# Distinguishing Stratospheric Sudden Warmings from ENSO as Key Drivers of Wintertime Climate Variability over the North Atlantic and Eurasia

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ABSTRACT

Stratospheric conditions are increasingly being recognized as an important driver of North Atlantic and Eurasian climate variability. Mindful that the observational record is relatively short, and that internal climate variability can be large, the authors here analyze a new 10-member ensemble of integrations of a stratosphere-resolving, atmospheric general circulation model, forced with the observed evolution of sea surface temperature (SST) during 1952–2003. Previous studies are confirmed, showing that El Niño conditions enhance the frequency of occurrence of stratospheric sudden warmings (SSWs), whereas La Niña conditions do not appear to affect it. However, large differences are noted among ensemble members, suggesting caution when interpreting the relatively short observational record. More importantly, it is emphasized that the majority of SSWs are not caused by anomalous tropical Pacific SSTs. Comparing composites of winters with and without SSWs in each ENSO phase separately, it is demonstrated that stratospheric variability gives rise to large and statistically significant anomalies in tropospheric circulation and surface conditions over the North Atlantic and Eurasia. This indicates that, for those regions, climate variability of stratospheric origin is comparable in magnitude to variability originating from tropical Pacific SSTs, so that the occurrence of a single SSW in a given winter is able to completely alter seasonal climate predictions based solely on ENSO conditions. These findings, corroborating other recent studies, highlight the importance of accurately forecasting SSWs for improved seasonal prediction of North Atlantic and Eurasian climate.

## 1. Introduction

El Niño–Southern Oscillation (ENSO) is the largest driver of climate variability on interannual time scales, and its effects are felt in many regions of the world (see, e.g., Trenberth et al. 1998; Alexander et al. 2002). However, its influences on the North Atlantic sector and the Eurasian continent have remained, until recently, somewhat elusive (Brönnimann 2007; Rodríguez-Fonseca et al. 2016). While a few studies have suggested the possible existence of tropospheric ENSO teleconnections reaching into the North Atlantic (Toniazzo and Scaife 2006; Graf and Zanchettin 2012), the notion of a ''stratospheric pathway'' has gained much attention in recent years. What is generally meant by that expression is that the stratosphere acts as a bridge, communicating tropical Pacific Ocean variability to those remote regions, and representing an alternate ENSO teleconnection path, distinct from the canonical Pacific–North America pattern (Horel and Wallace 1981).

It is worth recalling that, on seasonal time scales, the influence of ENSO on the Northern Hemisphere polar stratosphere is now well established. Shifts in tropical

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convective heating during El Niño and La Niña drive poleward-propagating planetary-scale Rossby waves. During El Niño, these anomalous planetary waves tend to constructively align with the climatological background wave pattern and amplify with height into the stratosphere (Fletcher and Kushner 2011; Smith and Kushner 2012; Fletcher and Minokhin 2015). Planetary waves break in the stratosphere (McIntyre and Palmer 1984), and the increased wave breaking during El Niño tends to warm the polar stratosphere and weaken the polar vortex. This has been shown in numerous observational studies (van Loon and Labitzke 1987; Garfinkel and Hartmann 2007; Free and Seidel 2009). Opposite but smaller anomalies are observed during La Niña winters.

Many modeling studies have confirmed these observations (Sassi et al. 2004; García-Herrera et al. 2006; Manzini et al. 2006; Cagnazzo et al. 2009; Calvo and Marsh 2011, just to cite a few). One needs to keep in mind, however, that these ENSO-induced seasonal anomalies—even if well observed and robustly modeled—are largely confined to the stratosphere. It is only when the stratosphere is severely perturbed, notably by the occurrence of a stratospheric sudden warming (SSW) event in midwinter, that stratospheric variability is communicated to the surface.

In winters with one or more SSWs, anomalous surface conditions are seen for several weeks following these extreme events, and the surface signal is strongest over the North Atlantic sector and Eurasia (Baldwin and Dunkerton 2001; Polvani and Waugh 2004; Charlton and Polvani 2007; Hitchcock and Simpson 2014). The importance of SSWs in bridging tropical Pacific anomalies into the North Atlantic and Eurasia was highlighted in a modeling study by Ineson and Scaife (2009), who showed that El Niño conditions lead to anomalous European climate only in winters when SSWs occur. This result has recently been confirmed in studies using different models (Domeisen et al. 2015; Richter et al. 2015).

Beyond modeling studies, some observational evidence for the existence of a stratospheric pathway was presented in Butler et al. (2014, hereafter BPD14). The fundamental limitation of that study, however, resides in the length of the observational record: using the entire period 1958–2013, after partitioning the different ENSO phases by SSW occurrence, several composites consisted of less than 10 events. One key goal of this paper, therefore, is to transcend that limitation.

To that end, we here supplement the observations with a 10-member ensemble of integrations with a stratosphere-resolving atmospheric general circulation model forced by the observed evolution of SSTs during 1952–2003, performed and analyzed by Richter et al. (2015). Rather than focusing on how SSWs alter the El Niño stratospheric pathway as done in Richter et al. (2015), we here focus on separating and contrasting the distinct signatures of ENSO and SSWs. After detailing our methods in the next section, we first consider the effect of ENSO on the frequency of SSWs and discuss the most recent observations in the context of our model ensemble. Then, leaving that effect aside, we demonstrate that the surface signatures of SSWs on North Atlantic and Eurasian winter climate are large, so much so that they clearly stand out irrespective of the ENSO phase. Finally, we attempt to quantify the relative importance of ENSO and SSWs on North Atlantic and Eurasian surface climate and we show that, in fact, they are of comparable magnitude. This implies that, for a given winter, the occurrence of a single SSW can be sufficient to considerably alter a seasonal forecast predicated uniquely on the phase of ENSO. We conclude with a brief summary and a discussion of the current challenges.

## 2. Methods

The model integrations analyzed here were performed with a 46-level version of the Community Atmospheric model, version 5 (denoted 46LCAM5), with an approximate horizontal resolution of 100 km. The model top is located at 0.3 hPa, so that the model is able to capture stratospheric variability, and notably SSWs. Furthermore, the gravity wave schemes are adjusted so as to produce a realistic quasi-biennial oscillation in the lower stratosphere. For further details on the model setup, the reader may consult Richter et al. (2015).

An ensemble of 10 integrations was performed with 46LCAM5, covering the 51-yr period 1952–2003. These integrations were forced with observed monthly sea surface temperatures (SSTs) and sea ice concentrations from Hurrell et al. (2008), in addition to known natural and anthropogenic radiative forcings (greenhouse gases, aerosols, volcanoes, and the solar cycle).

To identify SSWs we follow the simple algorithm of Charlton and Polvani (2007): between November and March, the central date of an event is set as the day when the zonal mean zonal winds at 10 hPa and 60°N become easterly. To avoid double counting events, once a warming is identified an interval of 20 consecutive days with westerly winds must exist before the next central date can be defined (Charlton-Perez and Polvani 2011). Also, simple criteria are applied to avoid so-called ''final'' warmings, when stratospheric winds return to easterlies in the late spring following the seasonal cycle

TABLE 1. The number of observed stratospheric sudden warmings (SSWs), over the period 1958–2013, for the different ENSO phases. The values earlier reported in Butler et al. (2014) are reproduced in the bottom row.

| | Reanalysis | SSTs | All winters | El Niño | La Niña | Neutral |
|---|---|---|---|---|---|---|
| | ERA-40/ERA-I | ERSSTv4 | 38 | 16 | 10 | 12 |
| | NCEP–NCAR | ERSSTv4 | 35 | 16 | 10 | 9 |
| (BPD14) | NCEP–NCAR | ERSSTv3b | 35 | 15 | 13 | 7 |

[for details, see Charlton and Polvani (2007)]. In addition, the results from 46LCAM5 are compared to reanalyses: we make use of both NCEP–NCAR (Kalnay et al. 1996) and ERA-40/ERA-Interim data (Dee et al. 2011).

Finally, to identify the ENSO phases we follow NOAA's Climate Prediction Center (CPC) procedure, as follows: when the time series of 3-month running mean anomalies in SSTs [we use ERSSTv4 (Huang et al. 2015)] over the Niño-3.4 region (5°N–5°S, 170°–120°W) exceeds either +0.5° or −0.5°C for a minimum of five consecutive overlapping 3-month "seasons" (November–January, December–February, etc.) an El Niño or La Niña event is defined. Mindful that ENSO events are often defined using a more stringent criterion (±1 standard deviation of the Niño 3.4 SSTs), we repeated the analysis presented below with this higher threshold, but found no qualitative differences of consequence.

## 3. Revisiting the "stratospheric pathway"

We start by revisiting the observational record, and updating the findings originally reported in Butler and Polvani (2011) and BPD14. Using the identical 1958–2013 period, we list in Table 1 the number of observed SSWs for each ENSO phase. We have computed these numbers using both NCEP–NCAR and ERA-40/ERA-Interim, to ensure that the results are not overly sensitive to the choice of reanalysis. For the sake of completeness, we report the actual dates of individual SSWs in online supplemental Tables S1 and S2, for NCEP–NCAR and ERA-40/ERA-Interim respectively; these can be directly compared with Table 1 of BPD14.

The key result that emerges from Table 1 is that while El Niño appears to considerably enhance the occurrence of SSWs, La Niña does not seem to affect it. This conclusion differs from the one in BPD14, who reported that only 7 of the 35 SSWs in the record occurred during ENSO-neutral winters, with nearly double that number for both El Niño and La Niña. The correction comes from the fact that we have here used the updated ERSSTv4 dataset (Huang et al. 2015). In changing from ERSSTv3b (used in BPD14) to the updated ERSSTv4, three weak La Niña winters with SSWs (1983/84, 2005/06, and 2008/09) were reclassified by the CPC as ENSO-neutral, and one ENSO-neutral winter with an SSW (1979/80) was reclassified as an El Niño.

Having revised the observational evidence, which appears to indicate that La Niña does not alter the frequency of SSWs, we now examine the 10-member ensemble of 51-yr-long model integrations. For each ENSO phase, the "frequency of SSWs" (measured in events per decade) is listed in Table 2 for each member of the ensemble, as well as for the ensemble mean. Using the frequency of SSWs, instead of the absolute count, allows for direct comparison between the model and the observations (which cover periods of different lengths).

The most striking aspect in Table 2 is how large the variability across the ensemble is. For instance, member 4 shows an overall frequency of 4.1 SSWs per decade, while member 6 shows almost 7 SSWs per decade, a more than 60% increase. Or consider this: member 5 shows a robust reduction in SSW frequency in both El Niño and La Niña years compared to ENSO-neutral years, while member 8 shows the opposite effect. One key lesson, therefore, to be gathered from

TABLE 2. Frequency of stratospheric sudden warmings (SSWs), in events per decade, across the different ENSO phases. Each member of the 46LCAM5 ensemble is shown, as well as the ensemble mean (bold font) and standard deviation (italic font). For the reanalyses (bottom rows), we use the period 1958–2013, for comparison with BPD14.

| Member | All winters | El Niño | La Niña | Neutral |
|---|---|---|---|---|
| 1 | 6.5 | 7.4 | 3.3 | 8.2 |
| 2 | 4.7 | 5.8 | 5.3 | 2.9 |
| 3 | 7.5 | 9.0 | 6.0 | 7.1 |
| 4 | 4.1 | 5.3 | 2.7 | 4.1 |
| 5 | 5.7 | 5.8 | 3.3 | 7.7 |
| 6 | 6.7 | 7.9 | 6.7 | 5.3 |
| 7 | 6.3 | 7.4 | 5.3 | 5.9 |
| 8 | 6.3 | 8.4 | 6.0 | 4.1 |
| 9 | 6.3 | 6.8 | 6.0 | 5.9 |
| 10 | 5.3 | 5.8 | 6.0 | 4.1 |
| Ensemble mean | **5.9** | **7.0** | **5.1** | **5.5** |
| Ensemble std. dev. | *1.0* | *1.3* | *1.4* | *1.8* |
| NCEP–NCAR | 6.2 | 8.0 | 6.3 | 4.5 |
| ERA-40/ERA-I | 6.8 | 8.0 | 6.3 | 6.0 |
| BPD14 | 6.3 | 7.9 | 7.2 | 3.7 |

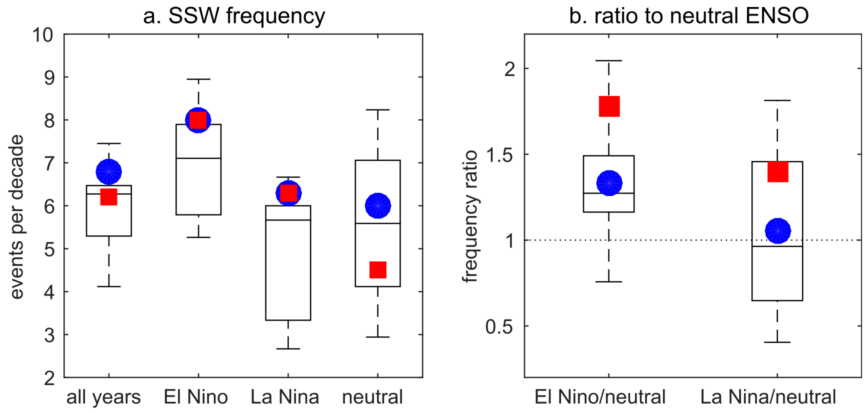


FIG. 1. (a) Frequency of stratospheric sudden warmings (in events per decade) for different ENSO phases. (b) Ratio of SSW frequency, for El Niño and La Niña, to ENSO-neutral frequency. Box plots: median (horizontal line), 25th and 75th percentile (box), and maximum and minimum values (whiskers) for the 10-member CAM5 ensemble. Red and blue markers show NCEP–NCAR and ERA-40/ERA-Interim reanalyses, respectively, for the period 1958–2013.

our ensemble is that the internal variability[1] of the coupled stratosphere–troposphere system is large. This implies that extreme caution is needed when drawing conclusions from the relatively short observational record. Recall that the latter is equivalent to a single member taken from what appears to be a rather broad distribution, assuming our model is faithfully capturing the internal variability of the stratosphere–troposphere system.

Next, we ask how the frequencies of SSWs in our model compare with the ones in the reanalyses. The question here is not whether the ensemble mean "matches" any one set of observations but rather whether the observations (which carry their own uncertainties) fall within the distribution provided by the ensemble of model integrations. As seen from Fig. 1a, the answer is yes: for *all* phases of ENSO the observed frequencies are bracketed by our 10-member ensemble (the numerical values of the observed frequencies are given in the bottom rows of Table 2).

With this validation, and armed with a 10-member ensemble of model integrations, we now revisit the question: does ENSO alter the frequency of SSWs? The answer appears to be yes, but only in one phase. As seen in Fig. 1b, El Niño (but not La Ninã) years are associated with an increased frequency of SSWs compared to ENSO-neutral years, both in our model and in the observations. Note, however, that this increase (1.5 additional SSWs per decade, in the ensemble mean; cf. Table 2) is slightly smaller than the standard deviation across the ensemble in the neutral ENSO phase ($\pm$1.8 SSWs per decade). In our model ensemble, therefore, the enhanced occurrence of SSWs during El Niño is at the border of statistical significance. Statistics notwithstanding, we believe that this effect is robust, as it has been reported in earlier studies. In particular, our 27% increase in SSW frequency during El Niño seen (from 5.5 to 7.0 events per decade) is in excellent agreement with the 30% increase reported in Bell et al. (2009) and the values reported by Garfinkel et al. (2012a), for a handful of models. Increase in SSW frequency during El Niño was originally suggested by Taguchi and Hartmann (2006), but with a nonstandard methodology.

In summary: the weight of the evidence is that, while internal variability may be quite large, La Niña does not appear to affect the frequency of occurrence SSWs whereas El Niño does enhance it, and the current modeling estimate is that roughly 30% more SSWs occur during El Niño than during ENSO-neutral winters. At this point, one is naturally led to ask: is this of practical importance? We believe so, and we attempt to demonstrate this in the next section.

## 4. SSWs: A large source of climate variability over the North Atlantic and Eurasia

Because ENSO is the dominant driver of variability for a great many aspects of the climate system, the majority of previous studies (e.g., García-Herrera et al. 2006; Ineson

[1] The drivers of this large variability remain poorly understood. There is some evidence that the quasi-biennial oscillation may be a player (Garfinkel and Hartmann 2007; Richter et al. 2011; Taguchi 2015). However, studies have suggested possible contributions from the Madden–Julian oscillation (Garfinkel et al. 2012b), the Pacific decadal oscillation (Woo et al. 2015; Kren et al. 2016), and even Arctic sea ice conditions in early winter (Kim et al. 2014).

and Scaife 2009; Bell et al. 2009; Domeisen et al. 2015, and several others) have focused on investigating how SSWs might enhance the impacts of ENSO, notably by providing an alternative pathway for climate variability actually originating in the tropical Pacific to reach into the North Atlantic and all the way into Eurasia via the stratosphere. It is entirely consistent with observations, however, to look at things from a different perspective, realizing that SSWs are—to a very large extent—an *independent* source of climate variability.

Consider the following simple question: what fraction of SSWs are actually ''caused'' by ENSO? Let us attempt to estimate this number using the results of the previous section. For simplicity, let us assume that the three phases of ENSO occur with approximately similar frequency (which is roughly the case for the 1958–2013 period; see Tables S1 and S2). Then let us assume that La Niña does not affect the frequency of SSWs, whereas El Niño increases it by 30%. Now, let $n$ be the number of SSWs in the ENSO-neutral phase; the number of SSWs during La Niña is then also $n$, while the number for El Niño is $1.3n$. The total number of SSWs is thus $3.3n$ (the sum of the three phases): of these, however, only $0.3n$ are due to ENSO. The point here is that a whopping 91% of SSWs ($3 \div 3.3$) in our model are not directly attributable to ENSO.

Of course such an estimate is very crude and rests on several assumptions. Nonetheless, the qualitative conclusion is clearly robust: the majority of SSWs occur irrespective of ENSO. Even if El Niño were able to double the frequency of SSWs, still 75% of them would occur irrespective of ENSO (using the same method as above). This is an important point, and it argues that the surface impacts of these events needs to be evaluated and understood in their own right. Hence, the goal of this section: to demonstrate that North Atlantic and Eurasian climate variability associated with SSWs is actually very large and, in fact, able to overwhelm the ENSO signal over those regions.

To evaluate the impact of SSWs, we need to disentangle it from the impact of ENSO. But this is easily accomplished: we just contrast winters with and without SSWs for each phase of ENSO *separately*. We start by examining ENSO-neutral winters, as this extracts the purest signal of SSWs, uncontaminated by any tropical Pacific SST anomalies (although we note that, owing to the seasonal averaging, some variability from sources other than SSWs may be aliased in).

Using our 10-member ensemble, in Fig. 2 we show composites of 500-hPa geopotential (Z500, top row), surface temperature ($T_s$, middle row) and precipitation ($P$, bottom row) anomalies, during the extended winter months [November–March (NDJFM)] for years in the model with a neutral ENSO phase. Compositing all such winters (Fig. 2a) is not very informative as the cancellation between strong and weak stratospheric polar vortices, in addition to the absence of ENSO anomalies, leaves little of statistical significance. The interesting results are seen in the composite of ENSO-neutral winters with one or more SSWs (Fig. 2b), where three notable features stand out:

1) A clear dipole in Z500 over the North Atlantic, typical of the negative phase of the North Atlantic Oscillation (NAO) or the northern annular mode (NAM).
2) Higher temperatures over Greenland, southern Europe, North Africa, and southern Eurasia, accompanied by cold anomalies over northern Europe and, especially, over Siberia.
3) A clear dipole in precipitation over the North Atlantic (see the highlighted red sector) bringing increased precipitation over southern Europe and drier conditions over northern Europe.

These features are easily understood to result from the anomalous dipolar tropospheric circulation over the North Atlantic, which is well known to be a consequence of the severely perturbed stratospheric circulation during SSWs (Baldwin and Dunkerton 2001; Polvani and Waugh 2004).

In ENSO-neutral winters without SSWs opposite-signed features, but of weaker amplitude, can be seen (Fig. 2c). While many of those winters exhibit an anomalously strong polar vortex, the tropospheric impacts accompanying such a vortex are smaller than those of SSWs [as recently noted by Scaife et al. (2016)]. Furthermore, those impacts are here partially obscured by naively compositing all winters without SSWs, whether the polar vortex is strong[2] or not. Be that as it may, the strong signal of SSWs is clearly amplified by subtracting the winters without SSWs (Fig. 2d), and the features listed above become larger and more significant in the difference plots.

We next demonstrate that those same features are found even during nonneutral ENSO winters, again exploiting the large number of events present in our 10-member

[2] We have, in fact, separately composited winters with a strong polar vortex, but found only slightly larger anomalies than those in Fig. 2c. This is not surprising since, obviously, the vortex becomes anomalously strong in most winters without SSWs. Such compositing, however, requires choosing a threshold for the vortex strength, which is unavoidably arbitrary. To eschew arbitrary choices and unnecessary complexity, therefore, we have decided to retain the simpler binary procedure (with or without SSWs), which emphasizes the key role of SSWs.

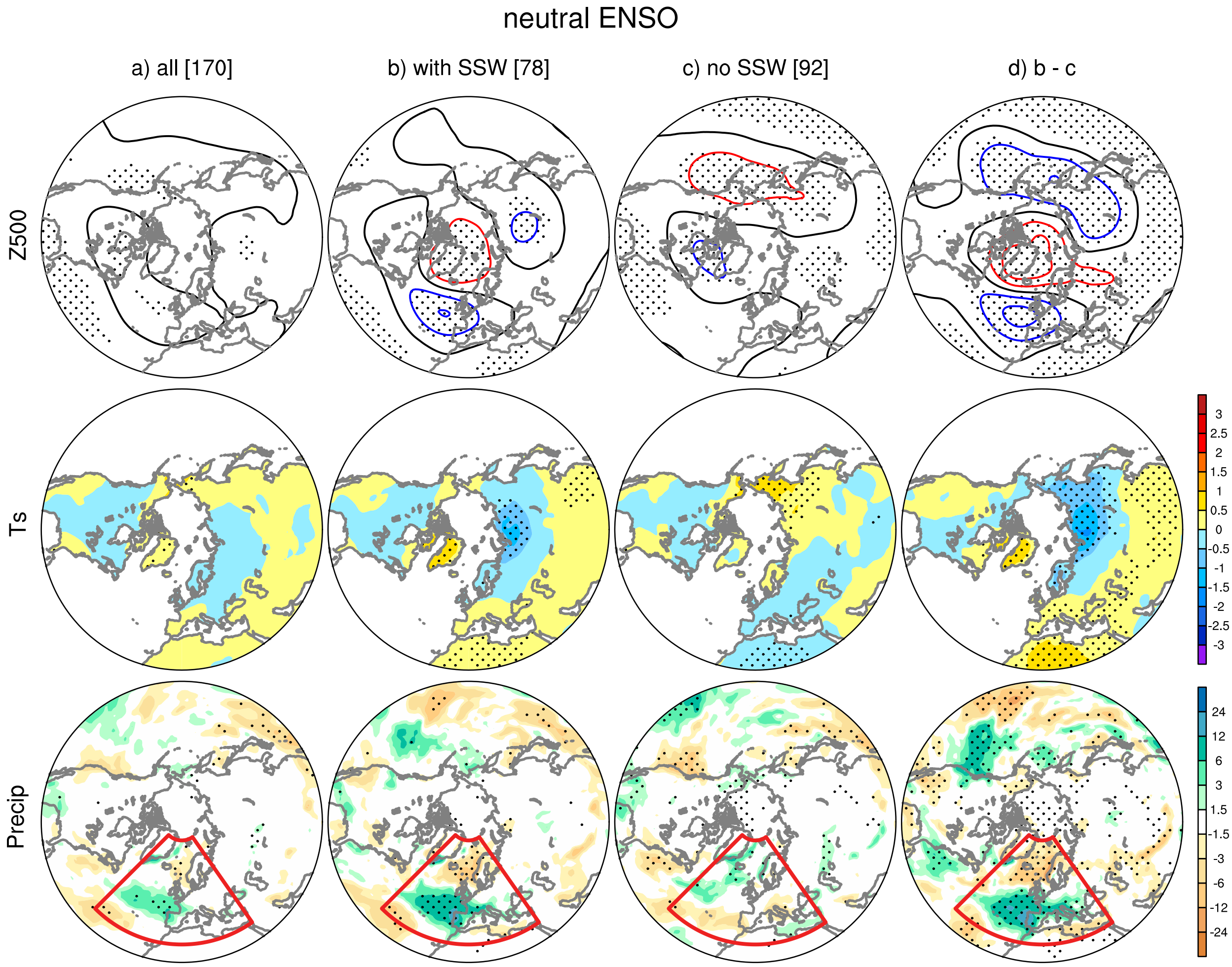


FIG. 2. Composite NDJFM anomalies for ENSO-neutral years in the 46LCAM5 ensemble. (a) All ENSO-neutral winters, (b) ENSO-neutral winters with SSWs, (c) ENSO-neutral winters without SSWs, and (d) the difference between (b) and (c). (top) 500-hPa geopotential height (contour interval 10 m). (middle) 1000-hPa temperature (in K). (bottom) Precipitation (in mm month$^{-1}$). Anomalies are computed with respect to the entire period of model integration (1952–2003). Stippling indicates statistical significance at the 95% level, based on a two-sided *t* test. The red box delimits the area with the clearest SSW influence on North Atlantic and European precipitation. The brackets at the top of each column indicate the number of composited winters.

ensemble. Let us consider El Niño first. Over the Pacific and the North American continent (Fig. 3a) El Niño is the dominant winter climate driver and the expected anomaly patterns are clearly reproduced in our model: one sees the familiar Pacific–North American (PNA) teleconnection in Z500, warmer anomalies in Canada, and cold anomalies with increased precipitation over the lower United States. Note that these features are also present in Figs. 3b and 3c (i.e., whether SSWs occur or not) since SSWs have a relatively small impact over the Pacific and North America.

In stark contrast, over the North Atlantic and Eurasia the wintertime anomalies change sign depending on the occurrence of SSWs. Compare Figs. 3b and 3c over those regions, and note how the NAO, surface temperatures over Europe, North Africa and Asia, and precipitation in the highlighted sector show statistically significant *but opposite-signed* anomalies. The large impact of SSWs is even clearer in the difference plots (Fig. 3d). More importantly, these impacts are nearly identical to those in Fig. 2d for the ENSO-neutral winters. This suggests that the phase of ENSO may not be the primary driver of climate variability of those regions.

This key finding is confirmed in Fig. 4, where we show similar composites during La Niña winters. First, compare Figs. 4a and 3a and note how the anomalies flip sign over the Pacific and North America: this confirms the well-known fact that ENSO is the dominant driver of climate variability in those regions. Next, contrast Figs. 4d and 3d and see how the anomalies do *not* flip sign over the North Atlantic and Eurasia. This

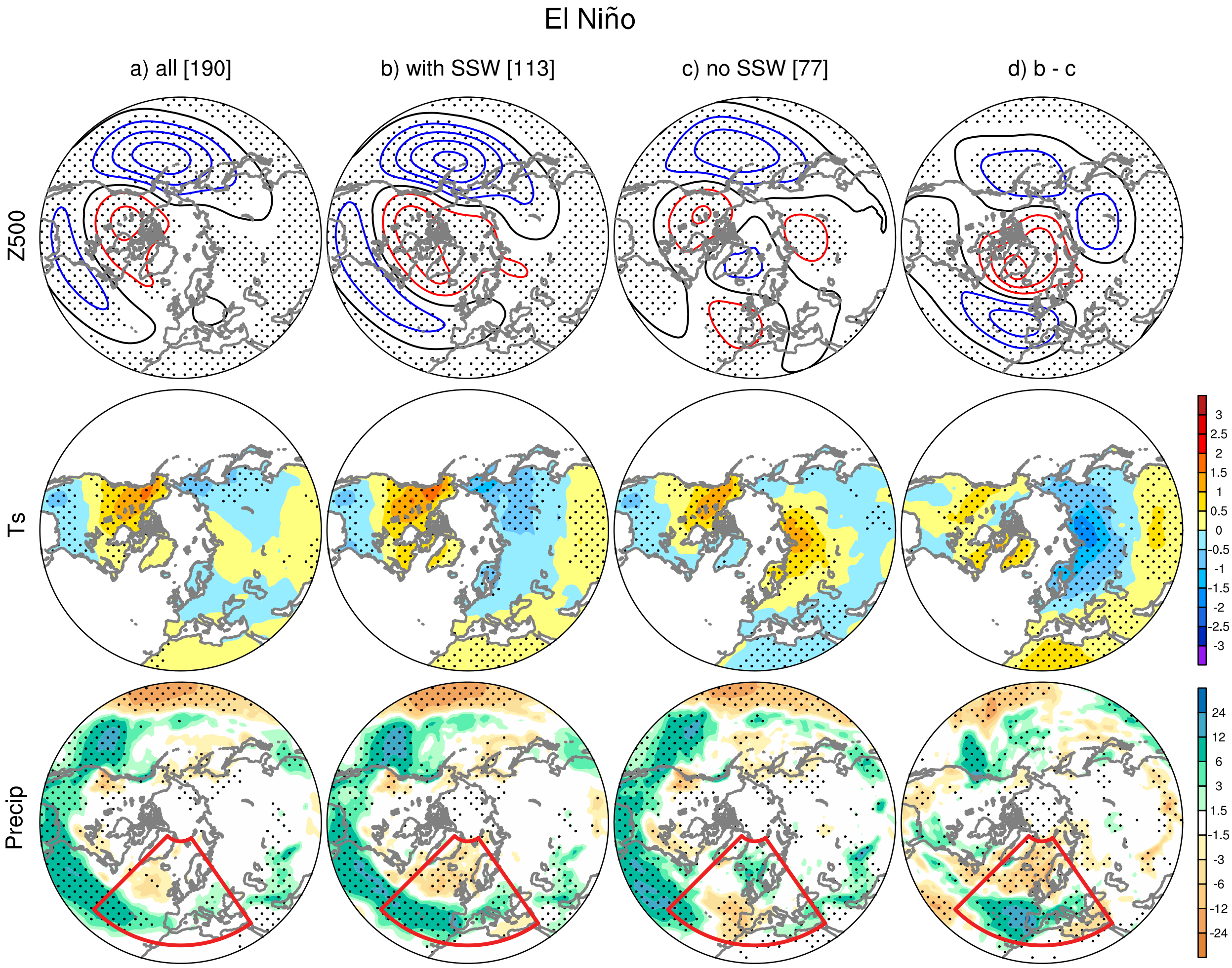


FIG. 3. As in Fig. 2, but for El Niño winters.

confirms that SSWs are a major driver of climate variability over the North Atlantic and Eurasia, so much so that their impact is the same irrespective of the ENSO phase.

That said, we hasten to emphasize that the phase of ENSO is also surely important for the NAO and for Mediterranean precipitation, although perhaps less so for East Asian temperature. Compare the Z500 fields in Figs. 3b and 4b: in the first we see a strong negative NAO pattern, but in the latter we see no anomalies at all. So, obviously, the ENSO phase matters as well. The way to understand these differences, is that in Fig. 3 El Niño adds to the SSW-induced anomalies (hence the large negative signal), whereas in Fig. 4 La Niña cancels those anomalies. The same addition/cancellation is clearly seen in the bottom row for Mediterranean precipitation anomalies.

Of course it is not surprising that ENSO would be a large driver of variability: what we wish to emphasize here, however, is that the impacts of SSWs are of a comparable magnitude as those of ENSO. Just to be clear, compare Figs. 4b and 4c, and see how the La Niña–induced positive NAO (Fig. 4c, top), the Eurasian warming (Fig. 4c, middle), and the precipitation anomalies (Fig. 4c, bottom) basically disappear when SSWs are present (Fig. 4b). This is telling us that, in a given winter, the occurrence of a SSW may be able to cancel out any ENSO-induced anomalies.

To conclude then, we feel compelled to ask: can one quantify how large is the climate variability associated with SSWs compared to the variability associated with ENSO, over the North Atlantic and Eurasia? The precise answer is difficult to compute, and we acknowledge that the question is slightly ill posed, given that ENSO does in fact increase the frequency of SSWs somewhat. Nonetheless, as we have explained above, that increase is not huge, so that the great majority of SSWs are clearly not related to ENSO: thus ENSO and SSWs can be thought of as largely independent sources of variability, at least for a first stab at the answer, which is given by the quantities shown in Table 3.

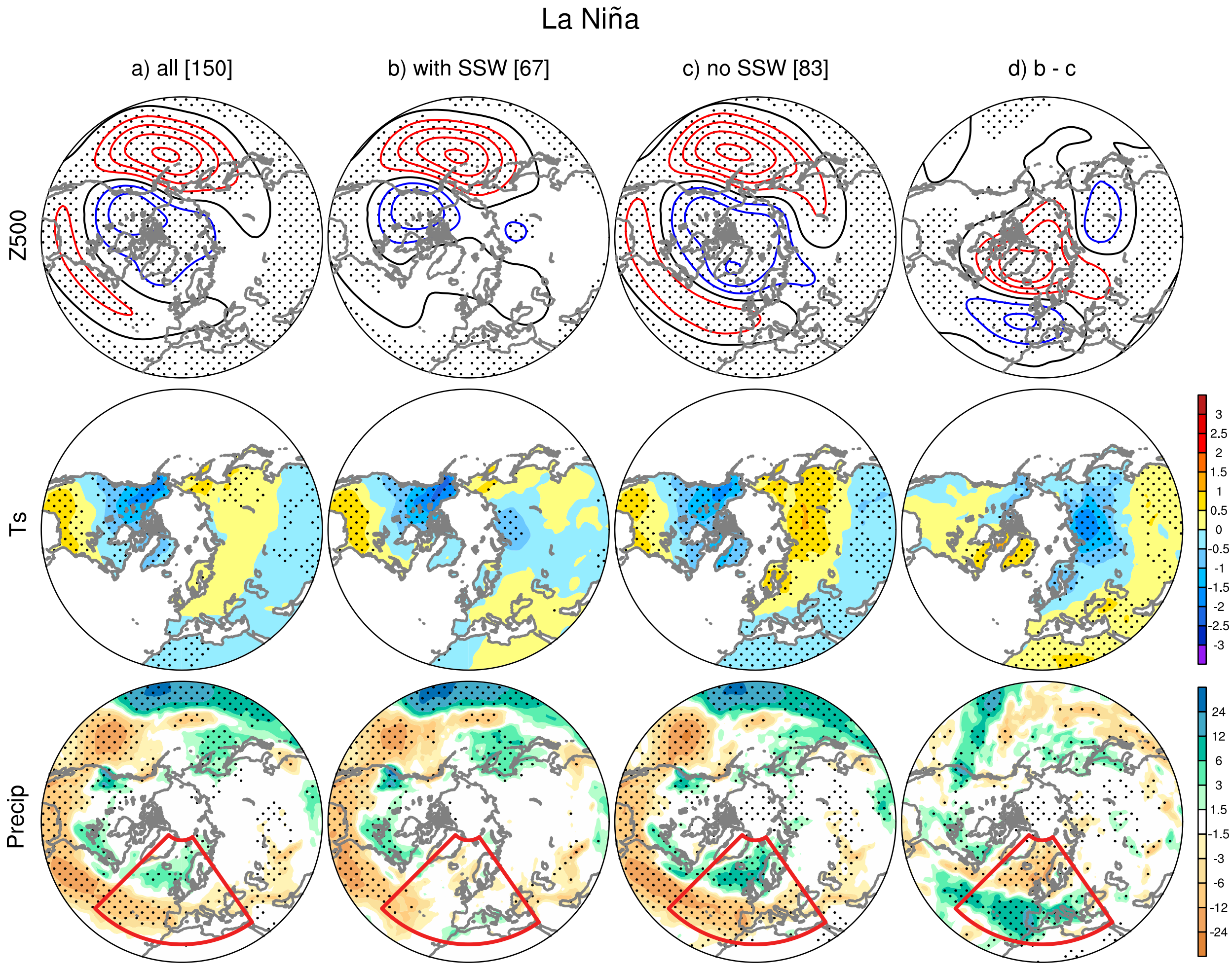


FIG. 4. As in Fig. 2, but for La Niña winters.

From the model output of our 10-member ensemble, we list in Table 3 the (top) standardized NAO index in JFM, and (middle) the Eurasian surface temperature and (bottom) precipitation anomalies in NDJFM for all phases of ENSO and all stratospheric conditions. Using the NCEP–NCAR reanalysis, identical quantities were reported in Table 3 of BPD14 (except for Mediterranean precipitation, which we have added here). To answer the question above, we suggest comparing, for each of the three quantities in Table 3 herein, the difference between the two bold entries in the first numerical column of that table (El Niño minus La Niña winters, averaged over all stratospheric conditions) with the differences between the two bold entries in the top row of each panel (winters with SSWs minus winters without SSWs, averaged over all ENSO phases). We realize this is terribly crude: nonetheless, the point of the exercise is simply to note that the differences between winters with and without SSWs are larger than the differences between El Niño and La Niña winter. In other words, stratosphere-induced anomalies over the North Atlantic and Eurasia (on average) appear to be larger than ENSO-induced anomalies (on average). This is especially true for Eurasian surface temperatures, where the effect of SSWs appears to be more than an order of magnitude larger than the effect of ENSO. Of course, since some fraction of SSWs (say, about 10%, if we are to believe our model) are associated with ENSO, the variability associated with ENSO over those regions is possibly a little larger than our crude estimate. Nonetheless, the key point remains: the polar stratosphere provides a large source of variability, whose amplitude is comparable to that associated with ENSO over large regions of the Northern Hemisphere.

## 5. Summary and discussion

Confirming a number of recent studies, the results presented here offer new, compelling modeling evidence

TABLE 3. North Atlantic and Eurasian climate variability indices associated with ENSO and SSWs, computed from our 10-member ensemble of 46LCAM5 integrations. (top) January–March North Atlantic Oscillation (NAO) index from NCEP/CPC, standardized using the January–March mean and standard deviation. (middle) Mean NDJFM surface temperature anomaly (K) for northern Eurasia (60°–75°N and 30°–120°E). (bottom) NDJFM mean Mediterranean (35°–45°N, 10°–25°E) mean precipitation rate anomaly (mm month$^{-1}$). For each of these three quantities, we report the values for different ENSO phases in separate rows and for different stratospheric winter conditions in separate columns, as indicated by the labels. See text for explanation of bold font.

| | All winters | Winters w/ SSW | Winters w/o SSW |
|---|---|---|---|
| | | JFM NAO index (standardized) | |
| All winters | 0.00 | **−0.22** | **+0.23** |
| El Niño | **-0.15** | −0.35 | +0.10 |
| La Niña | **+0.20** | −0.05 | +0.40 |
| Neutral | +0.01 | −0.19 | +0.18 |
| | | NDJFM Eurasian surface temperature (K) | |
| All winters | 0.00 | **−0.58** | **+0.59** |
| El Niño | **+0.09** | −0.47 | +0.91 |
| La Niña | **+0.14** | −0.53 | +0.69 |
| Neutral | −0.22 | −0.78 | +0.24 |
| | | NDJFM Mediterranean precipitation (mm month$^{-1}$) | |
| All winters | 0.00 | **+3.55** | **−3.63** |
| El Niño | **+1.90** | +5.10 | −2.80 |
| La Niña | **−3.58** | +0.13 | −6.57 |
| Neutral | +1.02 | +4.22 | −1.69 |

of the crucial role of the stratosphere in driving surface climate variability over the North Atlantic and Eurasia. One might ask, at this point, whether observational evidence can also be adduced to further strengthen these results. In many ways, the BPD14 study already provides much of the present observational evidence and, in fact, motivated the present modeling study. Nonetheless, since the compositing in BPD14 was done in a different way (meant to emphasize the notion of a stratospheric pathway), for the sake of completeness we have produced the NCEP–NCAR version of Figs. 3 and 4 (see supplementary Figs. S1 and S2, for El Niño and La Niña, respectively). It is important to stress how small the number of events in each of the observational composites is (with less than 10 winters, in most cases). That said, these supplementary figures offer some measure of confirmation of the modeling results.

Beyond the observational evidence, it is useful to put our results in the context of other studies with different models, several of which also emphasized the importance of SSWs for surface climate variability. Notably Sigmond et al. (2013) performed retrospective ensemble forecasts with the Canadian Middle Atmosphere Model (CMAM), and demonstrated enhanced seasonal skills only when the forecasts were initialized near the onset dates of SSWs. Similarly, Domeisen et al. (2015) carried out a predictability study of El Niño over Europe with the Max Plank Institute Earth System Model (ECHAM6) and showed increased predictability of the circulation up to 4 months ahead but only for those El Niño winters that were accompanied by SSWs. And, last, Scaife et al. (2016) used the UK Met Office Global Seasonal forecast system (GloSea5) to compute hindcasts of the NAO, and concluded that their seasonal NAO forecast skills actually *vanish* when members with SSWs are excluded from the ensemble.

Finally, although we have here focused on highlighting SSWs as an independent source of climate variability, we conclude by revisiting the fact that El Niño does in fact enhance the occurrence of SSWs. Our modeling results closely agree with the previous study of Bell et al. (2009) and suggest a 30% increase in the occurrence of SSW during El Niño, with no significant impact during La Niña. As for the observations: averaging the numbers obtained from NCEP–NCAR and ERA-40/ERA-Interim using the updated ERSSTv4 products (bottom panel of Table 2), we see roughly 50% greater frequency of SSW occurrence during El Niño than during ENSO-neutral winters.

While, in a climatological sense, this increase in SSW frequency with El Niño still leaves the majority of SSWs unrelated to ENSO, we suggest such an increase is nonetheless of considerable practical importance. The reason for this is that individual SSWs are essentially not predictable more than a couple of weeks ahead, in the most propitious circumstances (Tripathi et al. 2015, 2016). However, when an El Niño event is underway one can make a seasonal forecast (in the late summer or fall) of an increased probability of SSWs occurring the following winter. Since, as we have demonstrated above, the occurrence of SSWs in a given winter is able to overwhelm surface climate over the North Atlantic and Eurasia, early awareness of an increased likelihood of

SSWs would translate into an improved seasonal climate forecast for those regions.

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