Understanding Anomalous Synoptic Eddy Vorticity Forcing in Pacific–North American Teleconnection Pattern Events

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ABSTRACT

Utilizing a decomposition of anomalous eddy vorticity forcing (EVF) proposed by Song in 2016 and a modified Geophysical Fluid Dynamics Laboratory (GFDL) dynamical core atmospheric model, this study provides a different understanding of physical mechanisms that are responsible for the formation of the anomalous synoptic EVF (SEVF) associated with Pacific–North American teleconnection pattern (PNA) events. A series of short-term control experiments (CEs) and initial-value modified experiments (IVMEs) is conducted. In each case of CEs, there are no obvious PNA-like circulation anomalies. IVMEs are exactly the same as CEs except that appropriate small perturbations are introduced into the initial-value fields of CEs. The modified initial-value fields led to a gradual development of the PNA-like flow anomalies in IVMEs. Based on these numerical results, deformations of the synoptic eddy ψ'_D due to the emergence of the PNA pattern can be easily acquired by subtracting the synoptic eddy in CEs ψ'_C from the synoptic eddy in IVMEs ψ'_I . The anomalous SEVF associated with the PNA events in the model can be decomposed into ensembles of two linear ψ'_C and ψ'_D interaction terms (EVF1 and EVF2) and a nonlinear ψ'_D self-interaction term (EVF3). It is demonstrated that the physical essence of the anomalous SEVF associated with the PNA events is a competition result between EVF1 plus EVF2 and EVF3. Results also indicate that the different signs of SEVF associated with the positive and negative PNA events are not necessarily related to the different tilts of the synoptic eddy.

1. Introduction

Along with blocking (e.g., James 1994) and the North Atlantic Oscillation (NAO; van Loon and Rogers 1978; Kushnir and Wallace 1989), the Pacific–North American teleconnection pattern (PNA; Wallace and Gutzler 1981; Barnston and Livezey 1987) is one of prominent atmospheric low-frequency modes (LFMs) in the Northern Hemisphere. The PNA is characterized by a quadrupole or a wave train pattern that emanates from the tropical Pacific, arches through the North Pacific, and extends to North America. Its intrinsic dynamics operate on intraseasonal time scales with a typical life cycle of about 2 weeks (Cash and Lee 2001; Feldstein 2002; Franzke et al. 2011). The PNA is an internal mode of extratropical atmosphere over the Pacific–North American

sector (Simmons et al. 1983). However, in observations, the variations of PNA are also related to tropical forcing such as tropical sea surface temperature (e.g., Trenberth et al. 1998; Straus and Shukla 2002) and tropical convection (Mori and Watanabe 2008; Johnson and Feldstein 2010; Franzke et al. 2011; Dai et al. 2017; Seo and Lee 2017).

The PNA may be considered as a remote extratropical response to tropical forcing based on linear Rossby wave propagation and dispersion theory (Hoskins and Karoly 1981) or a rapidly growing atmospheric mode that efficiently extracts energy from a zonally varying background flow (Simmons et al. 1983; Mori and Watanabe 2008). Extensive investigations have shown that the PNA is accompanied by significant anomalous synoptic eddy vorticity forcing (SEVF), which also has an important effect on the PNA activity (e.g., Lau 1988; Held et al. 1989; Klasa et al. 1992; Sheng et al. 1998; Hall and Derome 2000;

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Jin et al. 2006; Kug et al. 2010; Franzke et al. 2011; Lee et al. 2012).

Similar to the PNA, the formations of blocking and the NAO are accompanied by significant anomalous SEVF as well (e.g., Green 1977; Shutts 1983; Illari 1984; Haines and Marshall 1987; Feldstein 2003; Benedict et al. 2004; Jin et al. 2006; Rivière and Orlanski 2007; Kunz et al. 2009; Barnes and Hartmann 2010; Kug et al. 2010; Song 2016). Many mechanisms have been proposed to understand the anomalous SEVF associated with blocking and the NAO. These mechanisms include but are not limited to an eddy straining mechanism (Shutts 1983), a barotropic shear mechanism (Hartmann and Zuercher 1998; Hartmann and Lo 1998), a baroclinic shear mechanism (Robinson 2000, 2006), a selective absorption mechanism (Yamazaki and Iton 2013), and a preexisting-eddies-determined mechanism (Luo 2005; Luo et al. 2007, 2014, 2015). A detailed review of these mechanisms is beyond the scope of this study.

However, at least according to the author's knowledge, few studies have attempted to understand the mechanisms that lead to the formation of the anomalous SEVF associated with the PNA. Roughly, the anomalous SEVF associated with the PNA is considered as a result of deformations of the synoptic eddy due to the interaction between the synoptic eddy and large-scale flows associated with the PNA (e.g., Franzke et al. 2011; Zhou et al. 2017). Here, the deformations of the synoptic eddy primarily denote changes of the eddy structure relative to the synoptic eddy in a normal situation (i.e., without PNA). However, because the deformations of the synoptic eddy caused by the PNA cannot be exactly identified or isolated using reanalysis data, there are presently no accurate direct calculation results to support this viewpoint.

Song (2016) proposed a procedure to decompose the nonlinear anomalous eddy vorticity forcing (EVF) associated with the LFMs by performing a series of initial-value experiments based on an idealized atmosphere model. He applied this EVF decomposition procedure to investigate the anomalous EVF associated with the NAO events. This study, as a follow-up work of Song (2016), offers a different understanding of the formation of the anomalous SEVF associated with the PNA events via applying the anomalous EVF decomposition procedure of Song (2016) to the PNA events.

The rest of this paper is organized as follows. Section 2 presents the data and model and outlines the anomalous EVF decomposition procedure. Section 3 verifies the similarity of the dynamics of the PNA between the reanalysis data and the model. Section 4 demonstrates the results of the initial-value experiments and the decomposition of the anomalous SEVF associated with

the PNA events in the model. Interpretations of the anomalous SEVF decomposition results are provided in section 5. Section 6 delivers some further discussions about the physical essence of the anomalous SEVF associated with the PNA events. Finally, section 7 contains a summary of this study.

2. Data, model, and methods

a. Data

This study uses National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis-1 daily data (Kalnay et al. 1996) for 62 boreal winters (DJF) from 1948/49 to 2009/10 (5580 days in all; 29 February in each leap year has been removed). The horizontal resolution of the data is $2.5^\circ \times 2.5^\circ$ with 17 standard pressure levels from 1000 to 10 hPa. Here, the term “anomalies” of the reanalysis data is defined as the deviation from a seasonal cycle, which is the time mean of each calendar day in the 62 boreal winters.

The daily index of the observed PNA is acquired by applying empirical orthogonal function (EOF) analysis to the daily sea level pressure (SLP) anomalies of the 62 boreal winters over the Pacific–North America region (20° – 85° N, 120° E– 100° W). Before performing the EOF analysis, the SLP anomalies were weighted by the square root of the cosine of latitude to account for the decrease in grid area toward the pole. The PNA corresponds to the EOF1. Therefore, the first normalized principal component is defined as the observed daily PNA index (PNAI). Its explained variance is 19.11%.

b. Anomalous EVF decomposition procedure

This study uses the anomalous EVF decomposition procedure proposed by Song (2016) to investigate the anomalous SEVF associated with the PNA events. Only a brief overview is given here. The EVF is defined as $-\nabla \cdot (\mathbf{U}'\zeta')$, where $\mathbf{U}' = (u', v')$, and u, v , and ζ denote the zonal wind, meridional wind, and vorticity, respectively. Parameter $\nabla \cdot (\cdot)$ is the horizontal divergence operator and a prime symbol denotes “anomaly,” that is, a departure relative to a long-term mean climatological value denoting the transient part of the variable (i.e., eddies).

Two series of short-term integrations are performed using an atmospheric model. One series consists of control experiments (CEs) and the other of initial-value-modified experiments (IVMEs). CEs contain many CE members with different initial values. In each member of CEs, there are no evident PNA circulation anomalies. Corresponding to each member of CEs, there is an

IVME. IVMEs are exactly the same as CEs except that some small appropriate perturbations are introduced into the initial-value fields of CEs. If the modified initial-value fields lead to a gradual development of noticeable positive (or negative) phase PNA-like flow anomalies in IVMEs, then the composite differences of the EVF between IVMEs and CEs are nearly equivalent to the anomalous EVF associated with the positive (or negative) PNA in the model:

$$\langle \text{EVF}_{\text{dif}} \rangle = \langle \text{EVF}_{\text{IVME}} \rangle - \langle \text{EVF}_{\text{CE}} \rangle \approx \text{EVF}'_{\text{PNA}},$$

where EVF_{IVME} and EVF_{CE} are the EVF in IVMEs and CEs, respectively, and the angle brackets denote an ensemble calculation. EVF'_{PNA} denotes the anomalous EVF associated with the PNA in the model and can be decomposed as follows:

$$\begin{aligned} \text{EVF}'_{\text{PNA}} \approx & \left\langle \overbrace{[-\nabla \cdot (U'_C \zeta'_D)]}^{\text{EVF1}} \right\rangle + \left\langle \overbrace{[-\nabla \cdot (U'_D \zeta'_C)]}^{\text{EVF2}} \right\rangle \\ & + \left\langle \overbrace{[-\nabla \cdot (U'_D \zeta'_D)]}^{\text{EVF3}} \right\rangle, \end{aligned} \quad (2)$$

where $U'_D = U'_I - U'_C$ and $\zeta'_D = \zeta'_I - \zeta'_C$, and U'_C (U'_I) and ζ'_C (ζ'_I) denote the anomalous wind and vorticity fields associated with the total/unfiltered eddy in each member of CEs (IVMEs), respectively. Details of the derivation of Eq. (2) are given in section 2b of Song (2016). Equation (2) can be used to decompose the anomalous SEVF associated with the PNA, provided the anomalous wind and vorticity fields associated with the total/unfiltered eddy are replaced by those associated with the synoptic eddy. Using ψ'_C and ψ'_I to represent the synoptic eddy in CEs and IVMEs respectively, and ψ'_D to denote the deformations of ψ'_C , we have $\psi'_D = \psi'_I - \psi'_C$. Clearly, in Eq. (2), EVF3 is the ψ'_D self-interaction term representing the anomalous EVF directly produced by the deformations of the synoptic eddy, while EVF1 and EVF2 also involve ψ'_D , as well as its interaction with ψ'_C .

c. Model

As in Song (2016), the Geophysical Fluid Dynamics Laboratory (GFDL) dynamical core atmospheric model (Held and Suarez 1994) is used to perform the short-term initial-value integrations. This model is a dry, sigma ($\sigma = p/p_s$) coordinate primitive-equation spectral model on a sphere driven by an equilibrium temperature profile T_{eq} . As a simplified model, it includes only idealized physical parameterizations. In the present study, experiments are carried out with a horizontal resolution of T42, using 20 evenly spaced sigma levels in the

vertical. The original model codes contain the ideal zonally symmetric T_{eq} of Held and Suarez (1994) resulting in highly zonally symmetric and ideal climatological mean circulation and storm tracks, which are obviously not suitable for a study of the PNA.

To overcome this shortcoming, a procedure developed by Chang (2006) and Chang and Zurita-Gotor (2007) is used to modify the model. First of all, a full topography is incorporated in the model. Then, the observed three-dimensional DJF time-mean temperature distribution with a reduced static stability (0.75 K km^{-1}) is used as the T_{eq} to drive the model. Besides that, a constant nonlinear diabatic heating Q is also implanted into the temperature tendency equation to mimic the atmosphere releasing latent heating. The value of Q is obtained by iteratively running the model 37 times (in each integration, the model is run for 1200 days) starting from a first guess of $Q_0 = 0$. A long-term run of the model then gives boreal winter climatological mean circulation and storm tracks that are highly similar to those in observations (not shown).

In section 3, the author will demonstrate that the dynamical properties of the observed PNA are well simulated in this modified model. Dai et al. (2017) argued that the observed PNA events could be categorized into “convective PNA events” and “non-convective PNA events.” The convective (nonconvective) PNA events are those PNA events that are (are not) associated with the PNA’s canonical tropical convection activity. Note that tropical convections are absent in this simplified dry model. Therefore, the generation of the PNA in this model is not related to the tropical diabatic heating and the growth of the PNA must be primarily caused by the internal dynamics of the midlatitude atmosphere (Simmons et al. 1983; Dole and Black 1990; Black and Dole 1993; Mori and Watanabe 2008). Thus, strictly speaking, the results reported in this study might only be applied to those nonconvective PNA events proposed in Dai et al. (2017).

d. Experimental setup

To perform the anomalous SEVF decomposition, the experimental setup is similar to that of Song (2016). First, an 8200-day long-term run is performed, and the first 200 days are discarded as spinup. Then, the daily PNAI in the model is calculated from daily SLP anomalies of the remaining 8000 days of model output over the Pacific–North America region (roughly 20° – 90° N, 120° E– 100° W). The calculation is the same as used for the NCEP data, and the explained variance of the EOF1 (PNA) in the model is 23.85%. Here, the “anomalies” in the model are departures from the long-term mean of the whole integration period (8000 days), since there is no seasonal cycle in the model.

Based on the daily PNAI in the model, the positive and negative PNA events are identified from the 8000 days of model's output using the following method. If the normalized daily PNAI ≥ 1 (PNAI ≤ -1) for at least three consecutive days, then a positive (negative) PNA event is considered to have taken place. The day with the maximum (minimum) PNAI is defined as the peak or mature day (lag 0 days) for a positive (negative) PNA event, and lag $\pm x$ days denotes x days lagging/leading the mature day. In the 8000 days of model's output, there are 130 and 113 positive and negative PNA events, respectively.

Next, the 8000 days of model's output are divided into 400 cases with a 20-day integration period. If the absolute value of the mean normalized daily PNAI during the first 9 days of each case is less than 0.3, which guarantees that there are no noticeable PNA-like circulation anomalies in the first half of this case, then this case is considered as a CE case. Based on this criterion, 102 CE cases are selected. Finally, these 102 CE cases are rerun while introducing some small perturbations into the initial-value fields. The small perturbations are the composite three-dimensional circulation anomalies of the positive and negative model PNA events at lag -8 days¹ including vorticity, divergence, temperature, surface pressure, zonal wind velocity, meridional wind velocity, and vertical velocity. Thus, corresponding to the 102 CEs, there are 204 PNA IVMEs: 102 experiments with precursor signals for the positive-phase PNA (denoted as PNA+_{Exp}) and the other 102 experiments with precursor signals for the negative-phase PNA (denoted as PNA-_{Exp}).

e. Definition of the synoptic eddy

Normally, high-frequency (e.g., 2–8-day bandpass) components of the transient eddy fields are used to represent the synoptic eddy. Therefore, in this study, high-frequency EVF (HFEVF) is used to represent SEVF. However, in each member of CEs and IVMEs, the integration time is only 20 days. It is impossible to filter out the high-frequency components of the transient eddy fields in such a short integration. Therefore, Fourier decomposition is also used as a spatial filter to isolate the synoptic-scale (zonal wavenumbers 5–12) transient eddy to represent the synoptic eddy when we analyze the results of CEs and IVMEs. The composite

anomalous EVF induced by the synoptic-scale transient eddy (referred to as SCEVF) and the HFEVE during the life cycles of the model's positive and negative PNA events are calculated (not shown). Compared with the composite anomalous HFEVF, the composite anomalous SCEVF has a slight eastward displacement with a weaker intensity. Apart from these differences, the composite results of anomalous SCEVF and HFEVF are generally highly similar, suggesting that the anomalous SEVF associated with the model's PNA events is largely insensitive to the methodology used to define the synoptic eddy fields. Since the synoptic eddy is more active in the upper troposphere and the focus here is on the large-scale characteristics of the anomalous SEVF, in the following analyses the HFEVF, SCEVF, EVF1, EVF2, and EVF3 are discussed in terms of the 300-hPa streamfunction tendency by inverting the Poisson equation.

3. Dynamical properties of the PNA

Clearly, the anomalous SEVF decomposition results of the model's PNA are meaningful for the observed PNA only if the dynamical properties of the model's PNA resemble those in observations. In this section, the dynamical properties of the PNA in the NCEP data and the model are compared and discussed.

a. PNA regressed results

Figure 1 shows spatial patterns of the observed and model's PNA at the surface and upper troposphere. These results are obtained by regressing the daily SLP and 300-hPa streamfunction anomalies in the NCEP data and the model onto the daily observed and the model's PNAI. At the surface, a positive- (negative-) phase observed PNA pattern corresponds to a deepening (shallowing) of the Aleutian low (see Fig. 1a). In the upper troposphere, the observed PNA pattern appears as a well-known quadrupolar structure over the Pacific and North American sector (see Fig. 1b). These features are well simulated in the model (see Figs. 1c,d). However, the amplitude of the regressed SLP anomalies for the model's PNA is only about two-thirds of that for observations, which is possibly related to the absence of tropical convection in the model. Consistent with the weaker regressed anomalous SLP, the action center of the model's PNA over the northeastern Pacific is apparently weaker than the observational counterpart. In addition, the action centers of the model's PNA over western Canada and the southeastern United States are less evident with a southeastward displacement (see Fig. 1d).

Similar to Fig. 1, Fig. 2 shows the anomalous 300-hPa zonal wind, high-frequency (2–8-day bandpass) eddy

¹ There is no specific reason for choosing the circulation anomalies associated with the PNA events at lag -8 day as the small initial-value perturbations. Any small circulation anomalies that can trigger the subsequent PNA development can be used as the initial-value perturbations.

FIG. 1. Daily PNA index regressed anomalous (a) SLP and (b) streamfunction at 300-hPa in the NCEP data. (c), (d) As in (a) and (b), but for the long-term GFDL model simulation. Solid (dashed) contours represent positive (negative) values; zero contours are omitted. The contour interval is 2 hPa for (a) and (c) and $1.5 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ for (b) and (d).

kinetic energy (HFEKE, denoting the storm track) and HFEVF regressed onto the daily PNAI for the NCEP data and the model. In Fig. 2, the climatological mean 300-hPa zonal wind and HFEKE for the NCEP data and the long-term model simulation are also shown. For both the NCEP data and the model, the spatial structures of the regressed anomalous zonal wind over the North Pacific are a “negative–positive–negative” tripolar mode in the meridional direction (Figs. 2a,d), while the regressed anomalous HFEKE patterns are a “negative over positive” meridional dipolar mode (Figs. 2b,e). Therefore, a positive (negative) phase of the PNA corresponds to a strengthening (weakening) and eastward extension (westward retreat) of the westerly

jet over the North Pacific, which is accompanied by a southward (northward) displacement of the Pacific storm track. The regressed anomalous zonal wind and HFEKE of the model’s PNA are similar to the observational results, especially over the North Pacific. However, the model’s PNA has two notable deficiencies. First, the observed PNA is also associated with evident zonal wind anomalies over North America, which are not apparent in the model. Second, the amplitudes of the regressed HFEKE anomalies over the North Pacific (North America) are weaker (stronger) than the counterparts in the NCEP data. These deficiencies may be also related to the absence of tropical forcing in the model.

FIG. 2. As in Fig. 1, but for regressed anomalous (a) zonal wind U (thin contours), (b) HFEKE (thin contours), and (c) HFEVF in terms of streamfunction tendency at 300-hPa in the NCEP data. In (a) and (b), the climatological mean 300-hPa zonal wind and HFEKE are also superposed by thick contours. (d)–(f) As in (a)–(c), but for the long-term GFDL model simulation. Solid (dashed) thin contours represent positive (negative) values; zero contours are omitted. The thin (thick) contour interval is 2 (20) m s^{-1} for (a) and (d), 5 (20) $\text{m}^2 \text{ s}^{-2}$ for (b) and (e), and 5 $\text{m}^2 \text{ s}^{-2}$ for (c) and (f). In (b) and (e), the minimum of the thick contours is $80 \text{ m}^2 \text{ s}^{-2}$.

The spatial pattern of the anomalous HFEVF regressed on the observed PNA is a zonal dipolar mode over the North Pacific region (Fig. 2c), which is consistent with the composite results of previous studies [see Fig. 6c in Feldstein (2002) and Fig. 8 in Franzke et al. (2011)]. The pattern of anomalous HFEVF regressed on the model's PNA is more like an arching wave train (Fig. 2f). However, in both the NCEP data and the model, the regressed anomalous HFEVF is spatially in phase with the SLP anomaly associated with the PNA in the North Pacific, suggesting that the anomalous SEVF associated with the PNA, as mentioned in section 1, plays a role in the formation and maintenance of the PNA.

b. Composite PNA events

Since the focus of this study is on understanding the physical mechanism responsible for the anomalous SEVF associated with the PNA events, it is useful to illustrate and compare the composite life cycles of PNA events in the NCEP data and the model. Using the same method as for the model, 76 positive and 75 negative PNA events in the 62 boreal winters of the NCEP data are identified. In both the NCEP data and the model, the composite life cycles of negative PNA events closely resemble those of positive PNA events but with opposite signs. Therefore, only the composite results for the positive PNA events are discussed in the following paragraphs.

Figure 3 shows the composite anomalous 300-hPa streamfunction of the positive PNA events in the NCEP data and the model spanning the time interval from lag -8 to $+8$ days. In the NCEP data, the positive PNA events originate from a “north negative–south positive” meridional dipolar mode over the North Pacific (Fig. 3c). Step by step, these circulation anomalies develop into a quadrupolar wave train pattern that closely resembles the well-known PNA at lag 0 days (Fig. 3e). Subsequently, the PNA-like circulation anomalies decay gradually. Note that the temporal evolution of the composite anomalous 300-hPa streamfunction of the positive PNA events in the NCEP data is very consistent with the result of Mori and Watanabe (2008, their Fig. 3) and Franzke et al. (2011, their Fig. 1), although their definition of the PNA and identification of the PNA events are different from the present study.² Clearly, the

composite 300-hPa streamfunction anomalies of the life cycle of the positive PNA events in the model are similar to the observational composite results. However, it seems that the attenuation of the anomalous PNA-like circulation anomalies in the model is quicker. Dai et al. (2017) reported that the nonconvective positive PNA events are preceded by a Eurasian wave train (see their Fig. 3) and their lifetime is shorter than that of the convective PNA events. Obviously, the model results presented here are coordinated with the observed nonconvective PNA results of Dai et al. (2017).

The composite anomalous HFEVF during the life cycles of the positive PNA events in the NCEP data and model are presented in Fig. 4. From lag -4 to 0 days, an anomalous cyclonic HFEVF monopole is collocated with the cyclonic northeastern Pacific action center of the observed PNA. Obviously, the composite anomalous HFEVF tends to reinforce this action center. After the peak day, the strength of the anomalous HFEVF decreases abruptly (Fig. 4f), but recovers slightly from lag $+4$ to $+6$ days (Figs. 4g,h). Note that the observed PNA events are most likely reinforced by the tropical convection (Dai et al. 2017), which might explain the rebound of the anomalous HFEVF. Overall, the behaviors of the composite anomalous HFEVF for the life cycles of the model's PNA are similar to that of the observed PNA. However, compared with the observed results, after the peak day the composite anomalous HFEVF in the model fades away very quickly and barely has a rebound. This deficiency is possibly related to the absence of the tropical convection in the model.

It should also be noted that the amplitude of the anomalous large-scale flows associated with the PNA events at lag $+2$ days both in the NCEP data and in the model is only slightly weaker than that at the peak day (see Figs. 3f,o). Therefore, deformations of the synoptic eddy are still notable due to interactions between the synoptic eddy and large-scale flow anomalies of the PNA.³ According to the viewpoint that “anomalous SEVF associated with the PNA is caused by deformations of the synoptic eddy,” there should still be evidence of anomalous HFEVF at lag $+2$ days. Clearly, this inference contradicts with the results shown in Fig. 4 that the anomalous HFEVF suddenly weakens/disappears at lag $+2$ days, which implies that anomalous SEVF

² Mori and Watanabe (2008) defined the PNA pattern as the EOF1 of the 10-day low-pass-filtered daily streamfunction at 500 hPa over the North Pacific region (20° – 90° N, 120° E– 60° W). Franzke et al. (2011) used the PNA definition of Franzke and Feldstein (2005), which is the first empirical teleconnection (ET) pattern. The ET patterns are obtained by using the modified empirical orthogonal teleconnection (EOT) methodology of van den Dool et al. (2000).

³ One-point correlation maps of high-frequency streamfunction anomalies show that the structures of the synoptic eddy at lag $+2$ days of observed and model's positive PNA events are indeed different with the climatological structures of the synoptic eddy (not shown).

PNA+ events

FIG. 3. (a)–(i) Composite anomalous 300-hPa streamfunction for the life cycle of the positive PNA events in the NCEP data from lag -8 to $+8$ days. (j)–(r) As in (a)–(i), but for the life cycle of the positive PNA events in the GFDL model. Solid (dashed) contours represent positive (negative) values; zero contours are omitted. The contour interval is $3 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ and composite results at the 95% confidence level are dotted.

PNA+ events

FIG. 4. As in Fig. 3, but for the composite anomalous HFEVF. The contour interval is $10 \text{ m}^2 \text{ s}^{-2}$.

associated with the PNA is not simply related to the deformations of the synoptic eddy.

Some studies (Feldstein 2002; Mori and Watanabe 2008) had proven that the growth of the observed PNA events is almost explained by linear processes while the nonlinear high-frequency transient eddy fluxes are considered playing a secondary or negligible role. To investigate whether the HFEVF is important for the PNA events in the model, a vorticity budget analysis similar to Feldstein (2002) and Mori and Watanabe (2008) is performed. Indeed, results of vorticity budget analysis indicate that the linear processes dominate the evolution of the model's PNA events. However, the role played by the HFEVF in the formation and maintain of the model's PNA events is by no means unimportant or negligible (the detailed results of the vorticity budget analysis are presented in the appendix).

In summary, the regressed results and the composite life cycle for the model's PNA share many features with those for the observed PNA, indicating that the model realistically reproduces the general dynamical properties of the observed PNA.

4. Results of experiments and SCEVF decomposition

The results of the experiments and the decomposition of the anomalous SCEVF are presented in this section. The focus is on composite differences between 102 PNA+_Exp, 102 PNA-_Exp, and 102 CEs during the 20-day integration period (i.e., from day 0 to day 19). Since composite results of CEs are nearly identical to the climatological mean of the model (not shown), the composite differences between IVMEs and CEs could also be concisely referred to as "anomalies."

a. Composite differences

Figure 5 shows composite differences of the 300-hPa streamfunction between PNA+_Exp and CEs (left column) and between PNA-_Exp and CEs (right column) from day 0 to day 18 with a 3-day interval. During the short-term integration of PNA+_Exp (PNA-_Exp), significant anomalous positive (negative) phase PNA-like circulations develop, mature, and then decay gradually, depicting a complete life cycle of the positive (negative) PNA event. As mentioned in section 2, PNA+_Exp/PNA-_Exp and CEs differ only in their initial-value fields, indicating that the PNA events, like the NAO events, can be considered as an initial-value problem as well.

Figure 6, similar to Fig. 5, shows composite differences in SCEVF between PNA+_Exp and CEs (left column) and between PNA-_Exp and CEs (right column) from day 0 to day 18. Generally speaking, the spatial patterns

of the anomalous SCEVF are somewhat complicated and noisy. However, there is notable anomalous cyclonic (anticyclonic) SCEVF over the northeastern Pacific, which obviously overlaps and corresponds well with the cyclonic (anticyclonic) northeastern Pacific action center of the PNA-like circulation from day 6 to day 9 in PNA+_Exp (PNA-_Exp). These results are consistent with the model's PNA regressed anomalous HFEVF (see Fig. 2f) and the composite anomalous HFEVF for the PNA events in the model (see Fig. 4).

b. SCEVF decomposition results

As mentioned in section 2b, the composite SCEVF differences between PNA+_Exp and CEs and between PNA-_Exp and CEs shown in Fig. 6 are equivalent to the anomalous SCEVF associated with the PNA-like circulation anomalies shown in Fig. 5 and can be decomposed into three terms according to Eq. (2). Figure 7 shows spatial patterns of ensembles EVF1, EVF2, and EVF3 from day 0 to day 18 for PNA+_Exp. First, note that the contour interval in Fig. 7 is 10 times greater than that in Fig. 6, which indicates that the amplitude of the components (EVF1, EVF2, and EVF3) is much greater than that of the anomalous SCEVF. Second, unlike the somewhat noisy spatial structures of the composite anomalous SCEVF shown in Fig. 6, the spatial patterns of ensembles EVF1 and EVF2 are neat and clear. With a "negative over positive" dipolar structure in the meridional direction, EVF1 emerges over the northeastern Pacific and then gradually strengthens and moves downstream to North America. It reaches its maximum at around days 6–9 (see Figs. 7c,d), followed by a gradual decline over the North Atlantic (see Figs. 7e–g). Clearly, EVF1 is largely offset by EVF2 since the spatial structure of EVF2 approximately mirrors that of EVF1 but with a reversed sign.

Unlike EVF1 and EVF2, EVF3 is very weak at the early stage of PNA+_Exp (see Figs. 7o,p) and is undetectable until day 6 (see Fig. 7q). In the last half of the integration period, EVF3 develops with a spatial pattern similar to the climatological mean SCEVF (see Figs. 7s–u). Generally speaking, the magnitude of EVF3 at the final integration day of PNA+_Exp is nearly twice that of the climatological mean SCEVF (not shown).

Spatial patterns of ensembles EVF1, EVF2, and EVF3 for PNA-_Exp are shown in Fig. 8. The spatial patterns and temporal evolutions of EVF1 and EVF2 for PNA-_Exp are almost the same as for PNA+_Exp but with the signs reversed. The behavior of EVF3 in PNA-_Exp is very similar to that in PNA+_Exp. Note that EVF3 represents the anomalous EVF directly caused by the deformations of the synoptic eddy. It is surprising that EVF3 is insensitive to the phase of the PNA.

IVMEs

FIG. 5. (a)–(g) Composite differences of 300-hPa streamfunction between PNA+ _Exp and CE from day 0 to day 18 (PNA+ _Exp minus CE). (h)–(n) As in (a)–(g), but for composite differences between PNA– _Exp and CE (PNA– _Exp minus CE). Solid (dashed) contours represent positive (negative) values; zero contours are omitted. The contour interval is $1.5 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ and composite results at the 95% confidence level are dotted.

5. Interpretations

In this section, the spatial patterns and temporal evolutions of ensemble EVF1, EVF2, and EVF3 shown in Figs. 7 and 8 are interpreted.

a. A “base-point-shifted fields” composite method

To understand behaviors of ensemble EVF1, EVF2, and EVF3, it is necessary to reveal the spatial structures of ψ'_C and ψ'_D , and their relative spatial relationships. Here, 300-hPa zonal wavenumber-5–12 streamfunction

anomalies in CE (IVMEs) are used to represent ψ'_C (ψ'_I). For each case of PNA+ _Exp (or PNA– _Exp), ψ'_D could be easily acquired by subtracting ψ'_C from the corresponding ψ'_I . However, it is impossible to extract the common characteristics of the spatial structures of ψ'_C and ψ'_D and their relative spatial relationships using simple composite results since their structures and the signs of their vorticity are highly variable. Therefore, a novel “base-point-shifted fields” composite method is used to reveal this information.

IVMEs

FIG. 6. As in Fig. 5, but for composite differences of the SCEVF. The contour interval is $2.5 \text{ m}^2 \text{ s}^{-2}$.

The base-point-shifted fields composite calculation is carried out as follows. For each day of each case of CEs, the point with a minimum value of ψ'_C over a specific domain of the midlatitudes is found. This point is defined as the base point of ψ'_D for this case on this day over that domain. This gives 102 base points of ψ'_C for each integration day, one for each case of CEs. Then, the fields of ψ'_C of the 102 cases of CEs are shifted in longitude and latitude so that the 102 base points coincide at a pseudolocation ($0^\circ, 0^\circ$). The 102 shifted fields of ψ'_C can then be composited to give the typical ψ'_C around the base points for each integration day of the 102 cases of CEs over that domain. Similarly, using the same base

points of ψ'_C to shift the fields of ψ'_I and ψ'_D in the 102 cases of PNA+_Exp (PNA-_Exp), the composite results of the shifted fields of ψ'_I and ψ'_D are calculated, which represent the typical ψ'_I and ψ'_D around the base points of ψ'_C , respectively.

b. EVF1 and EVF2 in PNA+_Exp

Figure 9 shows the composite ψ'_C (color shading), ψ'_I (thick contours), and ψ'_D (thin contours) for PNA+_Exp from day 0 to day 18 over the western North Pacific domain ($20^\circ\text{--}60^\circ\text{N}$, $120^\circ\text{E}\text{--}180^\circ$), the eastern North Pacific domain ($20^\circ\text{--}60^\circ\text{N}$, $180^\circ\text{--}120^\circ\text{W}$) and the North American domain ($20^\circ\text{--}60^\circ\text{N}$, $120^\circ\text{--}60^\circ\text{W}$).

PNA+_Exp

FIG. 7. (a)–(g) Ensemble EVF1 in terms of streamfunction tendency at 300-hPa for PNA+_Exp from day 0 to day 18. (h)–(n) As in (a)–(g), but for EVF2. (o)–(u) As in (a)–(g), but for EVF3. Solid (dashed) contours represent positive (negative) values; zero contours are omitted. The contour interval is $25 \text{ m}^2 \text{ s}^{-2}$.

As expected, the composite ψ'_C describes a typical zonal wave train of synoptic eddy with a structure that cyclones and anticyclones lined up next to each other. It is also apparent that, at day 0, the composite ψ'_I and ψ'_C are almost the same, while the composite ψ'_D is invisible (see Figs. 9a,h,o). This is because impacts of the initial-value perturbations introduced into PNA+_Exp on the synoptic eddy are small at the beginning. Thus, the deformations of ψ'_C are negligible on the first day of PNA+_Exp and the information of ψ'_C is well retained in ψ'_I . The positive PNA phase corresponds to positive westerly anomalies over the North Pacific (see Fig. 2d). Therefore, the total westerly jet over the North Pacific in PNA+_Exp is stronger than that in CEs. According to the equations for the phase speed of Rossby waves (e.g., section 5.7 of Vallis 2006), ψ'_I will have a faster eastward phase speed than ψ'_C . Thus, after day 0, the composite ψ'_I are located slightly downstream of the composite ψ'_C ,

especially over the eastern North Pacific and North America, leading to a small phase difference between the composite ψ'_I and ψ'_C (see Figs. 9i,j,p,q). Note that, as a result of this minor phase difference, a cyclone (an anticyclone) of the composite ψ'_C is embraced by an anticyclone (a cyclone) and a cyclone (an anticyclone) of the composite ψ'_D on its upstream and downstream sides simultaneously, forming a sandwich-like structure (see Figs. 9i,j,p,q).

Subsequently, the information of ψ'_C contained in ψ'_I is gradually blurred due to the chaotic nature of the atmosphere. Therefore, we may consider ψ'_I around the base point of ψ'_C as random synoptic eddies at the late stage of PNA+_Exp, which means that $\langle \psi'_I \rangle \approx 0$. Note that $\psi'_D = \psi'_I - \psi'_C$, therefore, $\langle \psi'_D \rangle = \langle \psi'_I \rangle - \langle \psi'_C \rangle \approx -\langle \psi'_C \rangle$. Consistent with these discussions, the composite anticyclone (cyclone) of ψ'_D gradually overlaps with the composite cyclone (anticyclone) of ψ'_C , destroying the

PNA-Exp

FIG. 8. As in Fig. 7, but for PNA-Exp.

sandwich-like structure (see Figs. 9l,s). At the last stage of PNA+Exp, the composite ψ'_D and ψ'_C are equivalent to each other but with opposite signs (see Figs. 9n,u). Note that from beginning to end, the sandwich-like structure is barely found over the western North Pacific domain (see Figs. 9a–g), which is upstream of the PNA generation region.

The sandwich-like structure of ψ'_D and ψ'_C shown in Fig. 9 indicates that strong interactions between ψ'_D and ψ'_C are inevitable. We argue that the sandwich-like structure of ψ'_D and ψ'_C can satisfactorily explain the spatial structures of ensemble EVF1 and EVF2 for PNA+Exp shown in Fig. 7. To demonstrate this point, Fig. 10 shows a schematic diagram of the sandwich-like structure of ψ'_D and ψ'_C . Without a loss of generality, ψ'_C and ψ'_D can be schematically considered as oval-shaped cyclones or anticyclones. Here, the situation in which a cyclone of ψ'_C lies sandwiched between an upstream anticyclone and a downstream cyclone of ψ'_D is considered. Note also that EVF1 and EVF2 for both

PNA+Exp and PNA-Exp are overwhelmingly dominated by their meridional component (denoted as EVF1V and EVF2V; not shown). Therefore, Fig. 10 only depicts the meridional vorticity flux produced by the interactions between ψ'_D and ψ'_C . As shown in Fig. 10, $v'_C \zeta'_D$ ($v'_D \zeta'_C$) converges (diverges) at higher latitudes and diverges (converges) at lower latitudes, forming a negative-over-positive (positive-over-negative) meridional dipolar pattern of streamfunction tendency. Note that if a reverse situation were considered, the conclusions would not be changed, since all variables would have an opposite sign. Therefore, the schematic sandwich-like structure of ψ'_D and ψ'_C shown in Fig. 10 could well explain why ensemble EVF1 (EVF2) has a negative-over-positive (positive-over-negative) meridional dipolar pattern for PNA+Exp (see Fig. 7). Figure 10 also suggests that a mutual cancellation between ensemble EVF1 and EVF2 is a natural result.

In Fig. 9, the sandwich-like structure clearly begins to appear over the eastern North Pacific and the North

PNA+_exp

FIG. 9. Composite ψ'_C , ψ'_I , and ψ'_D in terms of the 300-hPa anomalous synoptic-scale (zonal wavenumbers 5–12) streamfunction for CE and PNA+ _Exp from day 0 to day 18 over domains (a)–(g) 20° – 60° N, 120° E– 180° , (h)–(n) 20° – 60° N, 180° – 120° W, and (o)–(u) 20° – 60° N, 120° – 60° W. Parameter ψ'_C is denoted by color shading while ψ'_I (ψ'_D) is presented by thick (thin) contours. Solid (dashed) contours represent positive (negative) values; zero contours are omitted. The interval of thick (thin) contours is 3×10^6 (1.5×10^6) $\text{m}^2 \text{s}^{-1}$.

PNA+_Exp

FIG. 10. A Schematic diagram of sandwich-like structure of ψ'_D and ψ'_C for PNA+_Exp. Blue thick ovals represent cyclones of ψ'_C . Blue (red) thin ovals represent cyclones (anticyclones) of ψ'_D . Black thick arrows denote the anomalous meridional wind associated with the cyclones of ψ'_C . Black thin arrow denotes the anomalous meridional wind associated anticyclones and cyclones of ψ'_D . Solid (dashed) ovals or lines represent positive (negative) values.

American domain at day 3. After that, the sandwich-like structure gradually disappears over the North Pacific domain but is still evident until day 9 over the North American domain. The sandwich-like structure is not observed in the western North Pacific domain during the entire integration period. These features are highly consistent with the spatial distributions and temporal evolutions of ensemble EVF1 and EVF2 for PNA+_Exp shown in Fig. 7. Therefore, it is argued that the behaviors of ensemble EVF1 and EVF2 for PNA+_Exp can be reasonably explained by the formation and decay of the sandwich-like structure of ψ'_D and ψ'_C shown in Fig. 9.

c. EVF1 and EVF2 in PNA-Exp

To avoid an unnecessary reiteration, results of ensembles EVF1 and EVF2 for PNA-Exp are discussed briefly based on the above discussion for PNA+_Exp. Similar to Fig. 9, Fig. 11 shows composite results of ψ'_C , ψ'_I , and ψ'_D around the base points of ψ'_C but for PNA-Exp from day 0 to day 18 over the western North Pacific, the eastern North Pacific, and the North American domain. The most remarkable difference between Figs. 11 and 9 is that the composite ψ'_I is located slightly upstream, rather than downstream, of the composite ψ'_C (see Figs. 11i,j,p,q). This

is because the negative PNA phase corresponds to negative westerly anomalies over the North Pacific. Therefore, the total westerly jet over the North Pacific in PNA-Exp is weaker than that in CEs, leading to ψ'_I having a slower eastward phase speed than ψ'_C . There still is a sandwich-like structure of ψ'_D and ψ'_C . But now, a cyclone (an anticyclone) of the composite ψ'_C is clamped by a cyclone (an anticyclone) and an anticyclone (a cyclone) of the composite ψ'_D on its upstream and downstream sides (see Figs. 11i,j,p,q).

Similar to Fig. 10, Fig. 12 shows a schematic diagram of the sandwich-like structure of ψ'_D and ψ'_C but for the situation of PNA-Exp. Because there is now a cyclone of ψ'_C lying sandwiched between an upstream cyclone and downstream anticyclone of ψ'_D , then in contrast to the results of Fig. 10, $v'_C\zeta'_D$ ($v'_D\zeta'_C$) diverges (converges) at higher latitudes and converges (diverges) at lower latitudes, forming a positive-over-negative (negative-over-positive) meridional dipolar pattern in terms of streamfunction tendency. Thus, the schematic sandwich-like structure of ψ'_D and ψ'_C shown in Fig. 12 can explain why ensemble EVF1 (EVF2) has a positive-over-negative (negative-over-positive) meridional dipolar pattern for PNA-Exp shown in Fig. 8. Similar to the results shown in Fig. 9, the sandwich-like structure is only evident over

PNA-_{exp}

FIG. 11. As in Fig. 9, but for CEs and PNA-_{Exp}.

PNA-Exp

FIG. 12. As in Fig. 10, but for PNA-Exp.

the eastern North Pacific and the North American domain at the early stage of PNA-Exp (Fig. 11). This explains the behaviors of ensemble EVF1 and EVF2 in PNA-Exp well.

d. EVF3

Figures 7 and 8 show that, at the final stage of both PNA+Exp and PNA-Exp, the spatial distributions of ensemble EVF3 strongly resemble that of the climatological mean SCEVF. Thus, the behaviors of

ensemble EVF3 are not sensitive to the phase of the PNA. A simple interpretation is that during the integration period, the information of ψ'_C contained in ψ'_I is gradually lost due to the chaotic nature of the atmosphere. So, we might suggest that ψ'_I behave as random synoptic eddies at the later stage of the integration. Therefore, $\psi'_D = \psi'_I - \psi'_C \approx \psi'_R - \psi'_C$. Here, the subscript R denotes random synoptic eddies.

Thus,

$$\left\langle \overbrace{[-\nabla \cdot (U'_D \zeta'_D)]}^{\text{EVF3}} \right\rangle \approx \langle [-\nabla \cdot (U'_R - U'_C)(\zeta'_R - \zeta'_C)] \rangle = \langle -\nabla \cdot (U'_R \zeta'_R) \rangle + \langle \nabla \cdot (U'_R \zeta'_C) \rangle + \langle \nabla \cdot (U'_C \zeta'_R) \rangle + \langle -\nabla \cdot (U'_C \zeta'_C) \rangle. \quad (3)$$

Note that, here, the prime symbol denotes the anomalous fields associated with the synoptic eddy. Since U'_R and ζ'_C are independent to each other, $\langle \nabla \cdot (U'_R \zeta'_C) \rangle = \nabla \cdot \langle U'_R \rangle \langle \zeta'_C \rangle \approx 0$. Similarly, $\langle \nabla \cdot (U'_C \zeta'_R) \rangle = \nabla \cdot \langle U'_C \rangle \langle \zeta'_R \rangle \approx 0$. Therefore,

$$\left\langle \overbrace{[-\nabla \cdot (U'_D \zeta'_D)]}^{\text{EVF3}} \right\rangle \approx \langle -\nabla \cdot (U'_R \zeta'_R) \rangle + \langle -\nabla \cdot (U'_C \zeta'_C) \rangle. \quad (4)$$

According to an ergodic approximation, an ensemble-mean result of a large number of samples is approximately

equal to the average state (i.e., time mean) of the sample pool (see section 3 of Jin et al. 2006). Since ψ'_R and ψ'_C are sampled from the synoptic eddy of the model, then, $\langle -\nabla \cdot (U'_R \zeta'_R) \rangle \approx -\nabla \cdot \langle U'_R \zeta'_R \rangle$, $\langle -\nabla \cdot (U'_C \zeta'_C) \rangle \approx -\nabla \cdot \langle U'_C \zeta'_C \rangle$. Here, $\langle \cdot \rangle$ denotes a time-mean calculation and U' and ζ' denote the anomalous wind and vorticity fields associated with the synoptic eddy in the model. Then, $\left\langle \overbrace{[-\nabla \cdot (U'_D \zeta'_D)]}^{\text{EVF3}} \right\rangle \approx 2[-\nabla \cdot \langle U'_R \zeta'_R \rangle]$. This explains why the spatial patterns of ensemble EVF3 for both PNA+Exp and PNA-Exp strongly resemble the spatial

patterns of the climatological mean SCEVF but with twice the magnitude at the final stage of the integrations.

During the later stages of the integration,

$$\begin{aligned} \left\langle \overbrace{[-\nabla \cdot (U'_C \xi'_D)]}^{\text{EVF1}} \right\rangle &= \langle -\nabla \cdot [U'_C (\xi'_R - \xi'_C)] \rangle = \langle -\nabla \cdot (U'_C \xi'_R) \rangle - \langle -\nabla \cdot (U'_C \xi'_C) \rangle \\ &= -\nabla \cdot (\langle U'_C \rangle \langle \xi'_R \rangle) - \langle -\nabla \cdot (U'_C \xi'_C) \rangle \approx \langle \nabla \cdot (U'_C \xi'_C) \rangle \approx \overline{\nabla \cdot (U' \xi')}. \end{aligned} \quad (5)$$

Similarly, $\left\langle \overbrace{[-\nabla \cdot (U'_D \xi'_C)]}^{\text{EVF2}} \right\rangle \approx \overline{\nabla \cdot (U' \xi')}$. Therefore, the ensemble EVF3 is naturally balanced by the ensemble EVF1 plus EVF2.

6. Further discussion

a. Competition between EVF1 plus EVF2 and EVF3

Section 4b shows that the anomalous SCEVF associated with the PNA events in the model can be decomposed by Eq. (2) into ensembles EVF1, EVF2, and EVF3. One might question if the sum of ensembles EVF1, EVF2, and EVF3 is equal to the anomalous SCEVF. To answer this question, Figs. 13 and 14 show the sum of the ensembles EVF1, EVF2, and EVF3 (i.e., $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle + \langle \text{EVF3} \rangle$) from day 0 to day 18 with a 3-day interval for PNA+_Exp and PNA-_Exp. Referring to Fig. 6, $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle + \langle \text{EVF3} \rangle$ is exactly equal to the anomalous SCEVF associated with the PNA events in the model.

Figures 13 and 14 also show $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle$ and $\langle \text{EVF3} \rangle$ from day 0 to day 18. Clearly, like $\langle \text{EVF3} \rangle$, $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle$ for PNA+_Exp and PNA-_Exp are also highly similar. In both PNA+_Exp and PNA-_Exp, the spatial patterns of $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle$ are almost the same as that of $\langle \text{EVF3} \rangle$ but with reversed signs, indicating that $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle$ and $\langle \text{EVF3} \rangle$ largely offset each other. Therefore, the actual anomalous SCEVF associated with the PNA events in the model is the residual result of a competition between the ensemble linear ψ'_C and ψ'_D interaction terms (EVF1 and EVF2) and the ensemble nonlinear ψ'_D self-interaction term (EVF3). This is a novel view of the physical essences of the anomalous SCEVF associated with the PNA.

Since $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle$ and $\langle \text{EVF3} \rangle$ always offset each other, the signs of the anomalous SCEVF associated with the positive and negative PNA events in the model are determined by their competition. The most important feature of the anomalous SCEVF in PNA+_Exp (PNA-_Exp) is that, from day 6 to day 9, there is a cyclonic (anticyclonic) SCEVF monopole locating over the northeastern Pacific, which tends to reinforce the cyclonic (anticyclonic) northeastern Pacific action center of

the PNA-like circulation anomalies in PNA+_Exp (PNA-_Exp). Note that over the northeastern Pacific, in both PNA+_Exp and PNA-_Exp, $\langle \text{EVF3} \rangle$ always produces cyclonic SCEVF, while $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle$ always generates anticyclonic SCEVF. Therefore, the net cyclonic (anticyclonic) SCEVF from day 6 to day 9 over the northeastern Pacific occurs simply because the absolute intensity of $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle$ is weaker (greater) than that of $\langle \text{EVF3} \rangle$ in PNA+_Exp (PNA-_Exp) over that region.

b. Signs of the anomalous SEVF

Relative to the composite ψ'_C , the composite structures of ψ'_I in PNA+_Exp and PNA-_Exp are different. One has a slightly northeast–southwest tilt and the other one has a northwest–southeast tilt (see Figs. 9k, 11l). Franzke et al. (2011) argued that the different signs of anomalous SEVF associated with the positive and negative PNA events are due to the different tilts of the synoptic eddy. However, some results presented in this subsection will challenge this viewpoint.

Since ψ'_D are well resolved in every PNA+_Exp and PNA-_Exp member, then ψ'_D can be shifted artificially eastward and westward from their original positions by one model grid point (2.8125°). Then, $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle + \langle \text{EVF3} \rangle$ is recalculated after the westward and eastward shifts in ψ'_D . Figure 15 shows the recalculated results for PNA+_Exp. Compared with the results shown in Fig. 13, from day 6 to day 9 the cyclonic SCEVF monopole located over the northeastern Pacific becomes much more pronounced when ψ'_D is artificially shifted westward. Conversely, from day 3 to day 6, the SCEVF over the northeastern Pacific completely changes sign from cyclonic to anticyclonic when ψ'_D is artificially shifted eastward. Similar to Fig. 15, Fig. 16 shows the recalculated $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle + \langle \text{EVF3} \rangle$ but for PNA-_Exp. Clearly, in the PNA-_Exp situation, the artificial westward shift of ψ'_D leads to an enhanced anticyclonic SCEVF monopole from day 3 to day 9 over the northeastern Pacific while the artificial eastward shift in ψ'_D changes the original anticyclonic SCEVF monopole into a cyclonic SCEVF monopole from day 3 to day 6 over the northeastern Pacific.

PNA+_Exp

FIG. 13. (a)–(g) Ensemble EVF1 + EVF2 in terms of streamfunction tendency at 300-hPa for PNA+_Exp from day 0 to day 18. (h)–(n) As in (a)–(g), but for ensemble EVF3. (o)–(u) As in (a)–(g), but for EVF1 + EVF2 + EVF3. Solid (dashed) contours represent positive (negative) values; zero contours are omitted. The contour interval is $10 \text{ m}^2 \text{ s}^{-2}$ for (a)–(n) and $2.5 \text{ m}^2 \text{ s}^{-2}$ for (o)–(u).

Note that ψ'_D is artificially zonally shifted by only one model grid point (2.8125°), so the structures of $\psi'_I = \psi'_C + \psi'_D$ are little changed. The composite structures of ψ'_I in PNA+_Exp (PNA–_Exp) still have a slightly northeast–southwest (northwest–southeast) tilt after the westward and eastward shifts of ψ'_D (not shown). Thus, the results shown in Figs. 15 and 16 indicate that 1) the signs of the anomalous SCEVF could be totally opposite even when the synoptic eddy having a similar tilt, and 2) the signs of the anomalous SCEVF could also be the same although the tilts of the synoptic eddy are different. Obviously, these results strongly suggest that the different signs of SCEVF associated with the positive and negative PNA events are not necessarily related to the different tilts of the synoptic eddies.

In fact, the impacts of the artificial zonal shifts in ψ'_D on (EVF3) are negligible (not shown). Therefore, the

changes of the SCEVF over the northeastern Pacific shown in Figs. 15 and 16 are primarily due to the changes of $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle$ caused by the artificial zonal shifts in ψ'_D . We infer that the key factor in determining the sign of the anomalous SCEVF (i.e., the competition results between $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle$ and $\langle \text{EVF3} \rangle$) should be the relative spatial relationship between ψ'_D and ψ'_C that affects the intensity of $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle$ very sensitively.

7. Summary

Many studies have shown that the anomalous SEVF associated with the PNA plays a role in its formation and maintenance. Generally, deformations of the synoptic eddy due to multiscale interactions between the synoptic eddy and the large-scale flows of the PNA are regarded as the physical mechanism that generates the anomalous SEVF.

PNA-Exp

FIG. 14. As in Fig. 13, but for PNA-Exp.

This study provides a different understanding of the generation mechanism responsible for the anomalous SEVF associated with PNA events by using a modified GFDL dynamical core atmospheric model in which the general dynamical properties of the PNA are realistically reproduced together with the anomalous EVF decomposition procedure proposed by Song (2016).

A series of CEs with a 20-day integration period is performed. In each CE case, there are no obvious PNA-like circulation anomalies. Subsequently, two corresponding series of IVMEs (PNA+Exp and PNA-Exp) are performed by introducing appropriate small perturbations into the initial-value fields of CEs. The composite differences between CEs and PNA+Exp (PNA-Exp) depict a complete life cycle of the positive (negative) PNA event. Since CEs and IVMEs only differ slightly in their initial-value fields, $\psi'_I \approx \psi'_C$ at the beginning and ψ'_D due to the emergence of the anomalous PNA-like circulations in IVMEs can be easily acquired by subtracting ψ'_C from ψ'_I . Utilizing the results of CEs and IVMEs, the anomalous

nonlinear SEVF associated with the PNA in the model can be decomposed into ensembles of two linear ψ'_C and ψ'_D interaction terms (EVF1 and EVF2) and a nonlinear ψ'_D self-interaction term (EVF3).

At the early stage of PNA+Exp, ensembles EVF1 and EVF2 appear in a negative-over-positive and a positive-over-negative meridional dipolar pattern over the eastern North Pacific and North America and offset each other. Their intensities reach the peak at around days 6–9 and then decay gradually while the spatial patterns and temporal evolutions of ensemble EVF1 and EVF2 for PNA-Exp are almost the same as for PNA+Exp but with the signs reversed. In both PNA+Exp and PNA-Exp, ensemble EVF3 is hard to detect at the beginning of the integration but becomes evident in the following days. Its spatial distribution is similar to the climatological mean SCEVF but with twice the magnitude at the final stage of the integration.

Further analysis results show that for PNA+Exp (PNA-Exp), the composite ψ'_I is located slightly

PNA+_Exp

FIG. 15. Recalculated results of ensemble EVF1 + EVF2 + EVF3 in terms of streamfunction tendency at 300 hPa for PNA+_Exp from day 0 to day 18 when ψ'_D is artificially shifted (a)–(g) westward and (h)–(n) eastward by one model grid. Solid (dashed) contours represent positive (negative) values; zero contours are omitted. The contour interval is $2.5 \text{ m}^2 \text{ s}^{-2}$.

downstream (upstream) of the composite ψ'_C , leading to a small phase difference between them. This minor phase difference causes the composite ψ'_C to be embraced by the composite ψ'_D on its upstream and downstream sides simultaneously, forming a sandwich-like structure. The sandwich-like structure of ψ'_D and ψ'_C could well explain the meridional dipolar structures of ensembles EVF1 and EVF2 seen in PNA+_Exp and PNA–_Exp. The spatial distributions and temporal evolutions of the sandwich-like structure are also highly consistent with those of ensembles EVF1 and EVF2 for

PNA+_Exp and PNA–_Exp. Therefore, it is argued that the behaviors of ensemble EVF1 and EVF2 in PNA+_Exp and PNA–_Exp can be well explained by the sandwich-like structure of ψ'_D and ψ'_C . We might assume ψ'_I as random synoptic eddies at the later stage of the integration due to the chaotic nature of atmosphere. Under such an assumption, a series of simple derivations shows that the ensemble EVF3 approximately equal to the climatological mean SCEVE but with twice the magnitude.

This study further demonstrates that $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle + \langle \text{EVF3} \rangle$ is exactly equal to the anomalous

PNA-Exp

FIG. 16. As in Fig. 15, but for PNA-Exp.

SCEVF associated with PNA events in the model. The results also show that $\langle \text{EVF1} \rangle + \langle \text{EVF2} \rangle$ and $\langle \text{EVF3} \rangle$ largely offset each other. Therefore, the actual anomalous SCEVF associated with the PNA events in the model is the residual of a competition between the ensemble linear ψ'_C and ψ'_D interaction terms (EVF1 and EVF2) and the ensemble nonlinear ψ'_D self-interaction term (EVF3).

A viewpoint claims that the reversed signs of the anomalous SEVF associated with the positive and negative phases of the PNA are caused by different tilts of the synoptic eddy. However, the sign of the cyclonic (anticyclonic) SCEVF over the northeastern Pacific in PNA+Exp (PNA-Exp) can be reversed when we

artificially shift ψ'_D eastward from their original positions by only one model grid point. Obviously, the zonal shift of ψ'_D by one model grid point only slightly modifies the relative spatial relationship between ψ'_D and ψ'_C while keeping the tilting characteristics of ψ'_I almost unchanged. Therefore, it is argued that it is the relative spatial relationship between ψ'_D and ψ'_C , not the different tilts of the synoptic eddy, that determines the signs of the anomalous SCEVF associated with the PNA events.

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FIG. A1. Time-lagged projections of $\partial\psi'/\partial t$ (tendency; black lines) and other terms in the vorticity equation onto the PNA pattern for the composite positive PNA events in the model: (a) $\sum_{i=1}^7 \xi_i$ (terms 1–7) and residual, (b) ξ_1 (term 1) and ξ_2 (term 2), (c) ξ_3 (term 3) and ξ_4 (term 4), (d) ξ_5 (term 5) and ξ_6 (term 6), (e) $\sum_{i=1}^6 \xi_i$ (term 1_6, a combination of linear terms) and ξ_7 (EVF, nonlinear term), and (f) HFEVF and LFEVF.

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APPENDIX

Results of the Vorticity Budget Analysis

To evaluate the relative importance of linear processes and nonlinear HFEVF in the life cycle of the model's PNA event, vorticity budgets for various dynamical processes in the composite life cycle of the model's PNA events are examined based on a streamfunction tendency equation.

The streamfunction tendency equation is

$$\frac{\partial\psi'}{\partial t} = \sum_{i=1}^7 \xi_i + \text{Residual}, \quad (\text{A1})$$

where

$$\xi_1 = \nabla^{-2} \left(-\bar{u} \frac{\partial \xi'}{\partial x} \right),$$

$$\xi_2 = \nabla^{-2} \left(-\bar{v} \frac{\partial \xi'}{\partial y} \right),$$

$$\xi_3 = \nabla^{-2} \left(-u' \frac{\partial \bar{\xi}}{\partial x} \right),$$

$$\xi_4 = \nabla^{-2} \left[-v' \left(\frac{\partial \bar{\xi}}{\partial y} + \beta \right) \right],$$

$$\xi_5 = \nabla^{-2} \left[-\xi' \left(\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} \right) \right],$$

$$\xi_6 = \nabla^{-2} \left[-(\bar{\xi} + f) \left(\frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} \right) \right],$$

$$\xi_7 (\text{EVF}) = \nabla^{-2} [-\nabla \cdot (\mathbf{U}' \xi')],$$

$$\text{HFEVF} = \nabla^{-2} [-\nabla \cdot (U'_h \xi'_h)],$$

$$\text{LFEVF} = \nabla^{-2} [-\nabla \cdot (U'_l \xi'_l)], \quad (\text{A2})$$

and Residual is the residual component such as frictional dissipation and tilting term, ψ is the streamfunction, $\mathbf{U}$ is the horizontal wind vector, u and v are the zonal and

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FIG. A2. As in Fig. A1, but for the composite negative PNA events in the model.

meridional components of $\mathbf{U}$, ζ is the relative vorticity, f is the Coriolis parameter, and β is the planetary vorticity gradient. Overbar and prime symbols denote the time mean and its departure, respectively. The subscript h and l denote the high- and low-frequency components.

Briefly, ξ_1 (ξ_2) is the zonal (meridional) advection of anomalous vorticity by the background flows, ξ_3 (ξ_4) is the zonal (meridional) advection of background vorticity by the anomalous flows, ξ_5 and ξ_6 are the divergence terms, and ξ_7 is the EVF term. Here, HFEVF and LFEVF denote high- (2–8-day bandpass) and low-frequency (10-day low pass) EVF, respectively. It is noted that first six terms, ξ_i ($i = 1, \dots, 6$), represent linear processes, while ξ_7 is the nonlinear term.

We calculate composite results of all these terms in Eq. (A2) for the positive and negative PNA events in the model. The residual term is acquired by subtracting $\sum_{i=1}^7 \xi_i$ from $\partial\psi'/\partial t$. Similar to Feldstein (2002) and Mori and Watanabe (2008), the composite results are projected on the PNA pattern over a domain (roughly 20°–90°N, 120°E–100°W). The PNA pattern is defined as the PNA regressed anomalous 300-hPa streamfunction (see

Fig. 1d). Figures A1 and A2 show the corresponding projection time series for each term from lag –10 to lag 10 days of the positive and negative PNA events in the model.

Mori and Watanabe (2008) argued that the observed PNA events are primarily driven by the barotropic energy conversion from the zonally asymmetry climatological flow, and the forcing associated with high-frequency transient eddy fluxes is not crucial for the observed PNA's growth. Generally speaking, the growth of both phases of the model's PNA events is primarily driven by ξ_1 and ξ_2 . This is consistent with the viewpoint of Mori and Watanabe (2008). However, contrasting with results of Mori and Watanabe (2008), our results indicate that ξ_7 (EVF, especially HFEVF) also play an important role in driving the growth of both phases of the model's PNA events.

Overall, consistent with results of Feldstein (2002) and Mori and Watanabe (2008), linear processes are indeed the primary mechanism responsible for the growth of both phases of the model's PNA events [term 1_6 is a combination of linear terms ($\sum_{i=1}^6 \xi_i$); see Figs. A1e, A2e]. However, the contributions from the HFEVF are also notable (see Figs. A1f, A2f).

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