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El Niño, La Niña, and stratospheric sudden warmings: A reevaluation in light of the observational record

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[1] Recent studies have suggested that El Niño-Southern Oscillation (ENSO) may have a considerable impact on Northern Hemisphere wintertime stratospheric conditions. Notably, during El Niño the stratosphere is warmer than during ENSO-neutral winters, and the polar vortex is weaker. Opposite-signed anomalies have been reported during La Niña, but are considerably smaller in amplitude than during El Niño. This has led to the perception that El Niño is able to substantially affect stratospheric conditions, but La Niña is of secondary importance. Here we revisit this issue, but focus on the extreme events that couple the troposphere to the stratosphere: major, mid-winter stratospheric sudden warmings (SSWs). We examine 53 years of reanalysis data and find, as expected, that SSWs are nearly twice as frequent during ENSO winters as during non-ENSO winters. Surprisingly, however, we also find that SSWs occur with equal probability during El Niño and La Niña winters. These findings corroborate the impact of ENSO on stratospheric variability, and highlight that both phases of ENSO are important in enhancing stratosphere-troposphere dynamical coupling via an increased frequency of SSWs.
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1. Introduction

[2] The El Niño-Southern Oscillation (ENSO) is widely recognized to be the dominant mode of interannual variability in the climate system, and has well-known impacts on the Northern Hemisphere (NH) mid-latitudes via tropospheric teleconnections [e.g., *Horel and Wallace*, 1981]. More recently, ENSO has been hypothesized to exert additional influence on the mid-latitudes via a stratospheric pathway [*Brönnimann et al.*, 2004; *Bell et al.*, 2009; *Ineson and Scaife*, 2009]. Anomalously strong planetary-scale waves associated with ENSO are thought to propagate vertically into the stratosphere during NH wintertime, break at high-latitudes and weaken the polar vortex, and subsequently impact the troposphere below. The most dramatic of these events, called stratospheric sudden warmings (SSWs), involve a complete breakdown of the polar vortex and are often followed by anomalies that propagate downward into the troposphere on timescales of weeks to months [*Baldwin and Dunkerton*, 2001].

[3] A number of studies have examined the impact of ENSO on the mean state of the NH winter stratosphere [e.g., *Camp and Tung*, 2007; *Garfinkel and Hartmann*, 2007; *Free and Seidel*, 2009]. During an El Niño winter, it is well-established that (1) temperatures are colder than normal in the tropical stratosphere and warmer than normal in the polar stratosphere; (2) ozone concentrations are anomalously low in the tropics and anomalously high at the pole, reflecting an enhanced Brewer-Dobson circulation [*Randel et al.*, 2009; *Cagnazzo et al.*, 2009]; and (3) the planetary wave flux into the stratosphere is enhanced resulting in a weaker-than-normal stratospheric polar vortex [*van Loon and Labitzke*, 1987; *García-Herrera et al.*, 2006; *Garfinkel and Hartmann*, 2008].

[4] Opposite-signed stratospheric anomalies have been reported during La Niña winters, when tropical Pacific sea surface temperatures are anomalously cold, but these anomalies are generally weaker and less statistically significant in both observations and models forced with observed sea surface temperatures [*Sassi et al.*, 2004; *Manzini et al.*, 2006; *Garfinkel and Hartmann*, 2007; *Free and Seidel*, 2009]. Consequently, nearly all recent studies have focused on El Niño alone, discounting La Niña as basically of little consequence for the stratosphere.

[5] In this study, we revisit the ENSO-stratosphere connection, but rather than considering the mean state of the stratosphere, we focus on SSWs- the clearest and strongest manifestations of the dynamical coupling between the stratosphere and the troposphere. We examine over 50 years of reanalysis data, yet we find no evidence that SSWs occur more often during El Niño winters relative to La Niña winters as suggested by recent modeling studies [e.g., *Taguchi and Hartmann*, 2006]. In fact, the record of the last half century shows that (1) major SSWs occur with equal probability during El Niño and La Niña winters; (2) major SSWs occur nearly twice as often during both El Niño and La Niña winters compared to ENSO-neutral winters; and (3) all winters in the record with two SSWs in the same season are associated with non-neutral ENSO (three with El Niño and two with La Niña).

2. Methods

[6] To detect major, mid-winter SSWs, we follow the World Meteorological Organization (WMO) definition: a reversal of the climatological westerly winds at 10 hPa and 60°N in the Northern Hemisphere wintertime (November to March). As in *Charlton and Polvani* [2007], the "central date" of the warming is the first day on which the daily

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Table 1. The SSW Central Dates From the NCEP-NCAR Reanalysis, 1958–2010, and the ENSO Phase, Denoted as E (El Niño) for Values >0.5°C, L (La Niña) for Values <−0.5°C, or N (Neutral) for Absolute Values < = 0.5°C[a]

SSW Central Date	ENSO Phase
30-Jan-58	E
30-Nov-58	N
16-Jan-60	N
23-Mar-65	L
8-Dec-65	**E**
24-Feb-66	**E**
8-Jan-68	L
27-Nov-68	**E**
13-Mar-69	**E**
2-Jan-70	E
17-Jan-71	**L**
20-Mar-71	**L**
2-Feb-73	E
22-Feb-79	N
29-Feb-80	N
4-Dec-81	N
24-Feb-84	L
2-Jan-85	L
23-Jan-87	E
8-Dec-87	**E**
14-Mar-88	**E**
22-Feb-89	L
15-Dec-98	**L**
25-Feb-99	**L**
20-Mar-00	L
11-Feb-01	L
2-Jan-02	N
18-Jan-03	E
7-Jan-04	N
21-Jan-06	L
24-Feb-07	E
22-Feb-08	L
24-Jan-09	L
9-Feb-10	E

[a]Bold rows highlight winters with two warmings.

zonal wind at 10 hPa and 60°N is easterly, and no day within 20 consecutive days following the central date can be defined as an independent SSW. Cases where the zonal winds are easterly and do not return to westerly for at least 10 consecutive days before April 30th are considered final warmings and are not included. In this study, we analyze daily winds and temperatures from the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis [*Kistler et al.*, 2001], over the period 1958–2010.

[7] For the ENSO index, we use the Niño-3.4 time series from the NCEP Climate Prediction Center, calculated as sea surface temperature anomalies (base period 1971–2000) over the region 5°S–5°N and 170°–120°W, from 1958–2010. Unless otherwise specified, we define the phase of ENSO "winters" by the five-month average (November–March) of the Niño-3.4 index. We choose the five-month average because (a) these are the months when SSWs occur in the Northern Hemisphere and when ENSO events tend to peak in amplitude; (b) a given phase of the ENSO tends to persist throughout the winter season; and (c) ENSO events that peak in early winter in the tropics may have impacts in the extratropics that persist through late winter, even if the amplitude of the event weakens by March. The key results are robust to changes in this definition (i.e., using three-month averages or monthly-mean values of the index instead). In terms of a threshold, El Niño winters are defined as the NDJFM-mean index greater than 0.5°C; La Niña as the NDJFM-mean index less than −0.5°C; and all other winters as ENSO-neutral.

3. Results

[8] Over the period 1958–2010, a total of 34 major mid-winter SSWs were identified in the NCEP-NCAR reanalysis, listed in Table 1 (first column) together with the corresponding ENSO phase (Table 1, second column). Note that all events prior to 2003 are identical to the ones reported by *Charlton and Polvani* [2007, Table 1], which is extended to the year 2010 here. Of these 34 events, only 7 occur during ENSO-neutral winters, confirming the widely held belief that ENSO enhances stratospheric variability. Of the remaining 27, however, only 13 have occurred during El Niño winters; the other 14 have occurred during La Niña winters. This is the key finding of our study: that SSWs are as common during La Niña events as they are during El Niño events. This finding does not significantly change if SSWs are examined in the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40/ERA-interim reanalysis [*Uppala et al.*, 2005]: in that case, from 1958–2010, out of 37 total warmings, there are 15 SSWs during El Niño winters, 14 SSWs during La Niña winters, and 8 SSWs during ENSO-neutral winters.

[9] In rare instances, two SSWs have occurred in the same winter (a "double warming"); these are emphasized in bold font in Table 1. Of the 5 double warming winters from 1958–2010, not one has occurred during an ENSO-neutral winter. In fact, 3 have occurred during El Niño winters and 2 during La Niña winters, further confirming the key point of our study, that SSWs occur more often during *both* El Niño *and* La Niña winters.

[10] These results are presented graphically in Figure 1, illustrating the Niño-3.4 anomaly time series (black line). The shading highlights ENSO-neutral conditions, and the colored stars indicate the occurrence of SSWs and are placed

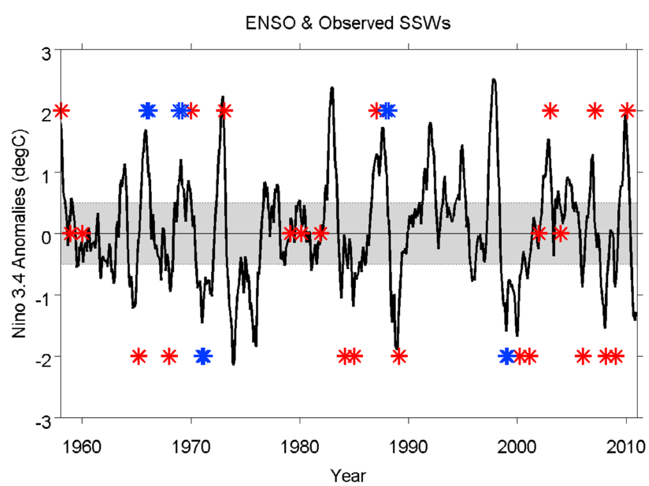

Figure 1. The Niño 3.4 monthly time series and markers showing the time of observed SSW events. Markers are placed at an arbitrary +2 if the SSW occurs during an El Niño winter, −2 if during a La Niña winter, and 0 if during a neutral winter. Blue markers indicate two SSWs in one winter. Grey shading indicates the ENSO-neutral range.

Table 2a. SSWs for El Niño, La Niña, ENSO-Neutral, and All Winters (Defined by the NDJFM-Mean)[a]

	1958–2010			1979–2010		
	Number of Winters	Number of SSWs	SSWs per Winter	Number of Winters	Number of SSWs	SSWs per Winter
El Niño	18	13	0.72	10	6	0.60
La Niña	18	14	0.78	10	10	1.0
Neutral	17	7	0.41	12	5	0.42
All	53	34	0.64	32	21	0.66

[a]The number of winters from 1958–2010 (first column), the number of observed SSWs (second column), the observed frequency of SSWs from 1958–2010 (second column divided by first column); the number of winters from 1979–2010 (fourth column), the number of observed SSWs (fifth column), and the observed frequency of SSWs from 1979–2010 (fifth column divided by fourth column). The 18 El Niño winters are 1957/58, 1963/64, 1965/66, 1968/69, 1969/70, 1972/73, 1976/77, 1977/78, 1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98, 2002/03, 2004/05, 2006/07, and 2009/10. The 18 La Niña winters are 1962/63, 1964/65, 1967/68, 1970/71, 1971/72, 1973/74, 1974/75, 1975/76, 1983/84, 1984/85, 1988/89, 1995/96, 1998/99, 1999/2000, 2000/01, 2005/06, 2007/08, and 2008/09. There are 17 remaining ENSO-neutral winters.

on the ordinate axis with the sign reflecting whether they occur during an El Niño, ENSO-neutral, or La Niña winter, respectively. It is clear from Figure 1 that SSWs occur with nearly equal frequency during El Niño and La Niña winters, and that they are relatively rare during ENSO-neutral winters. Note the existence of periods with very few SSWs, such as the mid-1970's and most of the 1990's [*Pawson and Naujokat*, 1999]. Note also that some of the largest El Niño events (notably 1982/83 and 1997/98) did not generate accompanying SSWs.

[11] One might wonder if the surprising number of SSWs in La Niña winters might be a simple consequence of the occurrence of more winters in the negative ENSO phase. This is not the case, as summarized in Table 2a. Using a threshold value of ±0.5°C to define ENSO phases, one finds an equal number of La Niña winters and El Niño winters (18) over the 53-year observational record, as well as 17 ENSO-neutral winters (Table 2a, first column). We calculate the frequency of SSWs per winter in each phase (Table 2a, third column) as the number of SSWs in each ENSO phase (Table 2a, 2nd column) divided by the total number of winters in each ENSO phase (double warmings are included here, so the frequency per year could be greater than 1). The observed SSW frequency during La Niña winters (0.78 yr^{-1}) is slightly higher though not significantly different than during El Niño winters (0.72 yr^{-1}). In addition, the frequency during both El Niño and La Niña winters is nearly double the frequency during neutral winters (0.41 yr^{-1}). Using a Monte Carlo test to count SSWs in 10,000 random subsamples of winters equal to the number of respective El Niño/La Niña and neutral winters, the probability that this difference in SSW frequency exists by chance is found to be $p < 0.1$.

[12] To test whether the pre-satellite era data might be skewing the results, we consider only the period 1979–2010 (shown in the fourth through sixth columns of Table 2a): in that case one also finds a much higher frequency of SSWs

Table 2b. Observed Frequencies per Winter of SSWs During El Nino, La Nina, and ENSO-Neutral Winters, Depending on Threshold Definition of the ENSO Phase, for 1958–2010

SSW Frequency	Threshold 0.4°C	Threshold 0.5°C	Threshold 0.6°C	Threshold 0.7°C
El Niño	0.76	0.72	0.75	0.86
La Niña	0.67	0.78	0.81	0.83
Neutral	0.36	0.41	0.43	0.44

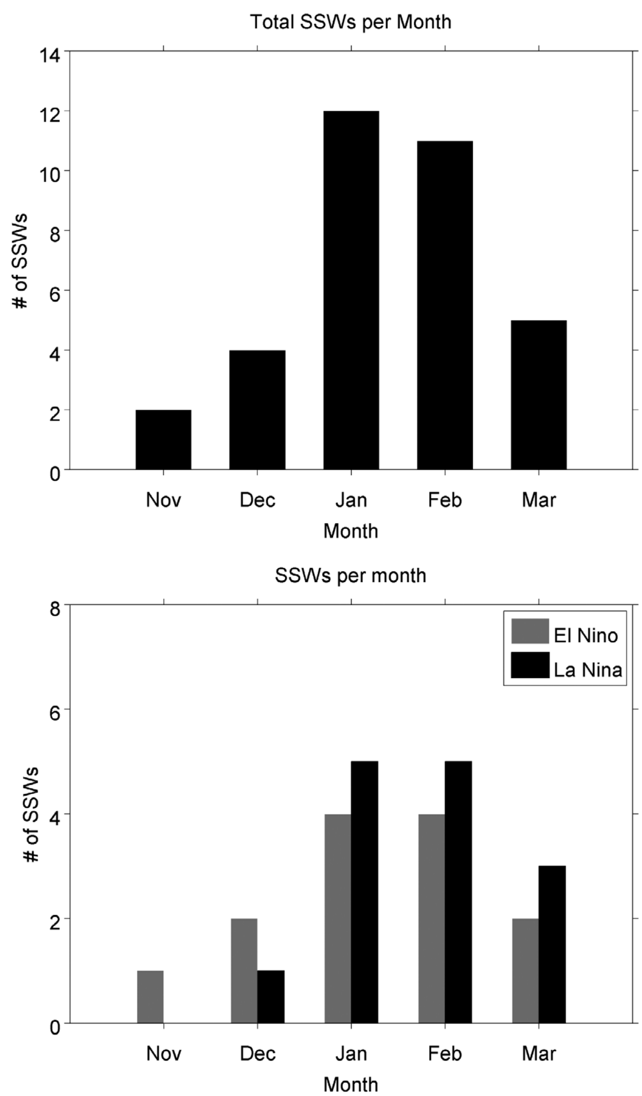

Figure 2. (top) Total number of observed SSWs from 1958–2010, as a function of month. (bottom) Number of observed SSWs during El Niño winters (grey) and La Niña winters (black), as a function of month.

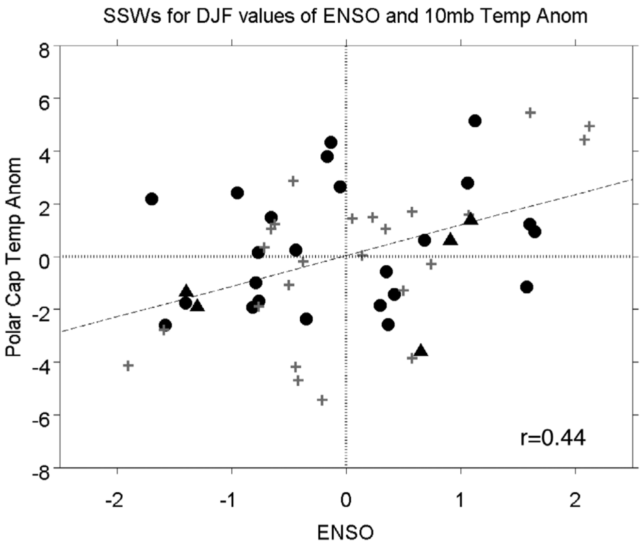

Figure 3. Scatterplot of the standardized DJF Niño 3.4 index and the 60–90°N DJF temperature anomalies at 10 hPa. Winters with one warming are indicated by black circles; winters with more than one warming are indicated by black triangles; winters with no warmings are indicated by grey crosses. The dashed line is the linear regression fit of the DJF ENSO index to the temperature anomalies for all winters.

during El Niño (0.60 yr^{-1}) and La Niña (1.0 yr^{-1}) winters than during ENSO-neutral winters (0.42 yr^{-1}). The likelihood that the observed SSW frequency difference between La Niña and neutral winters for this period exists by chance is $p < 0.05$, again using a Monte Carlo test. In addition, we note that from 1979–2010, there has been at least one SSW during every La Niña winter except for 1995/1996. Compare this distribution to the time period 1958–1979, in which only 4 SSWs occurred in 8 La Niña winters (0.50 yr^{-1}). This difference may be due to data improvement after 1979, to actual trends associated with climate change, to unforced decadal variability, or more likely, to the relatively small sample size of the data, particularly when subdivided.

[13] We also tested the robustness of the SSW frequency as a function of the ENSO phase to different threshold definitions of the NDJFM-mean ENSO index, ranging from 0.4°C to 0.7°C (Table 2b). As the threshold increases, more events are classified as ENSO-neutral and fewer as El Niño or La Niña. Surprisingly, the frequencies change little as the threshold value increases; in all cases, the SSW frequency during both El Niño and La Niña is approximately double the frequency during ENSO-neutral. This robustness implies that most warmings occur during significant (either in amplitude or duration) El Niño and La Niña events, so that the number of SSWs in each of these phases only decreases slightly as the threshold increases.

[14] Finally, we report a slight difference in the timing of SSWs during El Niño versus La Niña winters. Figure 2 (top) shows the total number of SSWs in each month over the period 1958–2010: as shown by *Charlton and Polvani* [2007], the total number of SSWs peaks in January and February, with only 2 SSWs recorded in November. Figure 2 (bottom) shows the number of SSWs in each month for El Niño (grey bars) and La Niña (black bars) winters: visual inspection of Figure 2 (bottom) suggests that SSWs may occur earlier (Nov/Dec) during El Niño winters relative to La Niña winters, though we hasten to add that sample sizes are very small. Overall, the timing of SSWs during both El Niño and La Niña winters is similar.

4. Discussion

[15] A few caveats pertain to the above analysis. First we acknowledge that the observational record is relatively short and that SSWs are extreme events: hence the statistical connection of SSWs to ENSO may be more difficult to establish than for the seasonal-mean state of the stratosphere in relation to ENSO. Nonetheless, we contend that Figure 1, by itself, is visually compelling. Second, we recognize that other external factors, notably the Quasi-Biennial Oscillation (QBO), are likely to have a significant influence on the frequency of SSWs [*van Loon and Labitzke*, 1987]. For instance, we find a higher frequency of SSWs during the easterly phase of the QBO, irrespective of ENSO phase (not shown). Also, we note that four out of five double warmings occur when the wintertime-mean QBO at 50 hPa is in its easterly phase. It is conceivable that the solar cycle, surface boundary conditions, or other factors may also impact the frequency of SSWs.

[16] Nonetheless, we find *a near doubling* of the frequency of SSWs during *both* El Niño and La Niña winters relative to ENSO-neutral winters in the 53-year observational record: this is a very large signal, and unlikely to be a statistical artifact. We also find no evidence that SSWs occur more frequently during El Niño winters than La Niña winters as reported by recent modeling studies [e.g., *Taguchi and Hartmann*, 2006]. Further analysis is warranted to understand this discrepancy, but the fact that many models are unable to simulate the correct frequency of major warmings, as defined by the WMO in terms of wind reversal at 10 hPa, may play a role. Our observational analysis strongly suggests both phases of ENSO are linked to an increased frequency of SSWs.

[17] Previous observational studies have established that El Niño winters are associated with a warm anomaly in the NH polar stratosphere [e.g., *van Loon and Labitzke*, 1987; *Garfinkel and Hartmann*, 2007; *Free and Seidel*, 2009], with an opposite though weaker effect during La Niña winters. To the degree that SSWs correspond to increases in stratospheric temperatures, one might naively guess that El Niño winters would be associated with more frequent SSWs, and La Niña winters with less frequent SSWs. This line of reasoning is shown to be erroneous in Figure 3, which illustrates the relationship between the December–January–February (DJF) ENSO and polar cap (60–90°N) temperature anomalies at 10 hPa. While the correlation between the seasonal-mean polar cap temperatures and ENSO is statistically significant (>95% using a two-tailed *t*-test, with r = 0.44), this relationship tells us nothing about the occurrence of SSWs (indicated by black markers, with black triangles indicating double warmings; the mean difference in temperature anomaly between winters with and without SSWs is not statistically significant). In other words, while SSWs temporarily increase temperatures on subseasonal timescales, the corresponding winters can nonetheless experience colder-than-normal temperatures in the seasonal-mean.

[18] Fundamentally, the difference in the seasonal-mean state of the stratosphere between El Niño and La Niña, while presumably dynamically-driven, does not give information about the individual spontaneous wave events that arise in the troposphere and generate SSWs [*Polvani and Waugh*, 2004]. A preliminary analysis (C. I. Garfinkel, personal communication, 2011) shows that, in both El Niño and La Niña winters, the Aleutian low over the North Pacific is deeper than the climatology prior to SSWs. It has been found that the tropospheric North Pacific is a key precursor region for intra-seasonal vortex variability [*Garfinkel et al.*, 2010]. Hence the likely scenario is that in both phases of ENSO, anomalies in the tropical Pacific are able, via some PNA-like teleconnection, to influence the North Pacific and thus produce an increased frequency of SSWs. A thorough analysis is beyond the scope of this study, but we hope to soon report the details in a forthcoming paper.

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