The western Pacific pattern precursor of major stratospheric sudden warmings and the ENSO modulation

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Abstract
Previous studies show that there is an apparent inconsistency between the impact of opposite phases of El Niño-Southern Oscillation (ENSO) on the seasonal-mean vortex and on major stratospheric sudden warmings (SSWs): El Niño (EN) leads to an anomalously warm, and La Niña (LN) leads to an anomalously cool seasonal-mean polar stratospheric state, but both phases of ENSO lead to an increased SSW frequency. This study examines the dynamics underlying this apparent paradox. First, this study demonstrates that 30 out of 35 SSWs occurred in 1957/1958 – 2012/2013 winters may be triggered by the western Pacific patterns (WPs). WPs can interact constructively with the climatological stationary waves and enhance wavenumber-1 waves and the associated upward wave activity fluxes, which leads to the occurrence of SSWs. This finding suggests that WPs may serve as a good precursor of SSWs. Furthermore, this study also demonstrates that WPs have larger amplitudes and longer durations during EN winters than ENSO neutral (NE) winters, which contributes dominantly to the increased frequency of SSWs from NE winters to EN winters. While for LN winters, both the ENSO modulation on WPs and the blockings over the eastern Pacific contribute to the SSW frequency increase from NE winters to LN winters. Finally, the question how EN modulates WPs is explored. It is found that more WPs with larger amplitude and longer duration develop from PNA during EN than NE winters, which contributes to the relatively larger amplitude and longer duration of WPs observed in EN, compared to NE.

1. Introduction
Major stratospheric sudden warmings (SSWs), which are characterized by an abrupt warming of the polar stratosphere and a reversal of the polar night jet, are induced by enhanced upward propagation of planetary Rossby waves from the troposphere into the stratosphere during winter (Matsumo 1971, Andrews et al 1987). Many studies have pointed out that tropospheric blockings can contribute to the enhancement of upward planetary wave propagation that leads to the occurrence of SSWs and can serve as a potential precursor of SSWs (Quiroz 1986, Martius et al 2009, Nishii et al 2009, Castanheria and Barriopedro 2010, Woollings et al 2010, Nishii et al 2011). The mechanism of the blocking-SSW linkage may be that the blockings can amplify tropospheric planetary-scale waves of wavenumbers 1 and 2 and thus induce SSWs. Early studies did not find significant changes in blocking activity either in periods before and after sudden warmings (Taguchi 2008); this was attributed to the fact that blocking is a more frequent phenomenon than SSWs (Barriopedro and Calvo 2014). Actually, the blocking-SSW associations are diverse and this diversity may have made the blocking-SSW issue controversial (Woollings et al 2010). Significant associations between blocking and SSWs only arise when SSWs are classified into vortex splitting and vortex displacement events (Martius et al 2009, Castanheria and Barriopedro 2010, Cohen and
Jones 2011). The blocking-SSW linkage is geographically dependent: blockings over the Euro-Atlantic sector tend to enhance upward planetary wave propagation and lead to stratospheric warming, and in some cases, to major SSWs (Nishii et al 2011). Furthermore, Barriopedro and Calvo (2014) investigated the ENSO influence on blocking-SSW relation and found that European and Atlantic blockings tend to precede SSWs during EN, whereas the eastern Pacific and Siberian blocks are the preferred precursor of SSWs during LN.

Actually, the ENSO impact on the Arctic stratospheric variability including SSWs on the interannual timescale has received much attention for the past decade or more. Many studies showed that the seasonal-mean and extreme stratospheric response to ENSO are quite different. The seasonal-mean stratospheric response to ENSO is linear: during EN the Northern Hemisphere polar vortex is anomalously weak and warm, with high ozone concentrations in the polar region (van Loon and Labitzke 1987, Garfinkel and Hartmann 2007, Randel et al 2009); while during LN, opposite-signed, but weaker and less statistically significant seasonal-mean stratospheric anomalies are observed (Manzini et al 2006, Garfinkel and Hartmann 2007, Free and Seidel 2009). The mechanism that leads to this ENSO-stratosphere relation is well established: ENSO modulates the mid-tropospheric geopotential heights in the midlatitude North Pacific and the associated upward planetary wave activity fluxes. Because a trough of climatological planetary wave is located in the North Pacific, an anomalous low (high) will enhance (reduce) the climatological planetary waves in the troposphere, which leads to weakening (strengthening) of the polar vortex (Limpasuvan et al 2005, Camp and Tung 2007, Garfinkel and Hartmann 2007, Garfinkel and Hartmann 2008).

Contrary to the seasonal-mean stratospheric response to the ENSO forcing, recent studies demonstrated that the extreme stratospheric response to ENSO is not linear but highly nonlinear. Butler and Polvani (2011) found that major SSWs occur during EN just as often as during LN, which is contrary to the usual thought and the modeling results that SSWs are suppressed during LN compared with EN (Taguchi and Hartmann 2006). The mechanism responsible for this ENSO-SSW relation is still unknown and understanding this ENSO-SSW relation is very important to extended forecast of weather and climate, for it serves as an important pathway for ENSO’s impact on tropospheric weather and climate (Ineson and Scaife 2009, Butler et al 2014).

It is obvious that possible tropospheric precursors of SSWs are not limited to tropospheric blockings and some other precursors may also exist. Garfinkel et al (2010) once found that a low height anomaly (LHA) over the subpolar North Pacific, which is located northwest to the region of the ENSO teleconnections, can interact constructively with the climatological planetary waves, increase the upward wave activity fluxes and lead to weakening of the polar vortex, or possibly SSWs. Based on this finding, Garfinkel et al (2012) further demonstrated that regardless of ENSO phase, LHAs in the subpolar North Pacific are present throughout the period in which the polar vortex is weakening. Particularly, the extreme negative height anomalies (exceeding −120 m) occur most often during LN winters, and more often during EN winters than NE winters. Garfinkel et al (2012) believed that this ENSO-LHA relation may be used to explain why the frequency of SSWs increases during both EN and LN winters.

Garfinkel et al (2010, 2012)’s findings may serve as a good start toward our understanding of the ENSO-SSW paradox, though the LHA-SSW relation and the ENSO-SSW linkage are still not completely understood yet. First, they primarily focus on the linkage of the LHA to the weakening of the polar vortex, not SSWs themselves. Second, they did not study how ENSO modulates the LHAs and the LHA-SSW relation. The present work will focus on these problems in order to get a better understanding of the ENSO-SSW paradox. Actually, the LHAs Garfinkel et al (2010, 2012) studied is not an isolated system but an anomalous center of the WP pattern (figure 1(a), Garfinkel et al 2010). From the WP perspective, this work studies the WP-SSW relation first, then, explores how ENSO modulates WPs and how the ENSO-SSW relation forms. The next section introduces the data set and the methods used. The main results are presented in section 2 and these are followed by the summary and conclusions.

2. Data and methods

This study uses unfiltered daily fields archived in the National Centers for Environmental Prediction (NCEP)-National Center for Atmospheric Research (NCAR) reanalysis dataset (Kalnay et al 1996) for 1957/58–2012/13 winters (November–March). The anomalies here are obtained by subtracting the seasonal cycle of the same calendar day at each grid point. The seasonal cycle is defined as the annual average plus the first three Fourier harmonics of the daily climatology. Prior to the EOF analysis, the gridded data are weighted by square root of cosine of latitude (North et al 1982). A Lanczos filter (Duchon 1979) with a nominal frequency cutoff period of 10 days is applied to obtain the low-frequency eddies (eddies with a period longer than 10 days) for calculation of the stationary wave activity fluxes (Plumb 1985).

As in Nishii et al (2010), WP is defined as the first EOF of the monthly 250 hPa geopotential anomalies over the western North Pacific sector (20°N–70°N, 120°E–180°) during November...
through March for 1979/80–2012/13 period. Then, the daily geopotential height anomaly field for all winter months (November–March) from 1957/1958 through 2012/2013 is projected onto this first EOF and the normalized time series will be used as the WP index. We define the positive phase of the WP patterns when the northern center of WPs over North Pacific is a cyclonic anomaly. The WP in this study refers to the positive phase of WP. Note that this definition of positive WP phase is contrary to that of Nishii et al. (2010). In view of the fact that both persistence and strength of the tropospheric forcing play an important role in generating SSWs (Sjoberg and Birner 2012), a WP event is defined when a 9-day running mean of the WP index reaches 0.5 or larger. Then, the middle day of the 9-day window is denoted as the day zero of the WP event. If there are several consecutive days with the running-mean larger than 0.5 (all denoted as the candidate day zero), only the one with the largest amplitude is retained as the day zero. Furthermore, adjacent events must be at least 15 days apart. Otherwise, the weaker event is discarded. The WP events defined in such a way may include both kinds of events that arise from extremely large but short-duration pulses and from moderately large but long-lasting pulses extending over the running-mean period. As a result, 192 WP events are detected for 1957/1958–2012/2013 winters.

This study will distinguish between the roles in triggering SSWs of WPs and LHAs over the SSW precursor region which are not the northern Pacific center of WPs (non-WP-LHAs). In order to get these non-WP-LHA events, we compute the area-mean of the 500 hPa height anomalies during November and March for 1957/58–2012/13 over the SSW precursor region (52.5°N–72.5°N, 165°E–195°E) as in Garfinkel et al. (2012). The inverted and normalized time series

Figure 1. Composites of 250 hPa geopotential heights (contours) for (a)–(b) WP events and (c)–(d) LHA events, superimposed on the climatological (a), (c) W-1 and (b), (d) W-2 height fields (shading). First, an average from day −4 to day +4 relative to the day zero is computed for each event, then, a composition is performed. Red (blue) contours (shading) indicate positive (negative) values. The contour (shading) interval is 20 m. Zeros lines are omitted. Stippling indicates anomalies that are statistically significant at the $p < 0.10$ level based on a Student’s $t$-test.
thus obtained are used as the LHA index. The LHA events are defined in the same way as the WP events: a LHA event is taken to be a non-WP-LHA event if the day zero of the LHA event and the nearest candidate day zero of a WP event are two days or a longer period apart. For brevity, LHA events are used simply hereafter to indicate non-WP-LHA events. In such a way, 58 LHA events are identified for 1957/1958–2012/2013 winters.

As in Charlton and Polvani (2007), a middle winter sudden warming occurs when the zonal-mean zonal winds at 60°N and 10 hPa become easterly during winter. The date when the zonal mean zonal winds at 60°N and 10 hPa first become easterly is defined as the ‘central date’ of each SSW event, while the date with local temperature maximum is denoted as the ‘key date’ (Kodera et al 2016). According to this criterion, there are totally 35 SSW events occurred during 1957/1958–2012/2013 winters (see table 1). The SSW events in table 1 are the same as those in Butler et al (2014).

Also as in Butler et al (2014), the ENSO phases are defined based on the Niño-3.4 index: For EN (LN) winters, the minimum of five consecutive overlapping seasons (NDJ, DJF and JFM) Niño-3.4 index must surpass the +0.5°C (−0.5°C) threshold. Based on this threshold, there are totally 19 EN winters, 18 LN winters and 19 NE winters, see table 1. Our results are not sensitive to changes in this definition, such as using the DJF Niño-3.4 index alone.

| EN | Preconditioned | LN | Preconditioned | NE | Preconditioned |
|----|----------------|----|----------------|----|----------------|
| Jan 1958 | W-1 | 23 Mar 1965 | W-2/W-1 | 16 Jan 1960 | W-1 |
| Nov 1958 | W-1 | 17 Jan 1971 | W-1 | 22 Feb 1979 | W-2/W-1 |
| Dec 1965 | W-1 | 20 Mar 1971 | W-1 | 29 Feb 1980 | W-1 |
| Feb 1966 | W-2/W-1 | 24 Feb 1984 | W-1 | 04 Dec 1981 | W-1 |
| Nov 1968 | W-1 | 02 Jan 1985 | W-2 | 02 Jan 2002 | W-1 |
| Mar 1969 | W-1 | 22 Feb 1989 | W-2 | 07 Jan 2004 | W-1 |
| Jan 1970 | W-1 | 15 Dec 1998 | W-1 | 07 Jan 2013 | W-1 |
| Feb 1973 | W-1 | 25 Feb 1999 | W-1 | 2000/01 | W-1 |
| Jan 1987 | W-1 | 20 Mar 2000 | W-1 | 2003/04 | W-1 |
| Dec 1987 | W-1 | 11 Feb 2001 | W-1 | 2012/13 | W-1 |
| Mar 1988 | W-1 | 21 Jan 2006 | W-1 | 2013/14 | W-1 |
| Jan 1989 | W-1 | 22 Feb 2008 | W-1 | 2014/15 | W-1 |
| Feb 2007 | W-1 | 24 Jan 2009 | W-2 | 2015/16 | W-1 |
| Feb 2010 | W-1 | 03 Feb 2010 | W-1 | 2016/17 | W-1 |
| Mar 2010 | W-1 | 09 Mar 2010 | W-1 | 2017/18 | W-1 |

3. Results

3.1. The WP-SSW relation

To reveal the WP-SSW relation, figure S1 (stacks.iop.org/ERL/11/124032/mmedia) (see the supplementary data) shows the evolution processes of the 35 SSWs occurred in 1957/1958–2012/2013 winters, represented by the central (key) dates of the SSWs, time series of 10 hPa zonal-mean zonal winds along 60°N, 10 hPa area-mean temperatures north of 50°N, and the WP index. We observe from figure S1 that WPs and SSWs are closely linked together. To be quantitative, we consider an SSW event as being preceded by a WP event if at least one candidate day zero of the WP event occurs within the twenty-day period before the central date or key date of the SSW event. The inclusion of the key date of SSWs is based on the fact that the central dates and key dates for SSWs do not always coincide accurately with each other (Kodera et al 2016). For most of the 35 SSWs, the central date and the key date are exactly or roughly coincident but a few of them are far apart (e.g. for 23 Mar 1965, 24 Feb 1966, 22 February 1979, 18 Jan 2003 and 7 January 2004, their central date and key date are more than 10 days apart), but WPs may be apparently responsible for the sudden warming indicated by the key date. Based on the above criteria, among the 35 SSW events, 30 SSW events are found to be preceded by WPs (see table 1), the percentage of which is 86% of the total 35 SSWs. Only 5 SSWs with central dates of 2 Jan 1985, 22 Feb 1989, 21 Jan 2006, 24 Feb 2007 and 24 Jan 2009 are not...
preceded by WPs. All these 5 SSWs occurred in LN winters except for the 24 Feb 2007 event which occurred in an EN winter. Unexpectedly and surprisingly, no SSWs are found to be preceded by LHAs when the same procedure is applied to the LHA events. This implies that the cyclonic anomalies that are responsible for SSWs are the footprints left by WPs. The dynamical difference of WPs and LHAs in triggering SSWs is explored below.

3.2. Dynamics underlying the WP-SSW relation

This subsection examines why WPs are favorable for SSWs while LHAs are not. Garfinkel et al (2010) pointed out that the anomalies in the troposphere are considered to be favorable for the weakening (intensifying) of the polar vortex if they can constructively (destructively) interact with the climatological planetary waves by enhancing (reducing) the amplitudes of wavenumber-1 (W-1) or wavenumber-2 (W-2) components. To see what happens with WPs and LHAs, we perform firstly composites of the 250 hPa geopotential height fields based on the WP events and the LHA events, respectively (figure 1). Superposed on figure 1 are the climatological W-1 and W-2 components (color shadings in figure 1). We observe that the composite height anomalies for WPs assume a typical structure of the WP pattern with two positive height anomalies centered at the subtropical North Pacific and the midlatitude North America and downstream area, and a negative height anomaly over the northern North Pacific. The negative height anomaly over the northern North Pacific and the positive height anomaly over North America and downstream area are in phase with the trough and ridge of the climatological W-1 wave component (figure 1(a)), while they are almost in quadrature with the low-high-low centers of climatological W-2 wave component located in East Asia, North Pacific and North America-North Atlantic (figure 1(b)). This implies a strong amplification of W-1 wave component and somewhat weak modulation of W-2 wave component. The composites based on LHAs (figures 1(c) and (d)) indicate that the height anomalies associated with LHAs do not exist as isolated negative height anomalies over North Pacific, instead, they are accompanied by a band of positive height anomalies over North America-North Atlantic, and a positive height anomaly over North Asia. All these anomalous centers are in phase with the troughs and ridges of the climatological W-1 wave component except the Asian center which is out of phase with the trough of the climatological W-1 wave component (figure 1(c)). Nevertheless, the overall structure implies an amplification of W-1 waves. Clearly, the band of positive height anomalies over North America-North Atlantic is in quadrature with the ridge and trough over North America and North Atlantic of the climatological W-2 wave component, while the positive height anomaly over North Asia and the negative height anomaly over North Pacific are out of phase with the corresponding troughs and ridges of the climatological W-2 wave component (figure 1(d)), which implies a weakening of W-2 waves. It is worth noting that for WPs, both their northern Pacific centers and North America-North Atlantic centers contribute to the enhancement of the planetary W-1 waves (figure 1(a)). The same situation applies to LHAs (figure 1(e)).

The above results indicate that both WPs and LHAs can constructively interact with the climatological planetary W-1 waves, which is favorable for the occurrence of SSWs. Then, what causes the difference in their relation with SSWs? As mentioned earlier, the key factors that determine the tropospheric precursor-SSW relation are the persistence and strength of the tropospheric forcing (Sjoberg and Birner 2012). We now take these factors into consideration by examining the persistence and strength of WPs and LHAs, their associated amplitudes of W-1 and W-2 waves and the vertical component of stationary wave activity fluxes (FZ). Here the duration is defined as the time period over which the composite time series is statistically significant at the p < 0.10 level.

Figures 2(a) and (b) show that WPs have a life-span about two weeks or so, while the life-span of LHAs is ten days or so. Besides, the amplitudes of the 250 hPa W-1 waves and the associated FZ at 250 hPa and 100 hPa are much larger for WPs than LHAs (figures 2(c), (e) and (g)). Furthermore, the durations of W-1 waves are also much longer for WPs than LHAs (figures 2(c), (e) and (g)). In contrast, the amplitudes of W-2 waves and the associated FZ at 250 hPa and 100 hPa are reduced for LHAs, compared to the climatological counterparts (figures 2(d), (f) and (h)), while no significant modulation of 100 hPa W-2 FZ is observed during the life-span of WPs (figure 2(h)). Here, the amplitudes of W-1 and W-2 waves and the associated FZ are the area-mean from 45°N to 75°N.

To further confirm the fact that WPs contribute to SSWs through enhancing W-1 waves, we apply the planetary wave analysis to all the 35 SSWs. To this end, we calculate the time-mean and area-averaged 100 hPa W-1 and W-2 FZ from 45°N to 75°N over the twenty-day period before the central dates or the key dates of SSWs. A SSW event is considered to be W-1 (W-2) type if W-1 (W-2) FZ dominates over W-2 (W-1) FZ. The results are given in table 1. From table 1, we can see that all the WP-preceded SSWs are the W-1 wave-preceded SSWs except for three SSWs with central dates 23 Mar 1965, 24 Feb 1966, and 22 Feb 1979, which are classified as W-2 (W-1) wave-preceded SSWs according to the central (key) dates. As is mentioned earlier, the central dates and key dates for the three SSWs are more than 10 days apart from each other, and the W-1 amplification induced by WPs are apparently responsible for the warming indicated by the key date (figure S1). It is interesting to note that all of the three W-2 wave-preceded SSWs (02 Jan 1985, 22
Feb 1989 and 24 Jan 2009) are found to occur in LN winters, we will return to this point later.

3.3. ENSO modulation on the WP-SSW relation

Table 2 indicates that the frequency of SSWs is 0.79 SSW events per EN winter, 0.72 SSW events per LN winter, and only 0.37 SSW events per NE winter. The SSW frequency for EN winters is as large as LN winters, which is twice as large as the frequency for NE winters. This subsection tries to understand the mechanisms driving this ENSO-SSW relation.

Table 2

|                | # of winters | # and Freq. of all SSW events | # and Freq. of WP-preceded SSW events | # and Freq. of WP events | # and Freq. of LHA events |
|----------------|--------------|-------------------------------|---------------------------------------|--------------------------|---------------------------|
| All            | 56           | 35                            | 30                                    | 0.54                     | 192                       | 3.43                      | 58 | 1.04 |
| EN             | 19           | 15                            | 14                                    | 0.79 (96)                | 14                        | 0.74 (93)                 | 67 | 3.53 (73) |
| LN             | 18           | 13                            | 9                                     | 0.72 (93)                | 9                         | 0.50 (68)                 | 63 | 3.50 (71) |
| NE             | 19           | 7                             | 7                                     | 0.37                     | 7                         | 0.37                      | 62 | 3.26 |

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Figure 2. Lagged-composites of (a) WP index for WP events and (b) LHA index for LHA events. Shown in (c), (e) and (g) are lagged-composites of W-1 250 hPa wave amplitude (unit: m) (c); 250 hPa W-1 FZ (unit: m$^2$ s^-2) (e) and 100 hPa W-1 FZ (g) for WP events (black curves) and LHA events (grey curves). (d), (f) and (h): same as (c), (e) and (g) except for W-2 component. Both amplitude and FZ are values area-averaged between 45°N and 75°N. Note that the values of FZ have been multiplied by a factor of 100 for a better graphical display. Black vertical line denotes the day zero for each event. Black-dashed horizontal line indicates the climatology of the full winter period. The red (blue) shading denotes the positive (negative) one standard deviation range above (below) the climatological winter mean value. Thick curves mark lag days for which the composite value is statistically significant at the $p < 0.10$ level determined with a Monte-Carlo test. Purple vertical lines indicate lag days for which the difference between the composite values is statistically significant at the $p < 0.10$ level determined with a Monte-Carlo test.
amplitudes of WPs are significantly enhanced during EN winters compared to NE winters at several lag days. The persistence of WPs is also increased from 12 days for NE winters to 16 days for EN winters. At the same time, the WP-associated W-1 wave amplitude and duration at 250 hPa, the WP-associated 250 hPa and 100 hPa W-1 FZ are also significantly enhanced during EN winters, compared to NE winters (figures 3(b),(d)). In contrast, significant change in the WP-associated W-1 amplitude is found to exist between LN winters and NE winters only for the early stage before day −10, which also implies a longer duration of the WP-associated W-1 amplification for LN winters than NE winters (figure 3(b)). Similar situation happens for the WP-associated 250 hPa and 100 hPa W-1 FZ for LN winters, compared to NE winters (figures 3(c) and (d)).

The above results suggest that EN can significantly enhance the WP amplitude, duration and the associated 250 hPa and 100 hPa W-1 wave amplitude and FZ, which contribute dominantly to the SSW frequency increase during EN winters. In contrast, the LN influence on WPs is not as significant as EN except for in the early stage before day −10, as a result, WPs contribute only partially to the SSW frequency increase from NE winters to LN winters, and some other explanations are desired.

Actually, we see from table 1 that in LN winters there are 4 SSW events which are not preceded by WPs: 02 Jan 1985, 22 Feb 1989, 21 Jan 2006 and 24 Jan 2009. Three of them, 02 Jan 1985, 22 Feb 1989 and 24 Jan 2009, are preceded by blockings over the eastern Pacific (Manney et al. 2009, Martius et al 2009, Garfinkel et al 2010, Harada et al 2010, Woollings et al 2010, Ayarzagüena et al. 2011, Bandal et al. 2012, Barriopedro and Calvo 2014, Kodera et al 2016). The eastern Pacific blocking and the associated downstream negative height anomaly are in phase with the ridge and trough
over the same area of the climatological W-2 waves (figure S2), leading to an enhancement of the upward W-2 wave activity fluxes (table 1) and the onset of SSWs. This implies that the eastern Pacific blocking occurred in LN winters also contributes to the SSW frequency increase from NE winters to LN winters, by roughly 0.17 events per winter.

For the 21 Jan 2006 SSW event, Nishii et al (2009) found that both the negative height anomaly south of Aleutian Islands and the positive anomaly over Europe contribute to this SSW event.

### 3.4. How EN influences WPs

Previous studies have also pointed out the WP-ENSO linkage with monthly data (e.g. Horel and Wallace 1981, Kodera 1998, Yu and Kim 2011, Tanaka et al 2016), but the mechanism still remains unclear. Here we explore the WP-ENSO relation further by examining how EN influences WPs with daily data.

In view of the fact that WPs and PNAs have similar spatial structures except that WPs is located in higher latitude and more westward than PNAs. There exists a possibility that some WPs develop from PNAs when they move into the region of WPs and this PNA-WP conversion may be strongly influenced by ENSO. To confirm this argument, we examine the WP-PNA relation first. The lagged-correlation based on daily WP and PNA indices (following the definition of Wallace and Gutzler 1981), shown in figure S3(a), indicates that PNAs lead WPs several days. This suggests that some WPs may develop from PNAs. To be quantitatively, we define a WP event as a PNA-precended event when the value of the nine-day running mean of the PNA index is greater than +0.5 at least once within the ten days before the day zero of the WP event. Otherwise, it is non-PNA preceded. Table S1 (third column) indicates that among the 192 WP events in the period 1958-2013, more than half WP events (106) are PNA-precended. Table S1 (third column) also shows that the frequency of the PNA-precended WP is larger in EN winters (2.53 events per winter) than LN winters (1.56 events per winter) and NE winters (1.58 events per winter).

Then, how ENSO modulates the amplitude and duration of these PNA-precended WPs? Figure S3(b) indicates that the amplitudes of the PNA-precended WPs are significantly larger and their duration is longer (about 6 days) in EN than LN and NE winters. The differences are illustrated clearly in the WPs’ evolution processes in height field (figure 4): WPs do develop gradually from PNA-like anomalies for both EN and NE winters, and the PNA-like anomalies are stronger and the matured WPs’ amplitude is larger in EN than NE winters. In contrast for the non-PNA preceded WPs, the ENSO modulation on WPs are slight (figure S3(c)).

The above findings suggest that higher frequency, larger amplitude, and longer duration of the PNA-precended WPs in EN winters are favorable for triggering SSWs: the frequency of the PNA-precended SSWs in EN winters is 0.53 events per winter, higher than NE (0.26) and LN (0.22) winters, see table s1. Sure, the question of how EN enhances the amplitudes of WPs is still unclear to the authors, which requires further detailed theoretical and modeling studies of the dynamical processes occurred in different ENSO phases, including the forcing of the tropical convection and associated excitation and propagation of the Rossby wave trains, interaction of high- and low- frequency waves, and wave-mean flow interaction in the mid-latitudes.

Further study indicates that the WP frequency is significantly larger for strong than weak El Niño and La Niña, but the amplitude and duration of the WPs are not sensitive to the ENSO (both El Niño and La Niña) amplitude.

It should be noted that our above results do not distinguish between the ENSO types, the eastern Pacific (EP) El Niño and central Pacific (CP) El Niño. Based on the monthly data, Yu and Kim (2011) and Yeh et al (2015) once detected the linkage between the CP El Niño and WPs (identically the North Pacific oscillation, NPO; see Linkin and Nigam 2008). Particularly, they found that WPs can trigger the CP El Niño, but they did not further examine how the CP El Niño influence WPs. We explore these questions further with daily data. It turns out that WPs have larger frequency in the EP El Niño than CP El Niño, but there are no significant differences in amplitude and duration of WPs for CP El Niño and EP El Niño (not shown). These results are consistent with the above ENSO-WP relation in terms of ENSO amplitude because EP El Niño is usually stronger than CP El Niño.

### 4. Summary and conclusions

The WP pattern is one of the well-known teleconnection patterns for wintertime North Pacific. Previous studies have found that the negative phase WPs can cause intensification and cooling of the stratospheric polar vortex (Limpasuvan et al 2005, Orsolini et al 2009, Nishii et al 2010, Woollings et al 2010, Nishii et al 2011). Consistent with this, this study shows that the positive phase WPs are closely linked to SSWs and this WP-SSW relation is strongly modulated by ENSO. From this study, the following conclusions are reached:

- (a) WPs can interact constructively with the climatological planetary waves, which enhances the W-1 waves amplitude and the associated FZ and triggers SSWs. 86% of the SSWs occurred in 1957/58–2012/2013 winters are preceded by WPs. So, WPs can serve as a good precursor of SSWs.
- (b) EN can enhance the frequency, amplitude, duration of WPs, and the associated W-1 wave amplitude and FZ, which contributes dominantly to the SSW frequency increase from NE winters.
Figure 4. Lagged composites of anomalous 250 hPa height for PNA-preceded WP events in (left) EN and (right) NE winters from lag day −20 to day 0 with a time interval of 2 days. Red (blue) contours indicate positive (negative) values. The contour interval is 40 m. Contours start from +/-20 m. Zeros lines are omitted. Shading indicates height anomalies that are statistically significant at the $p < 0.10$ level as determined with a Monte-Carlo test.
to EN winters. For LN winters, the frequency, amplitude and duration of WPs are enhanced somewhat. The LN modulation on WPs contributes only partially to the SSW frequency increase (0.13 events per winter) from NE winters to LN winters. It turns out that the eastern Pacific blockings also contribute partially to the SSW frequency increase (0.17 events per winter) through enhancing W-2 waves from NE winters to LN winters.

(c) EN influences WPs in the following way: during EN winters, more WPs develop from PNA s than during LN and NE winters, and these WPs have larger amplitude and longer duration, which is responsible for the increase of frequency of SSWs from NE to EN winters.

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