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Key Points:

- SSW occurrence dominates the CP-El Niño signal in the NH polar stratosphere
- In the absence of SSWs, EP- and CP-El Niño stratospheric responses are distinguishable
- Robust results regardless of the CP-El Niño index and the composite size used

Supporting Information:

- Figure S1

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Role of Stratospheric Sudden Warmings on the response to Central Pacific El Niño

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Abstract The Northern Hemisphere (NH) polar stratospheric response to Central Pacific El Niño (CP-El Niño) events remains unclear. Contradictory results have been reported depending on the definition and events considered. We show that this is due to the prominent role of Stratospheric Sudden Warmings (SSWs), whose signal dominates the NH winter polar stratospheric response to CP-El Niño. In fact, the CP-El Niño signal is robust when the events are classified according to the occurrence of SSWs and displays opposite response in winters with and without SSWs. In the absence of SSWs, polar stratospheric responses to Central Pacific and Eastern Pacific El Niño are clearly distinguishable in early winter, in relation to differences in the Pacific-North American pattern. Our results demonstrate that the occurrence of SSWs needs to be taken into account when studying the stratospheric response to CP-El Niño and explain why different responses to CP-El Niño have been reported previously.

1. Introduction

El Niño–Southern Oscillation (ENSO) is the main mode of interannual variability in the tropical troposphere. During boreal winter, the signal of El Niño propagates poleward by means of Rossby wave trains [*Hoskins and Karoly*, 1981]. In the North Hemisphere (NH), Rossby waves induce a deeper Aleutian low, strengthening the Pacific-North American (PNA) pattern in the midtroposphere [e.g., *Horel and Wallace*, 1981]. As a consequence, the upward propagation of planetary waves into the stratosphere is enhanced in the NH through the intensification of stationary wave number 1 [e.g., *Garfinkel and Hartmann*, 2008]. Anomalous wave dissipation occurs, resulting in a weakened polar vortex, warmer polar stratosphere, and strengthening of the downwelling branch of the Brewer-Dobson circulation [*Sassi et al.*, 2004; *García-Herrera et al.*, 2006; *Manzini et al.*, 2006]. These anomalies propagate downward from the upper stratosphere in early winter to the troposphere in late winter through wave-mean flow interaction [e.g., *Manzini et al.*, 2006] and can affect NH tropospheric climate [*Ineson and Scaife*, 2009; *Cagnazzo and Manzini*, 2009; *Bell et al.*, 2009]. These studies have shown that Stratospheric Sudden Warmings (SSWs) play a significant role in this downward propagation and thus in connecting the tropospheric tropical El Niño signal with the NH extratropical teleconnections through the winter stratosphere.

Recently a different type of El Niño has been identified [e.g., *Ashok et al.*, 2007], distinct from the traditional one. While the canonical El Niño has its largest sea surface temperature (SST) anomalies in the Eastern Pacific (EP-El Niño), this new type of event is characterized by SST anomalies that peak in the central Pacific. It has been referred to as Dateline El Niño [*Larkin and Harrison*, 2005], El Niño Modoki [*Ashok et al.*, 2007], central-Pacific El Niño [*Kao and Yu*, 2009], or Warm Pool El Niño [*Kug et al.*, 2009], and different indices have been used to characterize it, such as those based on EOF analysis (e.g., El Niño Modoki index) or SSTs averages over certain regions of the central Pacific (e.g., Niño4 index).

The tropospheric teleconnections of Central Pacific El Niño (CP-El Niño) have been investigated and compared with those from EP-El Niño [*Weng et al.*, 2007, 2009; *Kao and Yu*, 2009; *Kug et al.*, 2009]. However, there is no consensus about the NH winter stratospheric response to CP-El Niño [e.g., *Garfinkel et al.*, 2013, hereinafter G13]. Several studies have reported an opposite response in the polar stratosphere in CP- and EP-El Niño in reanalysis data, with a stronger and colder polar vortex during CP-El Niño in response to a weaker Aleutian low [*Hegyi and Deng*, 2011; *Sung et al.*, 2014]. In model simulations, *Zubiaurre and Calvo* [2012] also reported a temperature pattern consistent with a stronger polar vortex albeit not significant and inconsistent with the tropospheric PNA pattern. On the other hand, *Graf and Zanchettin* [2012] showed a weakened stratospheric polar vortex for both EP- and CP-El Niño in reanalysis data, although the response

Table 1. Identified EP- and CP-El Niño Winters[a] Used in This Study, CP-El Niño Winters Defined by G13, and CP-El Niño Winters by *Sung et al.* [2014][b]

Identified El Niño Winters		CP-El Niño Winters From G13			CP-El Niño Winters
EP-El Niño	CP-El Niño	Modoki[c]	Nin4 $>$ Nin3[d]	1.5N4–0.5N3[e]	Sung2014
1965–1966[f]	1968–1969[f]	1963–1964	1968–1969[f]	1968–1969[f]	1968–1969[f]
1972–1973[f]	1977–1978	1965–1966[f]	1977–1978	1990–1991	1977–1978
1976–1977[f]	1987–1988[f]	1967–1968[f]	1990–1991	1994–1995	1979–1980[f]
1982–1983	1990–1991	1968–1969[f]	1994–1995	2002–2003[f]	1990–1991
1986–1987[f]	1994–1995	1977–1978	1996–1997	2004–2005	1992–1993
1997–1998	2001–2002[f]	1990–1991	2001–2002[f]	2006–2007[f]	1994–1995
	2002–2003[f]	1991–1992	2004–2005		2001–2002[f]
	2004–2005	1994–1995	2005–2006[f]		2002–2003[f]
	2006–2007[f]	2004–2005	2006–2007[f]		2004–2005
	2009–2010[f]				

[a] EP-El Niño: $N3 > 0.5$ SD and $N3 > 0.1 \times N4$. CP-El Niño: $N4 > 0.5$ SD and $N4 > 0.1 \times N3$.
[b] CP-El Niño classification based on *Yeh et al.* [2009].
[c] El Niño Modoki index [*Ashok et al.*, 2007; *Zubiaurre and Calvo*, 2012].
[d] Both Niño3 and Niño4 exceed 0.5°C and Niño4 $>$ Niño3, similar to *Hurwitz et al.* [2011].
[e] $1.5 \times$ Niño4 $- 0.5 \times$ Niño3, similar to *Trenberth and Stepaniak* [2001].
[f] Winter with SSW occurrence.

was weaker and less significant for the latter. Similar results were found in idealized model experiments (G13). Very recently, *Hurwitz et al.* [2014] investigated the seasonal mean response to ENSO in Coupled Model Intercomparison Project Phase 5 models and concluded that EP- and CP-El Niño polar stratosphere responses were indistinguishable in their winter means, although *Sung et al.* [2014] argued that the differences between EP- and CP-El Niño arose from variations in the seasonal evolution of extratropical waves. In short, the question whether or not the EP- and CP-El Niño differ in their teleconnections in NH winter remains moot, in part, because of the different definitions and years employed in the literature to characterize CP-El Niño events. Interestingly, G13 compared the responses to different CP-El Niño indices in reanalysis data and concluded that the response to CP-El Niño was not robust and sensitive to the size of the composite and the index used.

In our study, we reexamine this issue by exploring the role of SSWs. Since SSW events are major disruptions of the stratospheric polar vortex, their impact on the observed stratospheric ENSO response should be assessed. We show that the SSWs signal overwhelms the polar stratospheric response to CP-El Niño. In particular, when only winters without SSWs are considered, the upper stratosphere polar stratospheric signals of EP- and CP-El Niño are distinguishable in early winter (November to January).

2. Data and Methods

This study uses monthly mean data from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis. The 40 year ECMWF reanalysis (ERA-40) is used from 1958 to 1978 [*Uppala et al.*, 2005] and the ECMWF Interim reanalysis (ERA-Interim) from 1979 to 2013 [*Dee et al.*, 2011]. The data are distributed in a horizontal grid of $2.5° \times 2.5°$ (longitude × latitude) and 23 vertical pressure levels, from 1000 to 1 hPa. Previous to the ENSO analysis, time series for each field have been detrended and anomalies computed with respect to the total monthly mean climatology from 1958 to 2013.

EP- and CP-El Niño events are defined using the standardized NDJF (November-December-January-February) sea surface temperature anomalies in the Niño3 (N3) (5°N–5°S, 150°W–90°W) and Niño4 (N4) (5°N–5°S, 160°E–150°W) regions, which are obtained from the National Center for Environmental Prediction Climate Prediction Center (NCEP/CPC). EP-El Niño winters are identified whenever N3 exceeds 0.5 standard deviations and N3 is larger than 0.1 times the N4 value. Analogously, CP-El Niño winters are defined whenever N4 exceeds 0.5 standard deviations and N4 is larger than 0.1 times the N3 value. Table 1 lists the identified EP- and CP-El Niño winters.

Major SSWs are defined following the criteria of *Charlton and Polvani* [2007], based on the zonal-mean zonal wind reversal at 10 hPa and 60°N from November to March. The list of SSWs is taken from *Barriopedro and Calvo* [2014], who used ERA-40 data from 1957 to 2002 and ERA-Interim data from 2002 to 2010. The same

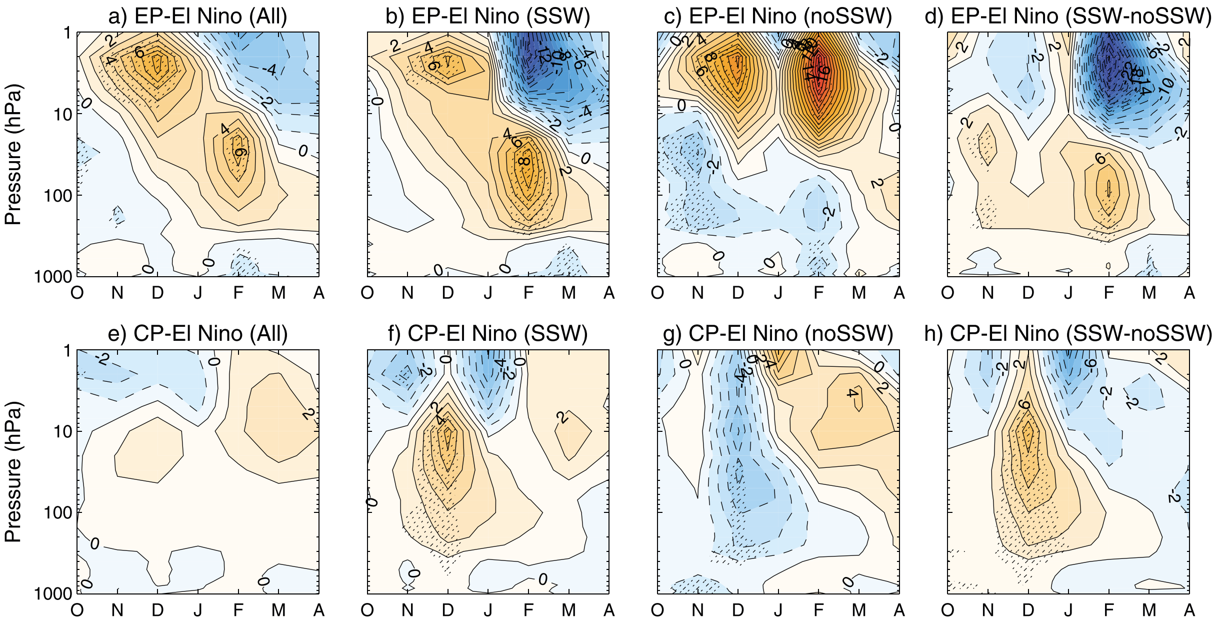

Figure 1. October to April composite of the monthly mean zonal-mean temperature anomaly at 80°N for (a–d) EP-El Niño and (e–h) CP-El Niño. Niño composites for all winters (Figures 1a and 1e), winters with SSWs (Figures 1b and 1f), winters without SSWs (Figures 1c and 1g), and the difference between winters with and without SSWs (Figures 1d and 1h). Contour interval is 1 K, and 2 K for differences. Solid (dashed) contours denote positive (negative) anomalies. Stippling indicates significance at the 95% level.

winters with and without SSWs are detected when ERA-40 is used from 1957 to 1978 and ERA-Interim from 1979 to 2013, as it is the case in our study. Winters with SSWs are marked in Table 1. Note that the frequency of occurrence of SSWs is similar in EP- and CP-El Niño winters.

Composites are computed to analyze the signals of EP- and CP-El Niño. The statistical significance of the signals is assessed with a Monte Carlo test of 10,000 trials at the 95% confidence level. Wave number decomposition is performed applying Fourier analysis to geopotential height fields.

3. Results

Figure 1 shows the time-pressure evolution of (a) EP- and (e) CP-El Niño anomalies for zonal-mean temperature at 80°N. Similar results are found at several high-latitude averages. During EP-El Niño winters a significant polar warming appears in the upper stratosphere in November and December. The warming descends to the middle stratosphere and becomes significant again in February. This is in agreement with previous studies [e.g., *Manzini et al.*, 2006; *Cagnazzo and Manzini*, 2009], who showed warm anomalies propagating downward during winter. Next, the influence of SSWs in the EP-El Niño response is investigated by distinguishing winters with and without SSWs (Figures 1b and 1c). The significant warming in early winter (November and December) appears in the upper stratosphere in both composites, and it is in agreement with anomalous wave dissipation in the stratosphere following the warm ENSO event [e.g., *García-Herrera et al.*, 2006]. However, the downward propagation of the warm temperature anomalies toward the lower stratosphere is only observed during winters with SSWs while it is missing in the composite without SSWs. These differences are significant in the lowermost stratosphere (Figure 1d). We are aware of the small composite size of the EP-El Niño without SSWs in the observational record. Nonetheless, the role of SSWs in propagating the canonical El Niño signal to the lower stratosphere is in agreement with those reported from model simulations with larger composite sizes [*Ineson and Scaife*, 2009; *Cagnazzo and Manzini*, 2009; *Bell et al.*, 2009].

The composite of all CP-El Niño winters (Figure 1e) reveals a much weaker and nonsignificant response compared to EP-El Niño, consistent with results of *Zubiaurre and Calvo* [2012] and G13. However, when the zonal-mean temperature responses are analyzed for winters with and without the occurrence of SSWs separately, significant and opposite anomalies are obtained from November to January in the middle and lower stratosphere. During CP-El Niño winters with SSWs (Figure 1f), a significant anomalous warming appears in the middle stratosphere, while in the absence of SSWs (Figure 1g), a significant cooling is observed in the middle and lower stratosphere. These differences are significant at the 95% level (Figure 1h). Additionally, our results reveal that in the absence of SSWs, the response of the polar stratosphere to CP-El Niño in early winter is different to that of EP-El Niño. At this point, it should be stressed that the observed warming during CP-El Niño with SSWs is likely due to the occurrence of the SSW itself and cannot be attributed to a downward propagating CP-El Niño warm signal, since the significant warm anomalies observed in early winter in the upper stratosphere during EP-El Niño are absent for CP-El Niño and the warming does not appear in the absence of SSWs.

To test the robustness of our results to the different definitions and composite sizes used in the literature, Figure 2 shows the composite of the winters defined by G13 to compare three different indices of CP-El Niño (see Table 1). We have used the largest composite sizes used by G13 to increase the number of cases when stratifying according to SSWs. The Hegyi-Deng index, used in G13, has been omitted because two of the winters identified by G13 as CP-El Niño, 1982–1983 and 1997–1998, are usually considered EP-El Niño winters [e.g., *Kao and Yu*, 2009; *Kug et al.*, 2009; *Hegyi and Deng*, 2011; *Hurwitz et al.*, 2011]. Instead, we have included the CP-El Niño winters identified by *Sung et al.* [2014] (Table 1). When no stratification according to SSW occurrence is applied (Figures 2a, 2e, 2i, and 2m), the response is weak, not significant, and depends on the index chosen, reproducing the results of G13. For CP-El Niño winters with SSW occurrence, all composites show a warming in the middle stratosphere from November to January. In contrast, during CP-El Niño winters without SSWs an anomalous cooling appears in early winter, robust across the different indices. Similar to Figure 1, differences between CP-El Niño winters with and without SSWs are statistically significant. These results do not change when other composite sizes are considered, following the methodology by G13 (not shown). All these results suggest that the CP-El Niño polar stratospheric response is dominated by the SSW signal. A separate analysis (not shown) has revealed that early winter SSWs, those occurring in November and December, are more effective in masking the signal of CP-El Niño events than those occurring later on.

Having shown that the CP-El Niño response is robust in the absence of SSWs, and opposite to that of EP-El Niño from November to January, we investigate next the mechanism behind these differences. The Aleutian low, through the PNA pattern, is known to be the main pathway whereby ENSO modulates the polar vortex [e.g., *Garfinkel and Hartmann*, 2008]. Figure 3 shows the November-December (ND) mean eddy geopotential height anomalies at 500 hPa in winters with and without SSWs. ND is chosen as these months show the largest signals in the polar stratosphere (Figure 1). Results are very similar for the November-December-January average. EP-El Niño events (with and without SSWs) and CP-El Niño events with SSWs all feature a strengthening of the PNA pattern: significant positive height anomalies over North America and a deepened Aleutian low. The deepening of the Aleutian low is weaker and shifted south in EP-El Niño events that occur in winters with SSWs. This is likely related to the weaker EP-El Niño events in this composite compared to that without SSWs (Figure 3c) and to the dates of occurrence of SSWs. While during CP-El Niño winters with SSWs (Figure 3b), half of the SSWs occurred in November or December; for EP-El Niño winters SSWs mainly occur in January, consistent with a deeper Aleutian low from January to February (not shown). As the precursors of SSWs are not yet clear, a deeper analysis of this feature is beyond the scope of this study.

Contrary to the behavior in EP-El Niño and CP-El Niño winters with SSWs, it is evident that CP-El Niño winters without SSWs are characterized by a significant “reverse PNA” pattern, with large negative height anomalies over North America and an anomalously weak Aleutian low, as reported by *Hegyi and Deng* [2011] and *Sung et al.* [2014] for early winter. Thus, PNA-like patterns of opposite sign are found for CP-El Niño winters in years with and without SSWs (Figure 3b versus Figure 3d) and also between all EP-El Niño winters and CP-El Niño winters without SSWs (Figures 3a and 3c versus Figure 3d). The observed different PNA patterns for EP- and CP-El Niño in the absence of SSWs were previously reported in other studies [e.g., *Weng et al.*, 2009; *Hegyi and Deng*, 2011] and seem to be related to differences in tropical convection due to the distinct location of SST anomalies in the tropical Pacific [*Zubiaurre and Calvo*, 2012; *Sung et al.*, 2014]. The weakened Aleutian low in CP-El Niño winters without SSWs is also accompanied by positive SST anomalies over the North Pacific region while in CP-El Niño winters with SSWs, colder SST anomalies appear in this region (Figure S1 in the supporting information). This is consistent with the idealized modeling study by *Hurwitz et al.* [2012],

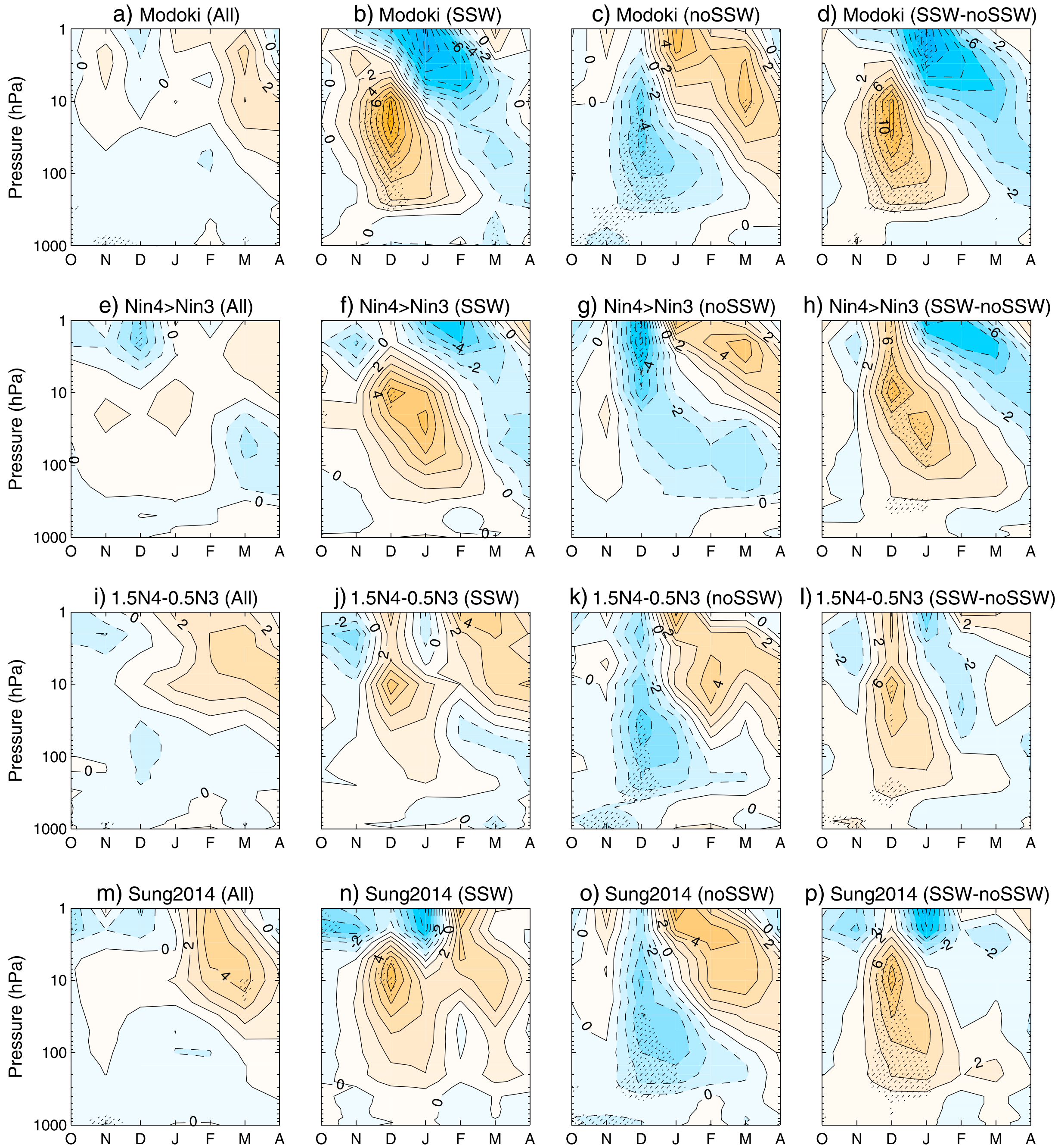

Figure 2. Same as Figure 1, for the indices used by G13 and winters identified by *Sung et al.* [2014]. (a–d) Modoki index, (e–h) Nin4 > Nin3 index, (i–l) 1.5N4–0.5N3 index, and (m–p) *Sung et al.* [2014] events (see Table 1 for details).

who found a weaker Aleutian low and a colder polar stratosphere in response to warm SST anomalies over the North Pacific. Whether the different SSTs in this region are related to SSWs precursors could be addressed in future studies.

The weakened PNA pattern for CP-El Niño winters without SSWs is in agreement with the subsequent observed stratospheric polar cooling, as it likely inhibits upward wave propagation. This is confirmed by the analysis of upward propagation of planetary waves that might induce winter polar vortex perturbation. Figure 4 shows the longitude-pressure cross sections of wave number 1 (wn1) and wave number 2 (wn2) components of geopotential height anomalies, averaged from 45°N to 75°N and November-December. Only

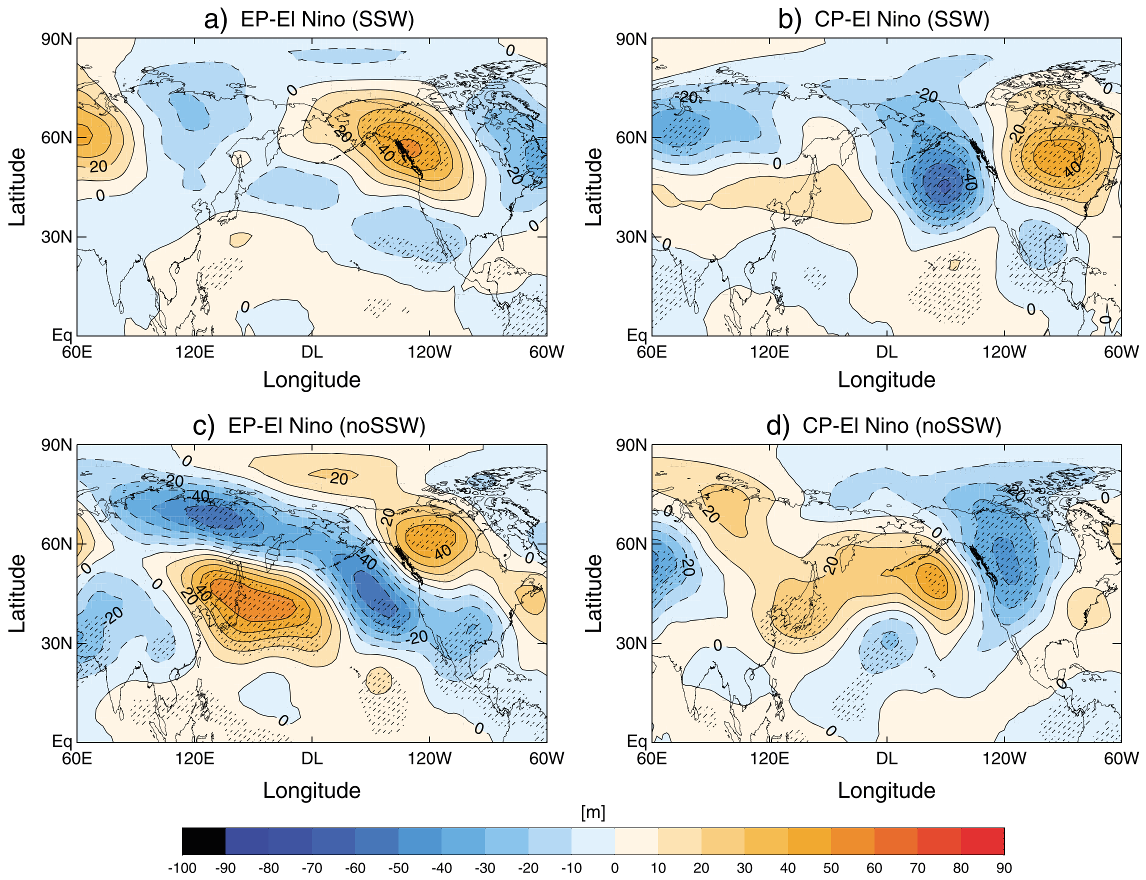

Figure 3. Longitude-latitude composite of the November-December average eddy geopotential height anomalies at 500 hPa for (a and c) EP-El Niño and (b and d) CP-El Niño winters (Figures 3a and 3b) with and (Figures 3c and 3d) without SSWs. Solid (dashed) contours denote positive (negative) anomalies. Stippling indicates significance at the 95% level.

EP- and CP-El Niño winters without SSWs are shown, as these can be understood in terms of linear dynamics, when interference theory applies. For EP-El Niño the wn1 geopotential height anomalies are in phase with the climatology, so the stationary wn1 is enhanced [*Manzini et al.*, 2006; *Garfinkel and Hartmann*, 2008]. Also, the anomalies exhibit a westward tilt with height, indicating upward propagation of Rossby waves. Wn2 anomalies are almost in quadrature with respect to the climatology, showing a mild weakening of wn2. These results are consistent with the extratropical wave modulation known for EP-El Niño [e.g., *Garfinkel and Hartmann*, 2008]. CP-El Niño wn1 anomalies are out of phase with the climatology such that the climatological stationary wn1 is weakened. This leads to suppressed anomalous upward propagation and a stronger polar vortex. Wn2 anomalies are weak in amplitude and tend to weaken the climatological pattern in the troposphere, while in the stratosphere they are almost negligible.

We conclude that in the absence of SSWs perturbations, a robust negative PNA pattern is observed during CP-El Niño events, which weakens the climatological wn1 pattern and its upward propagation into the stratosphere, in accordance with the previously shown stratospheric cooling for CP-El Niño winters with no SSW.

4. Summary and Discussion

The present study uses ERA-40 and ERA-Interim reanalyses to identify EP- and CP-El Niño signals in the NH polar stratosphere, characterized by N3 and N4 indices. We have found that the SSW occurrence, particularly those in November and December, dominates the CP-El Niño signal in the polar stratosphere. CP-El Niño winters with no SSWs exhibit a significant cooling in the middle polar stratosphere while in winters with SSWs a significant warming appears. Examinations of the PNA pattern and the wave anomalies in the stratosphere support the observed stratospheric signals. In the absence of SSWs, EP-El Niño winters are characterized by

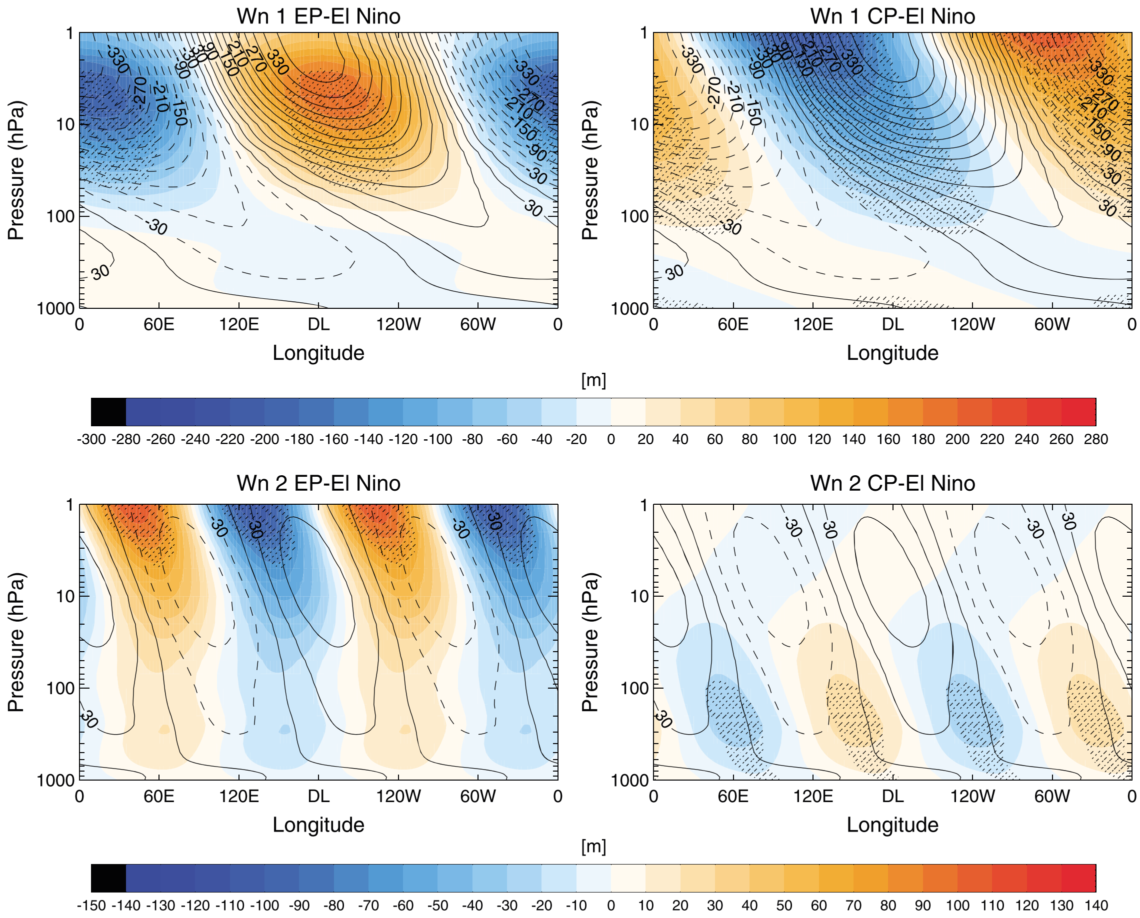

Figure 4. Longitude-pressure cross sections of the composite of (top) wn 1 and (bottom) wn 2 components of 45°N–75°N November-December geopotential height anomalies (color contours) for (left) EP-El Niño and (right) CP-El Niño winters without SSWs. Solid (dashed) line contours denote positive (negative) values of the climatology averaged for November and December (interval of 30 m). Stippling indicates significance at the 95% level.

astrengthened PNA pattern and enhanced propagation of planetary wn1 into the stratosphere, while the opposite occurs in CP-El Niño winters. Insofar as wave dissipation in winters without SSW might be expected to depend linearly on wave amplitude, this is consistent with a weaker polar vortex in EP-El Niño winters and a stronger vortex in CP-El Niño winters [*Manzini et al.*, 2006; *Garfinkel and Hartmann*, 2008; *Hegyi and Deng*, 2011].

Contrary to previous studies that investigated the CP-El Niño signal in the NH polar stratosphere, our results are robust regardless of the CP-El Niño definition and the size of the composite used. Thus, this work demonstrates that the influence of SSWs needs to be taken into account to obtain a statistically significant polar stratospheric response for CP-El Niño winters. Then, better predictions of the boreal winter polar stratosphere during El Niño events would require better understanding of SSW precursors. Our study also explain why different results have been reported regarding the CP-El Niño stratospheric response (e.g., G13), since, when compositing all CP-El Niño cases together, the occurrence of SSWs can mask the CP-El Niño signal, leading to nonrobust results. Moreover, our results shed light on the comparison of EP- versus CP-El Niño signals. For winters with SSWs the observed middle stratospheric signal for EP- and CP-El Niño is similar, due to the predominant impact of the SSWs. In the absence of SSWs the stratospheric responses to EP- and CP-El Niño events are distinct from November to January.

We are aware that the observational record is short, especially when distinguishing EP- and CP-El Niño winters with respect to the occurrence of SSWs. Nonetheless, the polar stratospheric response to CP-El Niño has been analyzed using four different indices and different thresholds to change the composite sizes, following the methodology of G13, and it was found to be consistent in all cases. That is, we invariably findthat the polar stratosphere response to CP-El Niño is ruled by the occurrence of SSWs: anomalously warm in winters with SSWs and anomalously cold in winters without SSWs. It would be of interest to see whether this result can be found in numerical models with a well-resolved stratosphere. In addition, long simulations with such models would make it possible to address the role of the quasi-biennial oscillation on the EP- and CP-El Niño polar stratospheric responses.

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