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Separating and quantifying the distinct impacts of El Niño and sudden stratospheric warmings on North Atlantic and Eurasian wintertime climate

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Abstract

Sudden stratospheric warmings (SSWs) significantly influence Eurasian wintertime climate. The El Niño phase of the El Niño–Southern Oscillation (ENSO) also affects climate in that region through tropospheric and stratospheric pathways, including increased SSW frequency. However, most SSWs are unrelated to El Niño, and their importance compared to other El Niño pathways remains to be quantified. We here contrast these two sources of variability using two 200-member ensembles of 1-year integrations of the Whole Atmosphere Community Climate Model, one ensemble with prescribed El Niño sea surface temperatures (SSTs) and one with neutral-ENSO SSTs. We form composites of wintertime climate anomalies, with and without SSWs, in each ensemble and contrast them to a basic state represented by neutral-ENSO winters without SSWs. We find that El Niño and SSWs both result in negative North Atlantic Oscillation anomalies and have comparable impacts on European precipitation, but SSWs cause larger Eurasian cooling. Our results have implications for predictability of wintertime Eurasian climate.

KEYWORDS

climate variability, ENSO, North Atlantic Oscillation, stratosphere–troposphere coupling, sudden stratospheric warming

1 | INTRODUCTION

The El Niño–Southern Oscillation (ENSO) and the occurrence of sudden stratospheric warmings (SSWs) have both been studied as important drivers of North Atlantic and Eurasian wintertime climate variability. On the one hand, the state of the stratospheric polar vortex, particularly an extreme weak vortex during SSWs, has been shown to influence the troposphere with a strong effect on the Northern Annular Mode (Baldwin and Dunkerton, 2001; Polvani and Waugh, 2004; Charlton and Polvani, 2007; Hitchcock and Simpson, 2014). On the other hand, ENSO is the major driver of inter-annual climate variability and influences atmospheric circulation in many parts of the world, including the North Atlantic region (Horel and Wallace, 1981; Trenberth *et al*., 1998; Alexander *et al*., 2002; Brönnimann, 2007; Rodríguez-Fonseca *et al*., 2016; Domeisen *et al*., 2019). The winter surface climate signature of El Niño over the North Atlantic resembles the negative phase of the Northern Annular Mode, similar to the effect of SSWs (Brönnimann, 2007; Butler *et al*., 2014; Calvo *et al*., 2017; Polvani *et al*., 2017).

However, these two sources of variability are not independent. SSWs are more common in the El Niño phase of ENSO than in the neutral phase, in both observations and stratosphere-resolving models, by a factor of about 30% (Bell *et al*., 2009; Butler and Polvani, 2011; Garfinkel *et al*., 2012; Polvani *et al*., 2017). This suggests an SSW pathway of El Niño influence on the North Atlantic and Eurasia, which has now been well-established by both observational (Garfinkel and Hartmann, 2007; Butler *et al*., 2014) and modeling studies (Bell *et al*., 2009; Cagnazzo and Manzini, 2009; Ineson and Scaife, 2009; Richter *et al*., 2015).

The effects of El Niño on Eurasia in the absence of SSWs have been less clear. Observational composites of El Niño winters without SSWs show a negative NAO index compared to neutral-ENSO winters without SSWs, but this effect is weak compared to that of SSWs (Butler *et al*., 2014). Seasonal prediction model studies such as Domeisen *et al*. (2015) and Scaife *et al*. (2016) showed considerably decreased predictability in the North Atlantic and Europe for El Niño winters without SSWs compared to those winters with SSWs. Other studies based on climate models (Ineson and Scaife, 2009; Richter *et al*., 2015) reported a negative NAO in a composite of El Niño winters with SSWs but a muted or different response in El Niño winters without SSWs. Also, observational (Toniazzo and Scaife, 2006; García-Serrano *et al*., 2011) and climate model studies (Hardiman *et al*., 2019) suggested a wave-like tropospheric response to El Niño in the North Atlantic, different from the NAO response to SSWs. However, Bell *et al*. (2009) found that in simulations with a degraded representation of the stratosphere, the negative NAO pattern in El Niño winters weakened but remained present. Li and Lau (2012) observed small negative shifts in the NAO with El Niño despite low vertical resolution in the model stratosphere and the resulting lack of a weak vortex signal. They attributed this effect to high-frequency transient eddies. Jiménez-Esteve and Domeisen (2018) also found a transient eddy-driven tropospheric pathway of El Niño that contributed to a negative NAO during mid-to-late winter in reanalysis.

To bring some clarity on both the importance of SSWs and the signal of El Niño on the North Atlantic, we here build on the work of Polvani *et al*. (2017). In that paper, the distinct impacts of ENSO and SSWs on North Atlantic and Eurasian wintertime climate were analyzed using an ensemble of 10 transient integrations in a high-top version of the Community Atmosphere Model, version 5, over the period 1951–2003. They formed November–March composites of winters with and without SSWs in each ENSO phase. For key surface climate features, they found that the difference in winters with and without SSWs across all ENSO phases was greater than the difference between El Niño and La Niña winters across all stratospheric states. This supports the key role of SSWs in determining Eurasian wintertime climate independent of ENSO phase.

The aim of our work is to further clarify the respective effects of SSWs and El Niño on wintertime climate in the North Atlantic and Eurasia by carefully identifying and quantifying their separate impacts. To that end, we use two ensembles of 200 1-year model integrations, one forced with El Niño sea surface temperatures (SSTs) and the other with neutral-ENSO SSTs. We compare the effects of El Niño and SSWs to a basic state represented by neutral-ENSO winters without SSWs. This isolates the distinct effects of each phenomenon more cleanly than in previous studies, and the ensemble size allows us to better capture the signals of both El Niño and SSWs.

Our methodology is described in detail in section 2. We then present the effects of SSWs and the tropospheric pathway of El Niño on the NAO and Northern Hemispheric surface climate in our simulation in section 3. We find that the two sources of variability independently result in negative NAO anomalies and comparable effects on precipitation, while SSWs contribute much more strongly to Eurasian cooling. We conclude in section 4 with a discussion of implications of the results.

2 | METHODS

The model integrations analyzed here are performed using the Community Earth System Model version 1 (CESM1) Whole Atmosphere Community Climate Model (WACCM; Marsh *et al*., 2013). The horizontal resolution of WACCM is 1.9° latitude by 2.6° longitude, and the model has 66 vertical levels with the model top at 5.1×10^{-6} hPa. Notably, WACCM accurately captures the frequency, seasonality and dynamical features of SSWs (de la Torre *et al*., 2012).

We perform two 200-member ensembles of 1-year integrations initialized on June 1. June 1 is chosen in order to simulate a realistic onset and full seasonal cycle of the stratospheric polar vortex, the growth and decay phases of El Niño warm anomalies in the tropical Pacific, and the atmospheric response to these El Niño conditions. Each ensemble of 200 atmospheric initial conditions for the integrations is generated using small air temperature perturbations, as in Kay *et al*. (2015). One ensemble is forced with monthly sea surface temperatures and sea ice corresponding to years with neutral-ENSO winters, and the other is forced with SSTs corresponding to years with El Niño winters. All members of each ensemble are forced with identical SSTs. SSTs for neutral-ENSO integrations are constructed using the observed 1950–2014 climatology from ERSSTv5 (Huang *et al*., 2017). SSTs for the El Niño integrations are constructed by averaging over years in the record with warm ENSO events, defined here as the 11 winters with

Oceanic Niño indices (SST anomalies in the Niño3.4 region, 5°S–5°N and 170°–120°W) above 1.0 K for three consecutive fall or winter 3-month "seasons" (September–November, October–December, etc.). This is the NOAA Climate Prediction Center (CPC) procedure but with a higher threshold for an El Niño event, resulting in an average Niño3.4 SST anomaly of 1.4 K over the November–March period (compared to a 1.0 K average anomaly over that period if a 0.5 K threshold is used). We use this higher threshold to focus on moderate-to-strong, realistic El Niño forcing.

We identify SSWs using the definition of Charlton and Polvani (2007; 2011). An event is considered to be an SSW if the zonal mean zonal winds at 60°N and 10 hPa become easterly in extended boreal winter (NDJFM). The first day on which these winds are easterly is designated as the "central date," and no other day is considered a separate SSW event until the winds have again been westerly for at least 20 consecutive days. This definition is among the optimal thresholds for identifying SSWs as described in Butler and Gerber (2018).

To study the separate effects of El Niño and SSWs, we composite years with and without SSWs in both ensembles, and we compute anomalies with respect to neutral-ENSO years without SSWs. For composites of winters with SSWs, we take 60-day periods beginning with the central date of the first SSW of each included year, following Baldwin and Dunkerton (2001). For the composites of El Niño winters without SSWs, we select the same 60-day periods as in the neutral-ENSO with SSW composite, taking each 60-day period from a randomly chosen El Niño without SSW run. We ensure that no single day appears in the composite twice. Results using 60-day periods drawn from the El Niño with SSW composite are similar because the seasonal distributions of SSWs under neutral-ENSO and El Niño conditions are not different. In the case of neutral-ENSO without SSW, we repeat this composite-building process 500 times and take anomalies of other phases with respect to the mean of the neutral-ENSO without SSW composite distribution. We use this distribution for Monte Carlo tests of statistical significance.

We calculate the North Atlantic Oscillation (NAO) index for all integrations with the principal component based method of Hurrell (1995). We find the principal components for the leading empirical orthogonal function of sea level pressure over the region 20°–80°N and 90°W–40°E. The NAO index time series for each ensemble member is calculated by normalizing the principal component time series using the mean and standard deviation of the neutral-ENSO without SSW members.

3 | RESULTS

Our main interest is in El Niño and SSWs as separate sources of variability. However, because El Niño increases the frequency of SSWs, we begin by analyzing the SSW frequency in our model. For both neutral-ENSO and El Niño conditions, we list in Table 1 the number of SSWs occurring in the 200 1-year integrations, the number of winters with SSWs, the SSW frequency and the number of winters with multiple SSWs.

The SSW frequency (in events per decade) in the El Niño phase is 8.7, higher than the observed frequency of 8.0 found in NCEP-NCAR and ERA-40/ERA-I reanalyses of 1958–2013 (Polvani *et al*., 2017). The frequency in the neutral phase is 4.3 SSWs per decade. The corresponding observed frequencies reported in Polvani *et al*. (2017) are 4.5 and 6.0 for NCEP-NCAR and ERA-40/ERA-I reanalyses, respectively, so the modeled neutral-ENSO SSW frequency is near that observed. Here, the ratio of the two frequencies is 2.0, higher than the typically reported value of 1.3 (Bell *et al*., 2009; Garfinkel *et al*., 2012; Polvani *et al*., 2017). The higher relative frequency of SSWs in the El Niño phase in our model is likely due to the high threshold used here to identify El Niño events. This results in stronger El Niño forcing in our model integrations, potentially deepening the North Pacific low (Garfinkel *et al*., 2018) and increasing wave disturbance of the stratospheric polar vortex and SSW frequency (Garfinkel *et al*., 2010).

We now turn to the quantification of the distinct effects of SSWs and El Niño on North Atlantic and Eurasian surface climate. Because the NAO serves as an important indicator of seasonal weather in the region (Loon and Rogers, 1978; Barnston and Livezey, 1987; Hurrell, 1995), we first consider the impact of the two phenomena on the NAO itself. We compute anomalies from the neutral-ENSO without SSW mean of the January–March NAO index, choosing January–March because this period best captures the wintertime surface influence of SSWs. Figure 1 shows distributions of JFM NAO indices for each state. All three distributions from SSW or El Niño conditions are

TABLE 1 Summary of SSW events in El Niño and neutral-ENSO phases

	EN	Neutral
Total winters	200	200
SSW events	174	85
SSW frequency/decade	8.7	4.3
Winters with SSWs	140	72
Winters with two SSWs	30	11
Winters with three SSWs	2	1

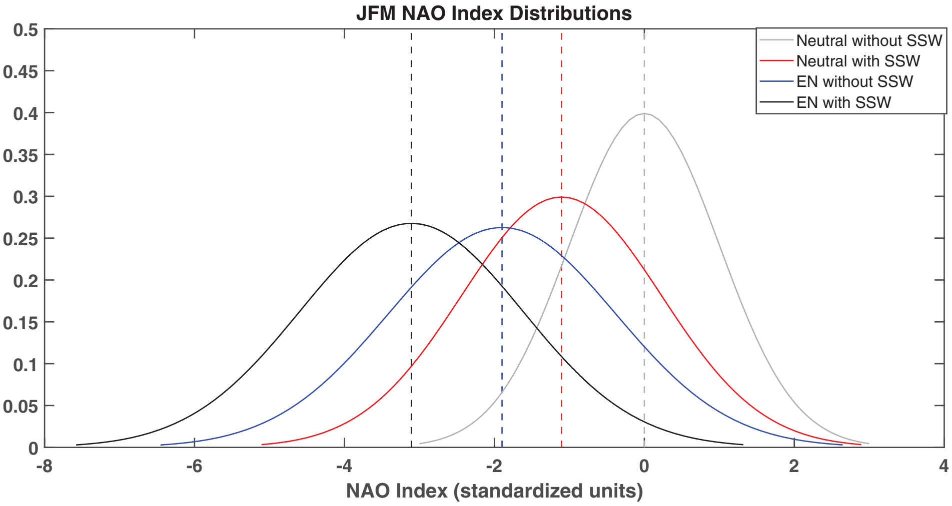

FIGURE 1 Fitted Gaussians of January–March NAO indices for each state normalized with respect to the neutral-ENSO without SSW base state. Vertical lines indicate distribution means

statistically different ($p < .01$) from the neutral-ENSO without SSW distribution according to a Kolmogorov–Smirnov test. The mean of the neutral-ENSO with SSW distribution is −1.10, and the mean of the El Niño without SSW distribution is −1.90, so the two sources of variability independently result in negative shifts of the NAO relative to the neutral-ENSO without SSW case. Using observations, Butler *et al.* (2014) finds negative shifts of the NAO due to El Niño, but the anomaly is about 40% of that due to SSWs. The strong El Niño forcing in our simulations likely contributes to the large response to El Niño here. The occurrence of both El Niño conditions and an SSW yields the most negative NAO values, with a distribution mean of −3.11. Hence, El Niño and SSWs are linearly additive in their effects on the NAO.

To examine the Northern Hemispheric impacts of SSWs and El Niño in more detail, we next plot composites of a few key climate anomalies for each state. Figure 2 shows 500 hPa geopotential height, temperature and precipitation anomaly composites for neutral-ENSO winters with SSWs, El Niño winters without SSWs, El Niño winters with SSWs and finally the difference between the latter two. Because all anomalies are taken with respect to neutral-ENSO winters without SSWs, Figure 2a,b cleanly isolates the effects of SSWs and El Niño. We calculate statistical significance by a Monte Carlo test, considering the value at a point to be significant if the magnitude of the anomaly is equal to at least two standard deviations of the neutral-ENSO without SSW distribution. Spatial patterns for extended winter anomaly composites (November–March, not shown) are similar but of lower magnitude.

We first consider the effects of SSWs in neutral-ENSO winters, shown in Figure 2a. There is a dipole in Z500 over the North Atlantic and western Europe, corresponding to a negative phase of the NAO or Northern Annular Mode. We also see cold anomalies of 2–3 K over much of Northern Eurasia, particularly Siberia. Finally, there is a precipitation dipole over the North Atlantic and Europe, with dry anomalies in Northern Europe and wet conditions in southern Europe. These features are in good agreement with previous model and observational studies of SSWs (Baldwin and Dunkerton, 2001; Charlton and Polvani, 2007; Butler *et al.*, 2014; Hitchcock and Simpson, 2014; Polvani *et al.*, 2017).

We next turn to the impacts of El Niño alone (i.e., for winters without SSWs) shown in Figure 2b. We first note the large anomalies over the Pacific in the Z500 field and the well-known temperature dipole over North America. These are associated with the Pacific/North America (PNA) teleconnection pattern typical of El Niño conditions (Horel and Wallace, 1981). We see a Z500 dipole over the North Atlantic of similar strength as in the neutral-ENSO with SSW case. This state also shows cooling across northern Eurasia, but it is weaker than in the neutral-ENSO with SSW case and is less concentrated in Siberia. A temperature anomaly average over Eurasia as shown in Table 2 allows us to more precisely quantify this difference. The temperature anomaly due to El Niño alone is a quarter of that due to SSWs alone. A similar precipitation dipole is seen to that in Figure 2a, but the increased precipitation, as with the Z500 low anomaly, extends across the Atlantic and impacts the Southern United States. The magnitudes of the anomaly over Europe are similar to those in the neutral-ENSO with SSW composite. These comparable values for precipitation in the Mediterranean region are reported in Table 2. The North Atlantic and Eurasian features are similar to the tropospheric pathway signals in Cagnazzo and Manzini (2009), Bell *et al.* (2009) and Li and Lau (2012) but are greater in magnitude than in these studies, likely due to the large El Niño forcing used here. Geng *et al.* (2017) found cooling consistent with the temperature anomalies here in East Asia and northern Europe during strong El Niños without downward-propagating geopotential height anomalies from the stratosphere in the observations.

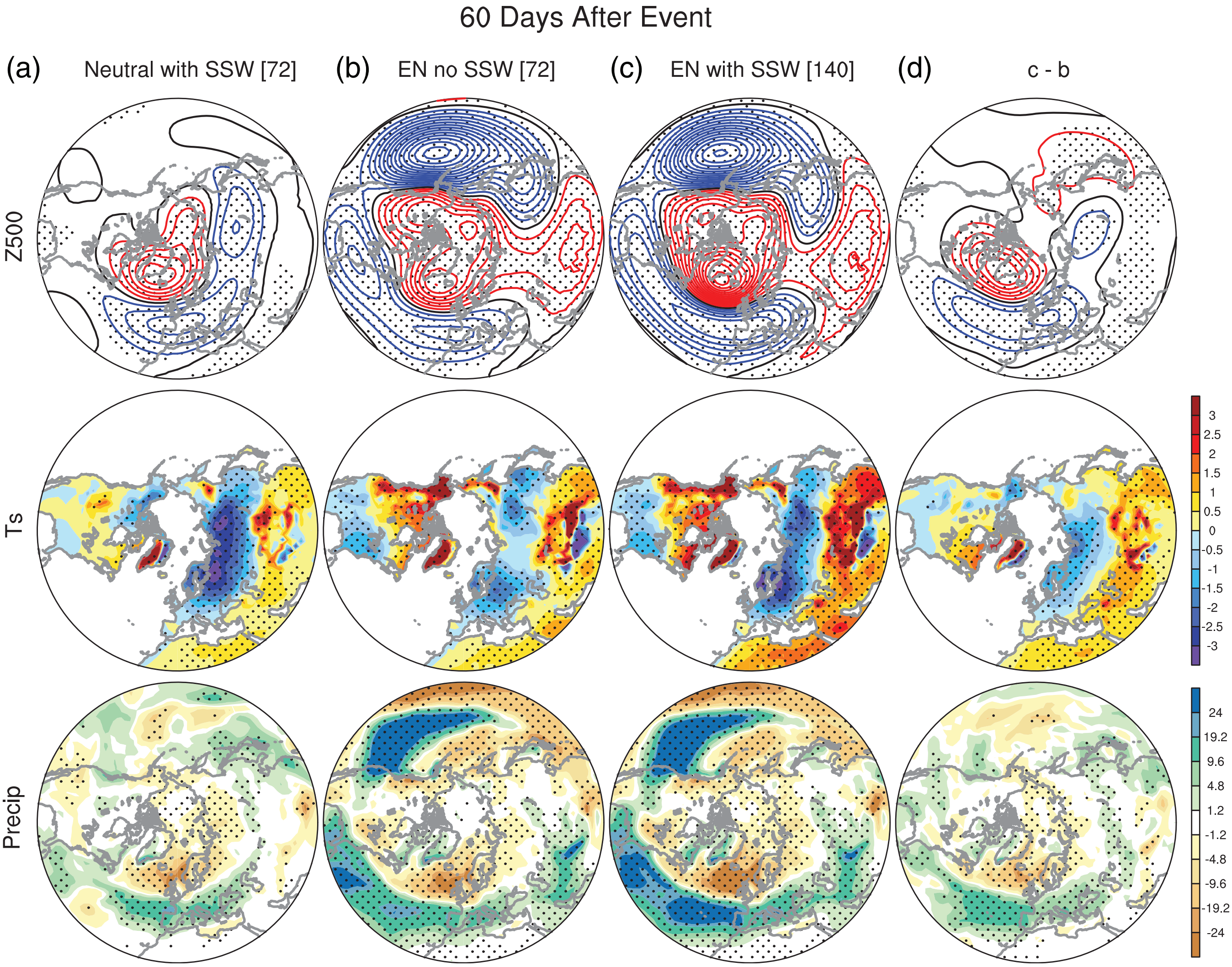

FIGURE 2 Rows are (top) mean geopotential height anomalies at 500 hPa, (middle) mean temperature anomalies at 1,000 hPa (K) and (bottom) mean precipitation anomalies (mm/month). (a) Neutral-ENSO winters with SSWs, (b) El Niño winters without SSWs, (c) El Niño winters with SSWs and (d) the difference between El Niño winters with and without SSWs. Composites are computed using the 60-day methodology, anomalies are taken with respect to neutral-ENSO winters without SSWs

The remaining columns of Figure 2 show the El Niño *with* SSW composites (c) and the differences in the composites of El Niño with and without SSWs (d). These composites reveal that treating the system as linearly additive captures most of the important features; we can then largely consider SSWs and the tropospheric pathway of El Niño as independent sources of surface climate variability. The El Niño with SSW composite retains the El Niño-related features from Figure 2b but with strengthening of the anomalies in regions where the SSWs have the most impact (as seen in the Figure 2a composites). Comparing Figure 2a and Figure 2d, we see similar structures and magnitudes of anomalies, but there are notable differences in the temperature. As shown in Table 2, the occurrence of both

TABLE 2 Eurasian (60°–75°N, 30°–120°E) surface temperature and Mediterranean (35°–45°N, 10°–25°E) precipitation anomalies for neutral-ENSO and El Niño winters with and without SSWs

	Neutral with SSW	EN without SSW	EN with SSW
60-day Eurasian surface temperature (K)	−2.51	−0.59	−2.21
60-day Mediterranean precipitation (mm/month)	+6.18	+6.91	+11.06

Note. Means are computed using the 60-day methodology with anomalies taken with respect to neutral-ENSO winters without SSWs. EN, El Niño; SSW, sudden stratospheric warming.

phenomena does not significantly change the Eurasian cooling from an SSW alone. This further supports the dominant role of SSWs on temperature variability in the region. In contrast, the regional average of Mediterranean precipitation anomalies in Table 2 further confirms the near-additivity of that quantity in the simulation. This additive linearity is not seen to the same extent in the observations, but that may be due to small observational sample size (Domeisen *et al*., 2019).

While the latitudinal structures of the surface effects of El Niño and SSWs are dipolar, it is important to appreciate that the nodes of the precipitation dipole are at different latitudes, possibly due to the wave-like response to El Niño noted above. To illustrate the consequences of this mismatch, in Table 3 we consider precipitation in three particular cities: Stockholm (59.3°N), Paris (48.9°N) and Madrid (40.4°N). This selection of cities allows us to study how the anomalies change across a broad range of latitudes in western Europe in the model as a result of these dipoles.

In Stockholm, the precipitation anomalies due to the two sources of variability lead to drier conditions and are of comparable magnitude. In Paris, however, these anomalies are of opposite signs. El Niño tends to result in drier winters in Paris, whereas SSWs lead to wetter ones. The north/south placement and extent of the precipitation anomaly dipoles for El Niño and SSWs are different, resulting in these opposite impacts in Paris. In Madrid, which is south of the nodal lines of the dipoles, both sources of variability result in wetter winters on average, and El Niño becomes relatively more important (nearly double the impact of SSWs). These results show that the superposition of two dipolar drivers of variability with nodes at different latitudes results in a complex climate response.

TABLE 3 Surface temperature anomalies (K) and precipitation anomalies (mm/month) for Paris, Stockholm and Madrid in neutral-ENSO and El Niño winters with and without SSWs

	Neutral with SSW	EN without SSW	EN with SSW
	Stockholm		
60-day surface temperature	−1.49	−1.34	−2.34
60-day precipitation	−25.58	−28.09	−44.24
	Paris		
60-day surface temperature	−0.45	−0.57	−1.06
60-day precipitation	+7.81	−4.75	−1.44
	Madrid		
60-day surface temperature	−0.20	−0.32	−0.42
60-day precipitation	+6.28	+11.83	+14.04

Note. Means are computed using the 60-day methodology with anomalies taken with respect to neutral-ENSO winters without SSWs. EN, El Niño; SSW, sudden stratospheric warming.

4 | SUMMARY AND DISCUSSION

The climate model results presented here show that SSWs and El Niño separately play key roles in North Atlantic and Eurasian wintertime climate. Confirming prior work, we find that both SSWs and El Niño cause negative NAO anomalies and increase precipitation in southern Europe. Both also lead to increased cooling in northern Europe and Eurasia, but that cooling is concentrated in different regions.

Corroborating previous studies, we find a clear effect of El Niño in the absence of SSWs on the annular mode in the North Atlantic (Bell *et al*., 2009; Li and Lau, 2012; Geng *et al*., 2017; Jiménez-Esteve and Domeisen, 2018). However, the effects of this pathway of El Niño found here are larger than those seen in previous modeling or observational studies. One reason for this is that the basic state here is taken to be neutral-ENSO winters without SSWs, as opposed to a climatology, allowing us to more cleanly isolate the effect of El Niño. The second reason for this difference is the larger size of our model ensemble, resulting in a better signal-to-noise ratio. That said, the results are robust to subsampling. Similar NAO distribution statistics to those seen in Figure 1 are seen in sample distributions of as few as 10 samples. This implies that the signals we observe here are meaningful and are not only discernible because of the large sample size. The third reason for the larger signal of the El Niño pathway in this work is that the El Niño forcing in our model is relatively strong, due to the 1 K threshold used for the SST composite.

Geng *et al*. (2017) found that strong El Niño events (anomaly of 2 K or more) in observations are associated with a shift to a negative NAO in January and cooling in northern Europe and East Asia in the absence of significant perturbation of the stratospheric polar vortex. However, Toniazzo and Scaife (2006) and Hardiman *et al*. (2019) found a negative NAO signal in moderate El Niño events but a wave-like response in strong (anomaly of 1.5 K or more) El Niño events in observations and a climate model; the wave-like response is consistent with the observational work of García-Serrano *et al*. (2011). Rao and Ren (2016a; 2016b) found significant nonlinearity in the effect of moderate (anomaly of 1 K or more) and strong (anomaly of 2 K or more) El Niños on the Arctic stratosphere in observations and WACCM simulations. The impact of El Niño variability on North Atlantic and Eurasian response, both with and without the influence of SSWs, warrants further study.

We also confirm the significant influence of SSWs on North Atlantic and Eurasian climate as described in Butler *et al*. (2014) and Polvani *et al*. (2017). The NAO and precipitation effects of SSWs are similar in magnitude to those of El Niño with an undisturbed stratosphere, and the Eurasian cooling due to SSWs is much stronger. Furthermore, the effects of SSWs are of similar magnitude in neutral-ENSO and El Niño conditions. As SSWs occur in 40–50% of winters even in neutral-ENSO conditions, SSWs are a key climate forcing for the North Atlantic and Eurasia whether or not ENSO is in the El Niño phase.

The results here indicate that a strong El Niño event may be important for wintertime seasonal forecasting for the North Atlantic and Eurasia not only for increasing the likelihood of SSWs, but also due to effects of El Niño through a tropospheric pathway. However, SSWs are frequent even in the neutral-ENSO phase and have surface impacts of comparable magnitude to El Niño. This makes it critical to resolve the stratosphere in seasonal climate forecasting for the North Atlantic and Eurasia, as Butler *et al*. (2016) found that high-top forecast models better simulate both variability in the winter polar vortex and the stratospheric response to ENSO. For many measures, SSWs and El Niño had independent effects on variability, which may allow forecasts to more easily take both El Niño and the corresponding increase in SSW likelihood into account.

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