}{dt} = -\omega_0 T, \quad \text{and} \quad (2.2)$$

$$\frac{d\xi}{dt} = -d\xi + w(t). \quad (2.3)$$

Here, λ is the damping rate (or $-\lambda$ is the growth rate) of the SST anomaly with $\lambda(t) = R_0 + \lambda_0 \sin(\omega_A t)$ varying seasonally in the annual frequency $\omega_A = (2\pi/12) \text{ month}^{-1}$, which leads to the phase locking of ENSO variance (Chen and Jin 2020) and SPB (Levine and McPhaden 2015). Also, ω_0 is the ENSO linear frequency; σ is the noise amplitude, with $w(t)$ being a white noise and ξ being a red noise with a decay time scale of 1 day⁻¹. The quadratic b and cubic c nonlinear terms roughly represent nonlinear dynamic heating from both nonlinear advection and upwelling, and from the upscale effects of ENSO modulation of tropical instability waves (An 2008).

An approximate analytical solution of SPB is obtained from the neutrally stable, unforced case of the recharge model with $R_0 = 0$, $\sigma = 0$, $c = 0$, and $b = 0$. Previous studies have shown that the approximate analytical solution of variance in this neutral model is able to explain the ENSO phase locking of variance (Stein et al. 2014). Here we will derive the

corresponding ACF and in turn study the SPB. The robustness of the results of the NRO model is then confirmed numerically in the recharge model in the damped regime with noise forcing ($R_0 > 0$, $\sigma > 0$, $c = 0$, and $b = 0$) or self-exciting unstable regime ($R_0 < 0$, $\sigma = 0$, $c > 0$, and $b = 0$). All of the numerical results are from the last 500 years of 1000 model years. The numerical model Eqs. (2.1)–(2.3) are solved at a time step of 4 h.

b. Definition of SPB strength and timing

The ACF is a function of initial months m and lag months τ (Ren et al. 2016; Jin et al. 2020), which can be written as $r(m, \tau)$. According to LJ19, ENSO SPB strength can be defined from ACF as follows. First, for a calendar month m , we identify $\tau_B(m)$ as the specific lag of maximum ACF decline, which is calculated as the lag gradient in the time step of 1 month as

$$S_B(m) = \left\{ \frac{r[m, \tau_B(m) - 1] - r[m, \tau_B(m) + 1]}{2} \right\} \\ = \max_{\tau} \left[\frac{r(m, \tau - 1) - r(m, \tau + 1)}{2} \right], \quad (2.4)$$

where $S_B(m)$ is the maximum gradient for every initial month. Second, the total intensity of the SPB is estimated as

$$S_{B_1} = \sum_{m=1}^{12} S_B(m). \quad (2.5)$$

For each calendar month m , the timing γ of SPB can be defined as

$$\gamma(m) = m + \tau_B(m). \quad (2.6)$$

Note here that, in the Langevin equation of seasonally varying growth rate, γ is a constant (LJ19). As such, the timing of SPB is phase locked to a specific month exactly. This is no longer true when the ENSO period is present, as shown below in section 3 in the NRO model.

c. The reanalysis dataset

The reanalysis dataset of SST used here in this study is the monthly Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST; 1° × 1°). Here we use HadISST v1.1 (<https://climatedataguide.ucar.edu/climate-data/sst-data-hadisst-v11>) to identify some general features of SPB. All monthly data used here with their climatological seasonal cycle and linear trends being removed.

3. Effect of ENSO period on SPB in the NRO model: Analytical solution

In this section, the role of ENSO period in SPB is studied by deriving an approximate analytical solution in the NRO model.

For the linear scenario of the NRO model ($R_0 = 0$, $\sigma = 0$, $c = 0$, and $b = 0$), an approximate analytical solution of T can be obtained for a weak annual cycle of the growth rate (i.e., small amplitude of this seasonal growth rate) or small λ_e [i.e., nondimensional amplitude of damping rate $[\lambda(t) = R_0 + \lambda_0 \sin(\omega_A t)]$],

FIG. 1. The (a) numerical and (b) analytical solutions of the persistence map (ACF) for $\lambda_\varepsilon = 1/\pi$ and $\omega_0 = (2\pi/48)$ month $^{-1}$ in the NRO model. The black circles on the persistence map mark the lag month of maximum auto-correlation decline for different initial months.

$\lambda_\varepsilon = \lambda_0/\omega_A \ll 1$]. By using the perturbation method, one special solution of T (An and Jin 2011; Chen and Jin 2020) is

$$T \approx \sin(\omega_0 t) - \frac{\lambda_\varepsilon \omega_A}{\omega_A^2 - 4\omega_0^2} \left[\omega_0 \sin(\omega_A t) \cos(\omega_0 t) - \frac{\omega_A^2 - 2\omega_0^2}{\omega_A} \cos(\omega_A t) \sin(\omega_0 t) \right]. \quad (3.1)$$

Denoting $A = (\omega_0 \omega_A)/(\omega_A^2 - 4\omega_0^2)$ and $B = (\omega_A^2 - 2\omega_0^2)/(\omega_A^2 - 4\omega_0^2)$, the T solution can be further written as

$$T(t) = \sin(\omega_0 t) - \lambda_\varepsilon A \sin(\omega_A t) \cos(\omega_0 t) + \lambda_\varepsilon B \cos(\omega_A t) \sin(\omega_0 t); \quad (3.2)$$

$T(t)$ is a function of year y and the calendar month m (from 1 to 12 to represent January–December). The seasonally varying variance $\sigma_T^2(m)$ can be derived as

$$\sigma_T^2(m) = E[T^2(y, m)] = \frac{1}{2} + \lambda_\varepsilon B \cos(\omega_A m). \quad (3.3)$$

Equation (3.3) shows that the variance always reaches the maximum in December ($m = 12$). It suggests that the seasonal growth rate of ENSO SST anomaly plays an important role in the phase locking of variance, which is consistent with Stein et al. (2014).

Here, to derive the ACF, the covariance function $S_{m, m+\tau}$ between $T(y, m)$ and $T(y, m + \tau)$ can be derived and written as follows:

$$S_{m, m+\tau} = E[T(y, m)T(y, m + \tau)] = \frac{\cos \omega_0 \tau}{2} \{1 + \lambda_\varepsilon B \cos[\omega_A(m + \tau)] + \lambda_\varepsilon B \cos(\omega_A m)\} + \frac{\lambda_\varepsilon A \sin \omega_0 \tau \{\sin[\omega_A(m + \tau)] - \sin(\omega_A m)\}}{2}. \quad (3.4)$$

Then, the ACF $r_{m, m+\tau}$ can be derived as follows (see more details in the appendix):

$$r_{m, m+\tau} = \frac{S_{m, m+\tau}}{\sqrt{\sigma_T^2(m)\sigma_T^2(m + \tau)}} \approx \cos \omega_0 \tau + \lambda_\varepsilon A \sin \omega_0 \tau \{\sin[\omega_A(m + \tau)] - \sin(\omega_A m)\}. \quad (3.5)$$

This approximate analytical solution of the ACF captures the major features of the ACF in the numerical solution of NRO model, as shown in Fig. 1. According to Eq. (3.5), ACF is determined by two terms. The first term $\cos \omega_0 \tau$ represents the basic state of the ENSO, with no damping. The second term, $\lambda_\varepsilon A \sin \omega_0 \tau \{\sin[\omega_A(m + \tau)] - \sin(\omega_A m)\}$, represents the interaction between the annual cycle ω_A and ENSO period ω_0 . It is the term that will lead to SPB. Setting $\lambda_\varepsilon = 1/\pi$ and $\omega_0 = (2\pi/48)$ month $^{-1}$ (Chen and Jin 2020), numerical solution (Fig. 1a) shows that a PB occurs in the early summer and that its strength is 2.00. The analytical solution (Fig. 1b) also indicates that a PB occurs in the early summer, but with a weaker SPB strength (1.83). The weaker SPB strength for the analytical solution is due to a low-order correlation between the annual cycle of growth rate and ENSO frequency. In all, this analytical solution can capture the main feature of SPB in NRO model.

For clarity, we further nondimensionalize the time by the annual cycle, such that the nondimensional times are $m_* = \omega_A m$, $\tau_* = \omega_A \tau$, and $\omega_* = \omega_0/\omega_A$. Now, the ACF r can be simplified to

$$r_{m_*, m_* + \tau_*} = \cos \omega_* \tau_* + \lambda_\varepsilon A \sin \omega_* \tau_* \{\sin(m_* + \tau_*) - \sin(m_*)\}. \quad (3.6)$$

The gradient of this ACF with lag is then

$$\frac{\partial r_{m_*, m_* + \tau_*}}{\partial \tau_*} = -\omega_* \sin \omega_* \tau_* + \lambda_e A \omega_* \cos \omega_* \tau_* [\sin(m_* + \tau_*) - \sin(m_*)] + \lambda_e A \sin \omega_* \tau_* \cos(m_* + \tau_*). \quad (3.7)$$

The lag of maximum gradient can be obtained approximately under the further assumption of a long ENSO period relative to the annual cycle

$$\omega_* \rightarrow 0 \quad (3.8)$$

at the leading order as

$$\frac{\partial^2 r_{m_*, m_* + \tau_*}}{\partial \tau_*^2} \approx -\omega_*^2 \cos \omega_* \tau_* - \lambda_e A \sin \omega_* \tau_* \sin(m_* + \tau_*) = 0. \quad (3.9)$$

This gives the timing of the SPB explicitly as

$$m_* + \tau_B = \arcsin\left(-\frac{\omega_*^2}{\lambda_e A \tan \omega_* \tau_B}\right). \quad (3.10)$$

Taking $A = (\omega_0 \omega_A)/(\omega_A^2 - 4\omega_0^2)$ and $\tan \omega_* \tau_* \approx \omega_* \tau_*$ into Eq. (3.10) yields

$$m_* + \tau_B \approx \arcsin(-E/\tau_B), \quad (3.11)$$

where

$$E = \frac{1 - 4\omega_*^2}{\lambda_e}. \quad (3.12)$$

The necessary forcing condition for the existence of maximum ACF decline, or PB, is that $E/\tau_B \leq 1$. For $\tau_B = \tau_{B0}$ ($E/\tau_{B0} = 1$), a barrier occurs with the timing of $m_* + \tau_{B0} = \arcsin(-E/\tau_{B0})$. As such, τ_{B0} indicates that the minimum lag month that PB occurs. In Fig. 1, the τ_{B0} occurs in the lag 4 months for the numerical solution (Fig. 1a) and 5 months for the analytical solution (Fig. 1b). This is a specific feature in the NRO model, because it lacks the system damping. In contrast to the NRO model, PB occurs when $\tau_{B0} = 0$ in the Langevin equation (LJ19).

The solution of Eq. (3.11) shows explicitly that, when τ_B increases, the timing $m_* + \tau_B$ is no longer a fixed phase; instead, it shifts earlier as $|E/\tau_B|$ becomes smaller. Therefore, in contrast to the Langevin equation in which the timing of SPB is strictly phase locked to a fixed month (Liu et al. 2019), the timing of SPB in NRO model varies in a range. That is, γ is no longer constant, which can be seen clearly in section 4. This may be caused by the interaction between the annual frequency and lower frequency (2–7 yr; ENSO period).

We examine the SPB for an entire annual cycle of initial months to explore the phase range of SPB. This feature indicates that although SPB occurs in May or June (Liu et al. 2019) for initial month January, when we start to forecast in October, the forecast skill will drop dramatically in the early spring,

shorter than we expect. We will explain this feature through the numerical solutions.

4. Effect of ENSO period on SPB in the NRO model: Numerical solution

In this section, the features of SPB in light of the analytical solution derived above, and furthermore in the numerical solution of NRO model, are discussed.

a. Impact of ENSO period on the intensity of SPB

We first show that a shorter ENSO period strengthens the SPB. According to Eq. (3.7) (gradient of the ACF), $\omega_* \sin \omega_* \tau_*$ is proportional to ω_* . The last two terms, which contain the seasonal growth rate, are the main reasons for SPB. As $A = (\omega_0 \omega_A)/(\omega_A^2 - 4\omega_0^2)$ is proportional to ω_* (ω_0/ω_A), the three terms are all proportional to ω_* , which indicates that a larger ω_* (shorter ENSO period) will contribute to a stronger gradient $\partial r_{m_*, m_* + \tau_*}/\partial \tau_*$, which will then be accumulated to give a stronger SPB as shown in Eqs. (2.4) and (2.5). This is confirmed in the numerical solution of ACF by comparing the two examples in Figs. 2a and 2c of ENSO periods of 3 and 5 years, respectively. Here $\lambda_e = (1.2/\pi)$. When the ENSO period is 3 years ($\omega_* = 1/3$), the SPB strength calculated following Eq. (2.5) is 3.85 (Fig. 2a), which is stronger than that of the 5-yr ENSO period case (1.95; Fig. 2c).

To confirm the impact of ENSO period on SPB strength systematically, we examine the modulation of the SPB strength by varying the ENSO period from 2.5 to 6 years (Fig. 3). In the NRO model, there is a parametric resonance when ENSO period is two years (Stein et al. 2014) such that we study the ENSO period from 2.5 years. For a small amplitude of seasonal cycle of damping rate $\lambda_e = 0.6/\pi$, both numerical solutions (blue triangles in Fig. 3) and approximate analytical solutions (green triangles in Fig. 3) show that a shorter ENSO period strengthens ENSO SPB. The difference between the analytical and numerical solutions increases modestly when the ENSO period becomes shorter, because the approximate analytical solution is derived in the limit of ENSO period much larger than the annual cycle. This weakening effect of a longer ENSO period on SPB is also robust for an increased amplitude of seasonal cycle: $\lambda_e = 1.8/\pi$ (squares in Fig. 3). The difference between the numerical solution and analytical solution is larger than that of $\lambda_e = 0.6/\pi$ case, because the analytical solution is derived in the limit of small amplitude of seasonal cycle $\lambda_e \ll 1$. The comparison of the cases of $\lambda_e = 0.6/\pi$ and $1.8/\pi$ shows that the SPB is stronger for larger λ_e (blue triangles vs blue squares or green triangles vs green squares in Fig. 3). This is consistent with the Langevin equation where the SPB intensifies with the amplitude of the seasonal period (LJ19). Note here that previous studies have shown the relationship between the SPB intensity and ENSO phase locking (Torrence and Webster 1998; Tian et al. 2019). According to Eq. (3.3), ENSO phase locking strength is directly related to the seasonal forcing amplitude λ_e . Moreover, the strength of ENSO SPB is also controlled by the seasonal forcing amplitude (triangles vs squares in Fig. 3; Liu et al. 2019). Both ENSO SPB and phase

FIG. 2. The numerical solution of the persistence map (ACF) for $\lambda_e = 1.2/\pi$, in the NRO model. (a) The $\omega_0 = (2\pi/36)$ month⁻¹ case. The black lines on the persistence map mark the lag phase of maximum autocorrelation decline for different initial phases [i.e., $\tau_B(m)$]. The gray line indicates that the phase of SPB (γ) is constant. Here the daily data are used to calculate the persistence map. (b) The relationship between γ and the maximum persistence decline τ_B . The blue plus signs indicate γ for the $\omega_0 = (2\pi/36)$ month⁻¹ case, and the black line suggests γ for the Langevin equation. (c),(d) As in (a) and (b), but for the $\omega_0 = (2\pi/60)$ month⁻¹ case.

locking strength are related to this amplitude, so both will show similar changes.

b. Impact of ENSO period on the phase of SPB

We now show that the timing of SPB in the NRO model is no longer phase locked to a fixed month. Instead, the SPB varies with a range of about 2 months, for some typical parameters. This is in contrast to the Langevin equation, where the timing of SPB is phase locked to a fixed month once SPB occurs. This change of the phase of SPB is caused by the presence of the ENSO period. As seen in Eq. (3.11), γ is no longer a constant in general, which can be shown in the examples in Fig. 2. For an ENSO period of 3 years (Fig. 2a), the first SPB lag τ_{B0} is 75° at the initial phase of 145°. According to Eq. (2.6), the timing of SPB is 75° + 145° = 220°. With the increasing lag τ_B to, say,

190° at the initial month of 0°, the timing of the SPB is therefore 0° + 190° = 190° and is shifted earlier by 30° (~1 month). With the further increased τ_B , the phase of the SPB is shifted even earlier. In particular, the relationship between the initial month m and maximum persistence decline τ_B is not linear (gray line in Fig. 2a), bending downward (black line in Fig. 2a). This change of SPB month can be seen more clearly in Fig. 2b (blue plus sign). For the 3-yr ENSO case, at $\tau_B = \tau_{B0}$, the SPB phase is $\gamma(\tau_{B0}) = 210^\circ$. As τ_B increases (m_* is modulated as well), γ decreases in the NRO model, in contrast to the Langevin equation in which the SPB month maintains at 210° (black line in Fig. 2b), and the timing of SPB decreases by ~60° (from 210° to 150°; ~2 months). This feature of changing SPB timing is also robust for the case of a 5-yr ENSO period (Fig. 2c, and blue plus sign in Fig. 2d), although the phase range is

FIG. 3. The relationship between ENSO period (yr) and SPB strength for $\lambda_e = 0.6/\pi$ (for clarity, we use $\lambda_0 = 0.1 \text{ month}^{-1}$ in the figure legend; triangles) and $\lambda_e = 1.8/\pi$ (here we use $\lambda_0 = 0.3 \text{ month}^{-1}$ in the figure legend; squares); the blue symbols are the numerical solution, and the green symbols indicate the results from the analytical solution of ACF.

reduced to $\sim 40^\circ$ (from 213° to 173° ; ~ 1.3 months). Indeed, the Langevin equation can be treated as the case of ENSO period of infinitely long period ($m_* = 0$), and the phase range is then reduced to zero (i.e., an exact phase locking), as shown in LJ19.

The phase range of SPB with ENSO period can be seen more systematically in the NRO model in both analytical and numerical solutions (Fig. 4), in which the ENSO period changes from 2.5 to 6 years. For the case of $\lambda_e = 0.6/\pi$, when the ENSO period is lengthened, the phase range of the SPB decreases monotonically in the numerical solution (blue triangles in Fig. 4). This decrease of phase range is well approximated by the analytical solution (except for very short ENSO periods; green triangle in Fig. 4). This is, in fact, straightforward to understand. When the ENSO period is longer ($\omega_* \rightarrow 0$), the NRO model behaves more like the Langevin equation, in which the phase range vanishes (LJ19). The phase changes of SPB with the modulation of ENSO period may be caused by the interaction between annual frequency and lower frequency. When ENSO period is shorter, this interaction is stronger and shifts the timing of SPB. Physically, the shortened ENSO period may be caused by the thermocline and zonal advective feedbacks (Lu et al. 2018). As such, these feedbacks may also affect the timing of SPB. In the case of a larger amplitude of seasonal cycle $\lambda_e = 1.8/\pi$, the phase range is reduced (green square vs green triangle or blue square vs blue triangle in Fig. 4). This may be understood as follows. A larger λ_e represents a stronger seasonal forcing. As indicated by LJ19, the SPB is caused by this seasonal forcing and intensified with the seasonal cycle. When the seasonal forcing is intensified in the NRO model, the phase locking of the SPB

FIG. 4. As in Fig. 3, but for the phase range of SPB.

to a fixed phase becomes more distinct, with the range of SPB phase decreased.

In sum, our study of the NRO model here shows that a shorter ENSO period tends to intensify the SPB and shift the timing of the SPB. These features will also be seen in the next section for ENSOs in the damped persistence regime, self-exciting regime, and observation.

5. Impact of ENSO period on the SPB features in the different ENSO regimes and observation

We now examine SPB response to ENSO period in the recharge oscillator model in the damped regime ($R_0 > 0$, $\sigma > 0$, $c = 0$, and $b = 0$), self-exciting regime ($R_0 < 0$, $\sigma = 0$, $c > 0$, and $b = 0$), and observation.

a. SPB for ENSO in the damped-persistence regime

In the damped regime, a shorter ENSO period will also strengthen the SPB. Parameters set for the observational ENSO are (Chen and Jin 2020) $R_0 = -0.1 \text{ month}^{-1}$, $\sigma = 1/9 \text{ month}^{-1}$, and $d = 0.66 \text{ month}^{-1}$. Here we set $\lambda_e = 1.8/\pi$ to show distinct ENSO SPB features. When ENSO period is 3 years, the SPB strength is 4.76 (Fig. 5a), which is significantly stronger than the case when ENSO period is 5 years (2.61; Fig. 5b). It shows that a shorter ENSO period will also strengthen SPB in the damped regime.

Furthermore, ENSO SPB is no longer phase locked to a fixed month in the damped regime as in the neutral case before. Here we use monthly data in the damped recharge oscillator model to directly compare it with the observation. When initial month is April (Fig. 5a), the maximum persistence decline τ_B occurs in the lag-2 month, which indicates that SPB occurs in June (red line in Fig. 5a). However, as the τ_B increases, for initial month January, SPB happens in May (black line in Fig. 5a). The timing of ENSO SPB moves forward, which is

FIG. 5. The SPB features in the damped recharge oscillator model. The numerical solution of persistence map for ENSO period is (a) 3 and (b) 5 years. The red line indicates an SPB timing, and the black line suggests another SPB timing.

consistent with SPB features in NRO model. The sudden jump of the SPB month is due to this monthly SST data used here. This feature of SPB also occurs when ENSO period is 5 years (Fig. 5b). It is noted that, as compared with the neutral oscillation in NRO model, damping produces one realistic feature of the SPB: the emergence of the SPB from the initial lag (i.e., $\tau_{B0} = 0$). This is consistent with the study in the Langevin equation, because the decline of persistence in the initial lags depends critically on the damping of the system (LJ19).

To confirm the impact of ENSO period on SPB features systematically in the damped regime, we vary the ENSO period from 2.5 to 6 years, as shown in Fig. 6. We find that when the ENSO period is shorter, the SPB strength is stronger

(squares or triangles in Fig. 6a). Meanwhile, ENSO SPB is stronger for a larger seasonal amplitude λ_e (squares vs triangles in Fig. 6a). It is consistent with the results in NRO model. We also find that a phase range of SPB in the damped regime exists (1–2 months). When λ_e is larger, the phase range of SPB is small (square vs triangle in Fig. 6b), which is the same as the results in the NRO model.

b. SPB for ENSO in the self-exciting regime

In the self-exciting regime, we set the parameter for realistic ENSO as $R_0 = 0.1 \text{ month}^{-1}$, $c = 1/62.3 \text{ month}^{-1}$, and $b = 0$ (Chen and Jin 2020). Here we set $\lambda_e = 1.8/\pi$ to be consistent with the damped regime. When the ENSO period is 3 years

FIG. 6. (a),(b) As in Figs. 3 and 4, respectively, but for the numerical solution in the damped recharge oscillator model. The unit in (b) is degrees, which is consistent with Fig. 4 (30° represents one month).

FIG. 7. As in Fig. 5, but for the SPB features in the unstable ENSO regime.

(Fig. 7a), the SPB strength is 4.59, which is significantly stronger for the case when ENSO period is 5 years (1.69; Fig. 7b). It shows that the SPB weakens with the increased period of ENSO period. Meanwhile, we find both in two cases, the timing of SPB is not phase locked (Fig. 7). For initial month May (Fig. 7a), the maximum persistence decline τ_B occurs in lag 2-month such that the month of SPB is July (red line in Fig. 7a). When τ_B is increased, for initial month January, τ_B is 5 months such that the month of SPB is June (black line in Fig. 7a), which is one month earlier for the case of initial month May. We also find similar SPB features when ENSO period is 5 years (Fig. 7b). In all, the phase of SPB moves forward as τ_B is increased in the unstable regime.

We also examine the SPB features systematically in the unstable regime by varying the ENSO period from 2.5 to 6

years (Fig. 8). It is found that the SPB is strengthened with decreased ENSO period (squares or triangles in Fig. 8a). Meanwhile, the SPB exists for a phase range in the unstable regime (square or triangle in Fig. 8b). When seasonal forcing amplitude is decreased, ENSO SPB strength is weaker (squares vs triangles in Fig. 8a) and the phase range of SPB is larger (squares vs triangles in Fig. 8b). In all, the SPB features caused by ENSO period are consistent with the results in NRO model.

c. SPB phase shift for observed ENSO

The earlier shifting of SPB can be identified in the observational ENSO. During the year 1958–80, for the initial lags of 2–3 months, which corresponds to the initial months of March to April, the timing of the SPB occurs in June (red line in

FIG. 8. As in Fig. 6, but for the SPB features in the unstable ENSO regime.

FIG. 9. As in Fig. 5, but for observational data during (a) 1958–80 and (b) 1980–2016.

Fig. 9a). However, for increased lag τ_B and the initial months of May–December, the SPB is shifted one month earlier to May (black line in Fig. 9a). This change of SPB month can also be seen for the years 1980–2016, when the timing of SPB also shifts earlier for increased lags, from June for the initial months of January to April (red line in Fig. 9b) to May for initial months of May to November (black line in Fig. 9b). This shift of the SPB month is not caused by the sampling error, since for the late half year (e.g., Fig. 9b) the timing of SPB moves forward systematically. Instead, our theory suggests that this shift is an intrinsic feature of the observed ENSO and it identifies that the timing of SPB will be shifted earlier from the early summer (May–June) to late spring (April–May), corresponding to the initial months of the early half year and later half year, respectively. This feature indicates that for later half year, ENSO predictability decreases as the cause of ENSO period.

In this section, we identify that the features of the SPB in the NRO model are robust for the damped persistence regime, self-exciting regime, and observational ENSO. We find that a shorter ENSO period will strengthen ENSO SPB. Moreover, the timing of SPB is no longer phase locked to a specific month. As τ_B is increased, the timing of SPB shifts earlier, indicating that ENSO predictability decreases for later initial months.

6. Summary and discussion

As a follow up of LJ19, this paper attempts to understand the role of ENSO period in SPB. In particular, on the basis of the approximate analytical solution of SST anomaly variance in the NRO model (Stein et al. 2014), we derive the ACF and develop a theory that sheds light on the influence of ENSO period on SPB. We find two effects of ENSO period on the SPB. First, a shorter ENSO period strengthens the SPB, implying that the prediction skill will drop more significantly if the ENSO period is shortened. Second, in contrast to the SPB in the Langevin equation (LJ19), the timing of SPB is no longer

phase locked exactly to a fixed month. Instead, the timing of the SPB shifts earlier by 1–2 months. Therefore, the maximum drop of ENSO prediction skill will depend on the forecast lead and initial forecast month. The forecast skill will drop dramatically in late spring for small forecast leads when the predictions start from the early half of the year, whereas the prediction skill will drop significantly in early spring for long-term leads of forecast when the prediction starts from the late half of the year. These two impacts of ENSO period on SPB are further found to be robust in the recharge model for ENSOs in the damped regime, self-exciting regime, and observation.

The physical mechanism of influencing ENSO SPB strength is complicated according to the analytical solution of NRO model and Bjerknes instability index (Jin et al. 2006). On the basis of the recharge oscillator framework, Lu et al. (2018) indicated that the thermocline and zonal advective feedbacks multiplied by the efficiency factor of discharging/recharging of the equatorial content driven by ENSO wind stress anomalies [ω_0 in Eqs. (2.1) and (2.2), respectively] control ENSO linear periodicity. As demonstrated by Eqs. (2.4) and (2.5), a larger ω_0 leads to a shorter ENSO period and a strengthened SPB. Accordingly, the thermocline and zonal advective feedbacks may affect the strength of SPB by controlling the ENSO period. On the other hand, the Bjerknes instability index is identified to play an important role in the strength of SPB (Jin et al. 2019, 2020). The thermocline and zonal advective feedbacks can also affect SPB strength by controlling this Bjerknes instability index. Therefore, the physical mechanism of affecting SPB strength still needs further study.

This study may have implications for ENSO prediction under a global warming scenario. As suggested by Collins et al. (2010), year-to-year ENSO variability is controlled by a delicate balance of amplifying and damping feedbacks, and it is not yet possible to determine whether ENSO period will change. As such, ENSO SPB, and in turn ENSO predictability, may not be strengthened or weakened as ENSO period will not change dramatically.

Overall, our theory provides an explanation of the role of ENSO period on SPB. We suggest that it can serve as a null hypothesis for the ENSO SPB.

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APPENDIX

Derivation of Autocorrelation Function Based on NRO Model

According to Eqs. (3.3) and (3.4), the ACF can be derived as follows:

$$r_{m,m+\tau} = \frac{S_{m,m+\tau}}{\sqrt{\sigma_T^2(m)\sigma_T^2(m+\tau)}} = \frac{\frac{\cos \omega_0 \tau}{2} \{1 + \lambda_\varepsilon B \cos[\omega_A(m+\tau)] + \lambda_\varepsilon B \cos(\omega_A m)\} + \frac{\lambda_\varepsilon A \sin \omega_0 \tau}{2} \{\sin[\omega_A(m+\tau)] - \sin(\omega_A m)\}}{\sqrt{\left(\frac{1}{2} + \lambda_\varepsilon B \cos(\omega_A m)\right) \left(\frac{1}{2} + \lambda_\varepsilon B \cos[\omega_A(m+\tau)]\right)}}. \quad (\text{A1})$$

Because $\lambda_\varepsilon \ll 1$, at the leading order, the following term can be written as

$$\sqrt{\left(\frac{1}{2} + \lambda_\varepsilon B \cos(\omega_A m)\right) \left(\frac{1}{2} + \lambda_\varepsilon B \cos[\omega_A(m+\tau)]\right)} \approx \sqrt{\frac{1 + 2\lambda_\varepsilon B \cos(\omega_A m) + 2\lambda_\varepsilon B \cos[\omega_A(m+\tau)]}{4}} \\ \approx \frac{1 + \lambda_\varepsilon B \{\cos(\omega_A m) + \cos[\omega_A(m+\tau)]\}}{2}. \quad (\text{A2})$$

As such,

$$r_{m,m+\tau} \approx [\cos \omega_0 \tau (1 + \lambda_\varepsilon B \{\cos(\omega_A m) + \cos[\omega_A(m+\tau)]\}) + \lambda_\varepsilon A \sin \omega_0 \tau \{\sin[\omega_A(m+\tau)] - \sin(\omega_A m)\} (1 - \lambda_\varepsilon B \{\cos(\omega_A m) + \cos[\omega_A(m+\tau)]\})] \approx \cos \omega_0 \tau \\ + \lambda_\varepsilon A \sin \omega_0 \tau \{\sin[\omega_A(m+\tau)] - \sin(\omega_A m)\}. \quad (\text{A3})$$

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