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La Niña Obscures the North Atlantic Response to Sudden Stratospheric Warmings in C3S Seasonal Forecasts

Verónica Martínez-Andradas[1,2], Alvaro de la Cámara[1], Pablo Zurita-Gotor[1,2], and Amy H. Butler[3]

[1]Dpto. Física de la Tierra y Astrofísica, Universidad Complutense de Madrid, Madrid, Spain, [2]Instituto de Geociencias (IGEO) UCM-CSIC, Madrid, Spain, [3]Chemical Sciences Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO, USA

Key Points:

- Seasonal forecasts confirm that while El Niño reinforces the circulation changes induced by sudden warmings, La Niña counteracts them
- The jet shift induced by sudden warmings is smaller during La Niña, possibly due to weaker lower stratospheric anomalies
- The dynamical changes triggered by sudden warmings in the perturbed El Niño-Southern Oscillation background affect the probability of regional extremes

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

V. Martínez-Andradas,
vemart05@ucm.es

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Abstract

Sudden stratospheric warmings (SSWs) can alter the North Atlantic circulation on subseasonal-to-seasonal timescales, typically leading to an equatorward shift of the eddy-driven jet. However, this response is highly variable and can be modulated by other sources of climate variability. Using seasonal forecasts, this study investigates the modulation of the North Atlantic response to SSWs by El Niño–Southern Oscillation (ENSO). Forecast systems reproduce the tropospheric variability following SSWs found in reanalysis, including an increase of events followed by a poleward-positioned jet during La Niña winters. Composite analysis reveals that SSWs increase the likelihood of an equatorward-shifted jet and negative North Atlantic Oscillation compared to non-SSW members during both ENSO phases, but La Niña masks this response due to their opposing influence on the North Atlantic mean state. This study highlights the importance of accounting for ENSO when predicting SSW impacts on the circulation and surface extremes on subseasonal timescales.

Plain Language Summary

Sudden stratospheric warmings (SSWs) are large-scale disruptions of the winter polar vortex that can influence weather patterns near the Earth's surface. This study analyzes how the tropospheric circulation responds to SSWs in different El Niño–Southern Oscillation (ENSO) phases using multi-model seasonal forecast data. Results show that SSWs typically lead to changes in the North Atlantic circulation, including a southward shift of the storm track. But this response is mixed with the background ENSO state: while El Niño tends to reinforce the SSW-induced changes, La Niña can partially counteract them. These differences affect not only the large-scale circulation but also the probability of cold and wet weather extremes in specific regions. Our results highlight how both the stratosphere and the tropics shape weather patterns and point to the potential for more skillful forecasts when both influences are accounted for.

1. Introduction

The main sources of extratropical predictability in seasonal forecasts are slowly varying components of the climate system, such as the ocean and the cryosphere, as well as the interactions between them (Shukla & Kinter, 2006). The stratosphere has also been recognized as a contributor of enhanced predictability skill on sub-seasonal to seasonal timescales (Gerber et al., 2012; Scaife et al., 2016; Tripathi et al., 2015). For example, sudden stratospheric warmings (SSWs), representing extreme disruptions of the polar vortex, can influence surface weather patterns for up to 60 days (Baldwin & Dunkerton, 2001; Gerber et al., 2009).

Typically, SSWs are followed by a negative phase of the North Atlantic Oscillation (NAO) (e.g., Baldwin & Dunkerton, 2001; Hitchcock & Simpson, 2014), reflecting a southward shift of the eddy-driven jet over the North Atlantic (e.g., Maycock et al., 2020). This circulation anomaly can lead to cold air outbreaks in northern Eurasia and the eastern United States, warming over Greenland and eastern Canada, and increased precipitation over the western Mediterranean, in addition to decreased precipitation in Scandinavia (e.g., Butler et al., 2017).

Although the mean tropospheric response to SSWs is robust, there is large event-to-event variability (Hitchcock & Simpson, 2014), such that the North Atlantic circulation after SSWs presents a variety of behaviors (Jucker, 2016; Karpechko et al., 2017; White et al., 2019). In particular, around two-thirds of SSWs in the reanalysis are followed by the canonical equatorward shift of the jet, while one-third show a poleward shift (Afargan-Gerstman & Domeisen, 2020; Martínez-Andradas et al., 2023).

Several factors with the potential to modulate the tropospheric response to SSWs have been identified. On the stratospheric side, events with persistent temperature anomalies in the lower stratosphere produce a deeper impact on the troposphere (Hitchcock et al., 2013; Jucker, 2016; Karpechko et al., 2017; Maycock & Hitchcock, 2015). The type of SSW, either vortex displacement or split, has also been proposed to influence the surface response, but evidence from reanalyses and model simulations does not support a systematic difference between the two types Maycock and Hitchcock (2015). On the tropospheric side, pre-existing weather regimes and blockings, can enhance or suppress the SSW downward signal (e.g., Charlton-Perez et al., 2018; Domeisen, Grams, & Papritz, 2020). Also, certain regional anomalies, such as a strengthening of the climatological Siberian high, have been identified preceding downward propagating SSWs (Nakagawa & Yamazaki, 2006; White et al., 2019), as well as pre-existing negative Northern Annular Mode (NAM) anomalies (Black & McDaniel, 2004) and enhanced zonal-mean wave activity (White et al., 2019).

Using reanalysis data, Martínez-Andradas et al. (2023) found that SSWs followed by a non-canonical, poleward-shifted North Atlantic jet predominantly occurred during winters with a cold phase (i.e., La Niña) of El Niño-Southern Oscillation (ENSO). ENSO has well-known teleconnections into the extra-tropical troposphere and stratosphere, which makes it the main source of predictability in these regions on seasonal timescales (Butler et al., 2016). In the Northern Hemisphere polar stratosphere, a warmer lower stratosphere and a weaker vortex is observed during El Niño, with opposite conditions during La Niña (see Domeisen et al., 2019, for a review). There is still some controversy about the frequency of SSWs during different ENSO phases: modeling studies point to an increased frequency during El Niño and decreased or unaltered during La Niña (Garfinkel et al., 2012; Palmeiro et al., 2023; Polvani et al., 2017; Taguchi & Hartmann, 2006; Trascasa-Castro et al., 2019), but the reanalysis record shows an increased SSW frequency during both ENSO phases (Butler & Polvani, 2011; Domeisen et al., 2019), although the results are sensitive to the SSW definition (Song & Son, 2018). In the North Atlantic region, the canonical ENSO teleconnection forms a dipole of pressure anomalies, projecting on an NAO pattern but with different associated dynamics (García-Serrano et al., 2011; Mezzina et al., 2020). The influence of ENSO on the North Atlantic can be explained by (not mutually exclusive) tropospheric and stratospheric pathways (e.g., Brönnimann, 2007; Butler et al., 2014; Cagnazzo & Manzini, 2009; Ineson & Scaife, 2009; Iza et al., 2016; Jiménez-Esteve & Domeisen, 2020; Mezzina et al., 2020, 2022). This teleconnection is often stronger after January, once the quasi-stationary Rossby wave train emanating from the equatorial Pacific is fully established (e.g., Ayarzagüena et al., 2018; Bladé et al., 2008). El Niño tends to favor a late-winter mean negative NAO, an equatorward-shifted jet, and enhanced storm activity over southern Europe (Brönnimann, 2007; Jiménez-Esteve & Domeisen, 2020). Although there are asymmetries and non-linearities in the response to ENSO (Hardiman et al., 2019; Iza et al., 2016; Jiménez-Esteve & Domeisen, 2020), La Niña is on average associated with a positive NAO and a poleward-displaced jet.

Although the impacts of ENSO and SSWs on the North Atlantic occur on different timescales (seasonal and sub-seasonal, respectively), the magnitude of the variability induced by both is comparable (Polvani et al., 2017). As La Niña and SSWs tend to drive opposing signals in the North Atlantic, predicting an SSW can notably affect seasonal forecasts. Indeed, Domeisen et al. (2015) showed that the tropospheric impacts of SSWs are better predicted during El Niño winters than during La Niña. Generally, seasonal forecasts tend to underestimate the ENSO-related responses in the North Pacific and North Atlantic, while overestimating the response of the stratospheric polar vortex strength and linearity to the ENSO phase (e.g., Abid et al., 2021; Ayarzagüena et al., 2018; Baker et al., 2024; Johnson et al., 2019; Portal et al., 2022; Scaife et al., 2014; Taguchi, 2022; Williams et al., 2023).

This study aims to investigate the response of the North Atlantic circulation to SSWs in the seasonal forecast systems in the Copernicus Climate Change Service (C3S) database, with particular focus on the modulating role of ENSO, and whether La Niña may obscure the North Atlantic signal associated with SSWs. There are two main reasons for using this data set. First, it is a large, multi-model data set that allows a robust statistical separation of the effects of ENSO and SSWs on the North Atlantic. And second, an assessment of the multi-model skill for capturing the impacts of SSWs and associated ENSO modulation is still lacking in this data set to the best of our knowledge.

2. Data and Methods

The C3S seasonal forecasting service collects output of different seasonal forecasts from operational general circulation models. We use six systems from the Euro-Mediterranean Center on Climate Change (Centro euro-Mediterraneo sui Cambiamenti Climatici, CMCC), Deutsche Wetterdeinst (DWD), Environment and Climate

Change Canada (ECCC), the European Center for Medium-range Weather Forecasts (ECMWF), Météo-France, and the United Kingdom Met Office. Data from the National Centers for Environmental Prediction is not used as it only extends up to 200 hPa. For simplicity, we refer to the models by the center name. The systems used in this study are the latest versions available as of mid-2024. The data includes the hindcast period and, for some models, also the forecasts. Specific details on the model version, period covered and ensemble size can be found in Table S1 in Supporting Information S1. We use initializations from November 1st that extend up to May with sub-daily data, that is, every 12 hr. The resolution used is $2.5 \times 2.5°$ with 12 levels from 1,000 to 10 hPa. For comparison, we also use ERA5 reanalysis data from 1950 to 2020 (Hersbach et al., 2023), with $2.5 \times 2.5°$ spatial resolution and 6-hourly data. Additionally, we use the observed monthly SST anomalies from ERSST V5 (Huang et al., 2017) to identify different ENSO phases in ERA5.

The different members of an ensemble forecast are taken as individual winters. Anomalies are computed by removing the sub-daily climatological seasonal cycle in each model, defined as the ensemble mean of initializations over the 1993–2016 common period for each model. A linear trend is also removed.

To ensure equal weighting across models, multi-model means are computed using the ensemble mean of each model. Similarly, multi-model distributions are constructed weighting by the number of ensemble members of each model, avoiding biases toward systems with larger ensemble sizes.

The detection of SSWs is based on the reversal of the wind at 10 hPa 60°N from November to March (Charlton & Polvani, 2007), enforcing a minimum separation of 20 consecutive days of westerlies between events and a follow up of 10 consecutive days of westerlies to eliminate final warmings. The day of the reversal is set as the onset date.

To characterize the North Atlantic eddy-driven jet shift, we use the PCNAjet index, defined in Martínez-Andradas et al. (2023), which is derived from a principal component analysis of zonal wind anomalies at 300 hPa over the North Atlantic sector. The index captures the dominant dipolar mode of jet variability, with positive (negative) values indicating a poleward (equatorward) displacement. Importantly, the analysis is performed individually for each model to minimize the influence of model-specific biases in the jet position. The impact of SSWs is quantified by the mean value of the PCNAjet index after the occurrence of an SSW, averaged from +15 to +45 lags as in Martínez-Andradas et al. (2023). Events are categorized as poleward (PL) or equatorward (EQ) jet shifts if the mean index exceeds +0.1 or falls below −0.1 standard deviations, respectively.

The phase of the ENSO is assessed using the Niño3.4 index. It is computed for each member taking the area-average over [−5,5]°N [170,120]°W of standardized anomalies of the sea surface temperature. Winters are classified into El Niño (EN) or La Niña (LN) based on the mean value of the Niño3.4 index from November to March, with a threshold of 1 std.

To represent the state of the lower stratosphere we define a NAM index based on the standardized geopotential height anomaly averaged over the polar cap (latitudes north of 70°N), with its sign reversed so that negative values correspond to a weaker polar vortex.

3. Results

The frequency of SSWs is higher in the seasonal forecasts than in the ERA5 reanalysis, with the exception of the CMCC model (Table 1), in agreement with previous studies (Portal et al., 2022; Taguchi, 2022). It should be noted that we compare different periods for the forecasts (1993–2016) and for ERA5 (1950–2020) due to the small reanalysis sample size. However, the frequency of SSWs during the common period (1993–2016) is 0.63 in ERA5, similar to the value for 1950–2020 (0.65). In all seasonal forecast models the SSW frequency increases during El Niño and decreases during La Niña. This is typical of forecast and climate models (e.g., Palmeiro et al., 2023; Song & Son, 2018; Taguchi & Hartmann, 2006; Trascasa-Castro et al., 2019), in contrast with the observed increase in SSW frequency during both ENSO phases in reanalysis (see also Butler & Polvani, 2011; Domeisen et al., 2019).

The proportion of SSWs with a canonical equatorward (EQ) North Atlantic jet shift compared to those with a poleward (PL) shift is consistent between models and reanalysis (Table 1). During El Niño winters, the multi-model proportion of EQ/PL SSWs changes from 0.53/0.32 to 0.75/0.14. In other words, the likelihood of an equatorward (poleward) shifted jet after SSWs is enhanced (reduced) in El Niño winters. This occurs in all forecast models but not in the reanalysis. On the other hand, during La Niña the probability of EQ/PL SSWs

Table 1
Frequency of Sudden Stratospheric Warmings (SSWs) and of EQ and PL Locations of the North Atlantic Jet Following SSWs (+15 to +45 Lags From the Onset) in the Copernicus Climate Change Service Seasonal Forecast Models During the Common Period 1993–2016

	(a) All winters			(b) El Niño winters			(c) La Niña winters		
Model (center)	SSW	EQ	PL	SSW	EQ	PL	SSW	EQ	PL
CMCC	0.59	0.58	0.27	0.77	0.77	0.09	0.43	0.35	0.46
DWD	**1.01**	0.52	0.31	1.18	0.71	0.18	0.76	0.33	0.51
ECCC	**1.07**	0.50	0.36	1.27	0.67	0.18	0.99	0.35	0.55
ECMWF	**0.91**	0.55	0.30	1.08	0.76	0.11	0.87	0.32	0.48
Météo-France	**0.97**	0.51	0.32	1.10	0.71	0.22	0.83	0.43	0.34
UKMO	*0.88*	0.52	0.35	1.17	0.89	0.04	0.76	0.37	0.58
MMM	0.91	0.53	0.32	1.10	0.75	0.14	0.77	0.36	0.49
ERA5	0.65	0.63	0.26	0.90	0.67	0.22	0.80	0.25	0.63

Note. ERA5 reanalysis is included for comparison, covering the period 1950–2020. (a) All winters, (b) El Niño winters, and (c) La Niña winters. EQ and PL frequencies do not add up to 1 because the restrictive criterion used leaves some SSWs unclassified. Bold (italic) frequencies in (a) are statistically significant different from ERA5 at the 95% (90%) confidence level based on a Poisson test as in Gu et al. (2008). MMM refers to multi-model mean values.

changes to 0.36/0.49 in the multi-model mean. This implies a slightly higher probability for a poleward than for an equatorward shifted jet after SSWs during La Nina winters, consistent with reanalysis in Table 1 and in previous studies (Afargan-Gerstman & Domeisen, 2020; Martínez-Andradas et al., 2023). The rest of the analysis is based on the multi-model ensemble means because there are no big outliers. The corresponding analysis for each model can be found in the Supporting Information S1.

We further explore the North Atlantic jet shift following SSWs and the potential modulation by ENSO in Figure 1. The left column of Figure 1 shows the multi-model seasonal forecast relative frequency distribution of the daily PCNAjet index, comparing lags +15 to +45 after SSW events (post-SSW) with daily values from JFMA months in years with no SSWs (non-SSW). The JFMA period is selected to cover the time window when the response to SSW typically occurs, 15–45 days after the onset, considering that the events are identified from November to March. December is excluded due to the different ENSO teleconnection signal in early and late winter (Ayarzagüena et al., 2018; Bladé et al., 2008). When all winters are considered, the post-SSW distribution is clearly shifted toward negative PCNAjet values relative to non-SSW years (Figure 1a), indicating the well-known preference for an equatorward shift of the North Atlantic jet following SSWs (e.g., Baldwin & Dunkerton, 2001; Maycock et al., 2020).

It is also well-known that ENSO modulates the late-winter mean position of the North Atlantic jet. During El Niño winters, the distribution of the daily PCNAjet index for non-SSW years is centered close to zero and slightly skewed toward negative values (Figure 1c), not showing preference for any jet shift. This is consistent with Domeisen et al. (2015) in that they did not find increased predictability of a negative NAO during El Niño winters in the absence of SSWs. In contrast, during La Niña winters the distribution is slightly displaced toward positive values (Figure 1e), consistent with a more poleward climatological jet position and a positive NAO during La Niña reported in previous studies (Brönnimann, 2007; Iza et al., 2016; Jiménez-Esteve & Domeisen, 2020, e.g.).

After the occurrence of SSWs, the PCNAjet distributions during both El Niño and La Niña are displaced toward more negative values relative to non-SSW winters. But again, a modulation by the ENSO phase is visible. The mean post-SSW value of the PCNAjet index is more negative for El Niño (−0.73) compared to all winters (−0.28) while during La Niña winters it approaches zero (0.05), consistent with the approximately equal number of EQ and PL SSWs under La Niña conditions. This behavior is robust across individual models and ERA5 reanalysis (see Supporting Information S1), although for ERA5 the shift is only visible when reducing the ENSO threshold to 0.5 STD and not for the small sample size resulting from a 1 STD threshold. These results indicate that the impact of SSWs is to shift the position of the North Atlantic jet toward the equator, but this response occurs with respect to the ENSO-modulated winter-mean position. These results further support the idea that ENSO modulates the jet position following SSWs, with El Niño enhancing and La Niña masking the response to SSWs.

One should note that the shift is larger during El Niño than for La Niña in the multi-model mean. Although not all models agree in this behavior (see Supporting Information S1), the majority do. For example, the difference in the mean between post-SSWs and non-SSWs winters is larger during El Niño than during La Niña in all models except ECCC. This suggests a weaker response to SSWs during La Niña. We propose that differences in the lower stratospheric NAM during both ENSO phases play a role for the reduced response of the North Atlantic jet to SSWs during La Niña. Previous studies based on reanalysis and models have shown that SSWs with a stronger tropospheric signal tend to show stronger and more persistent circulation anomalies in the lower stratosphere for several weeks after the events (Hitchcock et al., 2013; Karpechko et al., 2017; White et al., 2019). To test this, the right column of Figure 1 shows the multi-model distributions of the NAM index at 100 hPa for winters without SSWs and during the aftermath of the events. As expected, SSWs clearly shift the lower stratospheric NAM distribution toward negative values relative to non-SSW years, also in El Niño and La Niña winters (Figures 1b, 1d and 1f). But again, the post-SSW distribution is positioned at less (more) negative values for La Niña (El Niño) compared to all winters. As a result, the probability of positive NAM values in the lower stratosphere following

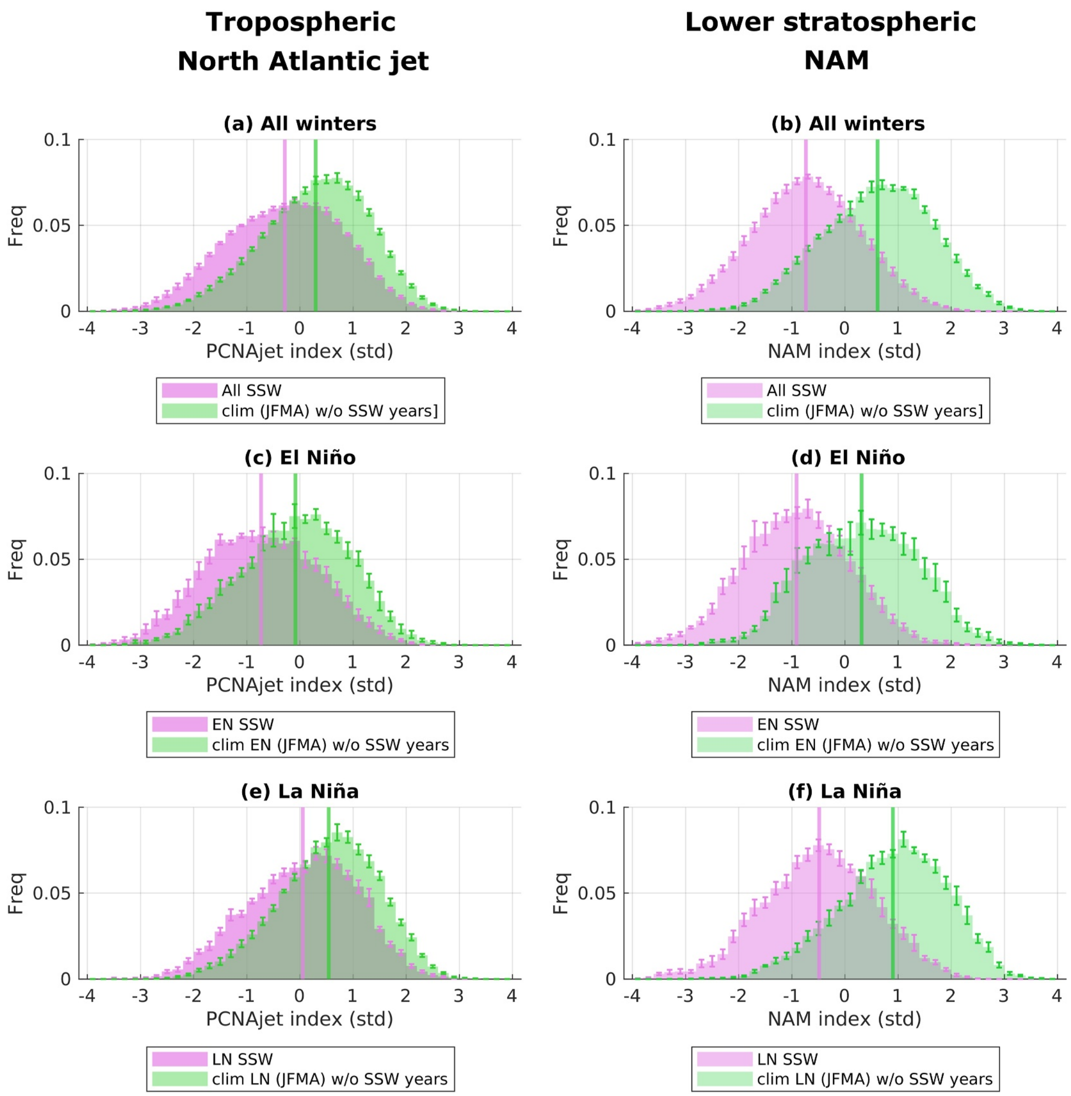

Figure 1. Multi-model seasonal forecasts relative frequency distribution of daily PCNAjet index (left) and Northern Annular Mode (NAM) at 100 hPa (right). Distributions show the daily values of both indexes for +15 to +45 lags in PCNAjet and +5 to +45 lags in NAM after sudden stratospheric warmings (SSWs) (pink) and for JFMA of years without SSWs (green). Every winter is included in (a), (b) and only El Niño and La Niña winters are included in (c), (d) and (e), (f), respectively. Vertical lines represent the mean value of each distribution. The multi-model distribution is obtained from normalized model distributions, ensuring equal weighting, with error bars indicating the standard error of the multi-model means distribution.

SSWs is higher for La Niña (33%) than for El Niño (18%). This suggests that the slightly weaker impact of SSWs on the jet position during La Niña compared to El Niño (Figures 1c and 1e) may be influenced by weaker absolute values of the lower stratospheric NAM after La Niña SSWs. The non-SSW distributions again support that the lower stratospheric NAM is modulated by the ENSO phase. The non-SSW distribution for La Niña is placed toward more positive values than for El Niño, in agreement with a colder lower polar stratosphere during La Niña winters (Iza et al., 2016). The shift between post-SSW and non-SSW distributions is similar in both ENSO phases, suggesting that differences in the lower stratosphere do not arise from a different strength of the SSW response.

To assess the spatial structure of the SSW responses under different ENSO phases, we perform multi-model ensemble composites of geopotential height anomalies at 500 hPa averaged from +15 to +45 days after SSW onset for both ENSO phases (Figures 2a and 2d). El Niño SSWs are followed by a clear dipolar pattern in the North Atlantic with positive anomalies over Greenlad and negative at midlatitudes (Figure 2a), consistent with the stronger equatorward jet shift shown in Figure 1. In contrast, La Niña SSWs show weak or negligible anomalies

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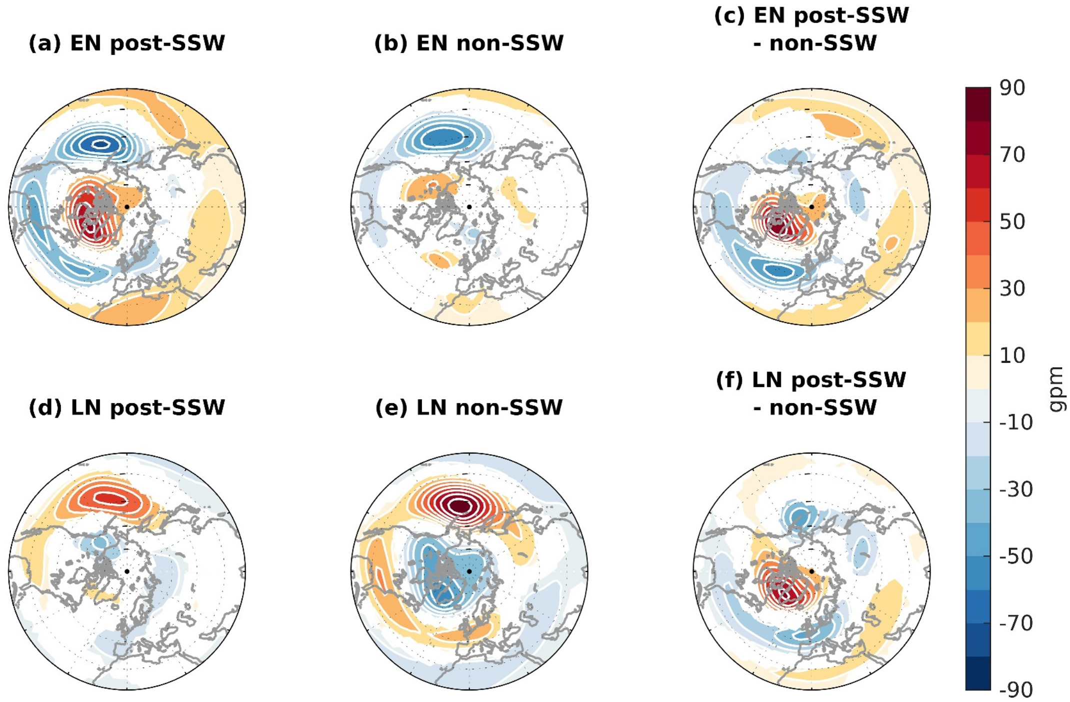

Figure 2. Geopotential height anomalies (shading) at 500 hPa in the multi-model ensemble mean for El Niño (upper row) and La Niña (lower row). (a), (d) Sudden stratospheric warming composite mean, averaged from +15 to +45 lags after the onset. (b), (e) Mean JFMA daily anomalies of non-SSW years during El Niño and La Niña. (c), (f) Differences between (a), (b) and (d), (e), respectively. Only areas where all models coincide in sign are colored.

over the North Atlantic (Figure 2d). However, these anomalies reflect the combined impacts of ENSO and SSWs as noted before. To separate the two effects, we also show the El Niño and La Niña anomalies for non-SSW years. During La Niña non-SSW years there is a clear dipolar pattern in the North Atlantic of the opposite sign to Figure 2a (Figure 2e), while for El Niño a much weaker and deformed pattern is found (Figure 2b). When comparing the impacts of SSWs with respect to non-SSW realizations of the forecast the resulting signal due to SSWs alone is similar for both ENSO phases, resembling a negative NAO (Figures 2c and 2f). This confirms, using the seasonal forecast database, the findings of Polvani et al. (2017) with a climate model: the impact of SSWs is distinguishable from the ENSO signal in the North Atlantic. Nonetheless, this response is slightly weaker for La Niña (Figures 2c and 2f) similar to what was found for the North Atlantic jet shift, though not all models agree (see Supporting Information S1). What is common to all models is that the El Niño response to SSWs extends further westward in the North Atlantic, including circulation anomalies over the southeastern United States.

Finally, we analyze how these circulation changes following SSWs under different ENSO phases affect the occurrence of weather extremes. Previous studies indicate an increased probability of cold spells over Eurasia and southeastern North America after SSWs (Domeisen & Butler, 2020), and heavy rainfall over southwestern Europe (Ayarzagüena et al., 2018; Kidston et al., 2015). Figure 3 shows the mean probability of extreme precipitation and cold temperatures following SSWs (post-SSW), in non-SSW winters, and the differences between them, for El Niño and La Niña years. These extremes are defined as daily values exceeding the 95th percentile for precipitation, and falling below the 5th percentile for 2-m temperature. The likelihood of extreme precipitation increases over western and southern Europe and decreases over northern Europe after SSWs, compared to winters without SSWs, for both El Niño and La Niña winters (Figures 3c and 3f). This increase is more pronounced during El Niño winters, whereas La Niña winters exhibit a marked decrease in extreme precipitation over northern Europe. These changes are consistent with an equatorward shift of the eddy-driven jet following SSWs.

Interestingly, although the direction of the SSW-induced change is similar in both ENSO phases, that is, a southward displacement of the jet, the implications in extreme events differ. In La Niña winters without SSWs,

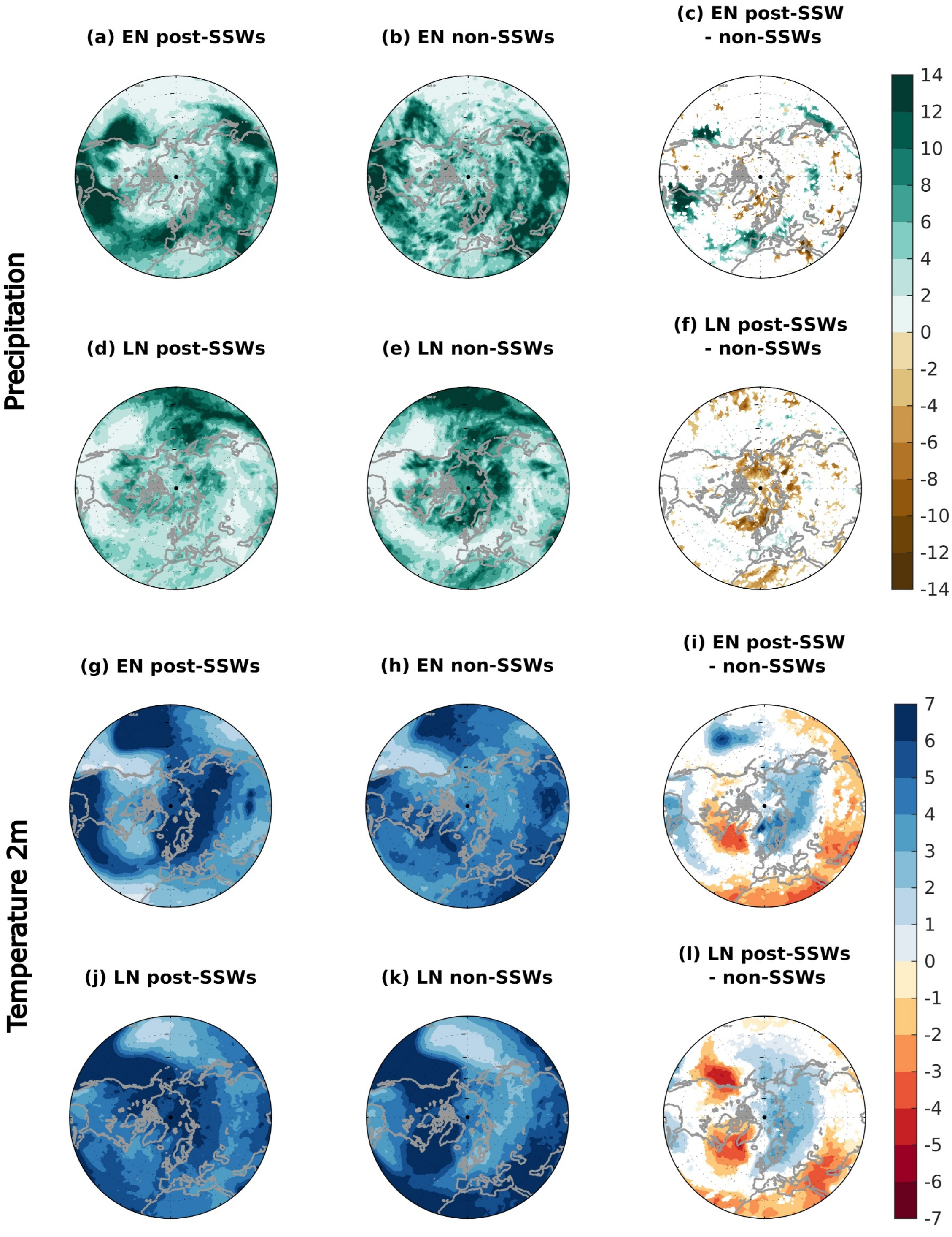

Figure 3. Probability of extreme precipitation (upper rows) and cold temperatures (lower rows) for El Niño and La Niña winters in the multi-model mean. Left column (a, d, g, j) show the sudden stratospheric warming (SSW) composite mean, averaged from +15 to +45 days after the SSW onset. Central column (b, e, h, k) show the average from January to April on non-SSW years for El Niño and La Niña. Right column (c, f, i, l) shows the percentage point difference between left and central column. Probabilities are calculated as a percentage of days (number of extreme days over total days × 100). Extremes are defined as daily values exceeding the 95th percentile for precipitation and falling below the 5th percentile for 2-m temperature. In maps of differences (right column) only areas where at least five out of the six models coincide in sign are colored.

extreme precipitation is concentrated over northern Europe due to a more poleward jet (Figure 3e), and the SSW-induced shift leads to a marked reduction in extremes in that region, with only modest increases over southern Europe (Figure 3f). In contrast, the eastward shift of convection in the Pacific during El Niño enhance precipitation extremes over the United States and downstream (Figures 3a and 3b). This increase in moisture combined with the anomalous equatorward jet path after SSWs, increases the likelihood of extreme precipitation in southern Europe (Figure 3a). This points to an interaction between dynamical changes triggered by SSWs and the thermodynamic background set by ENSO, including differences in tropical convection and moisture supply (e.g., eastward-shifted convection during El Niño and westward-shifted during La Niña).

Similarly, the probability of cold temperature extremes over northern Eurasia increases after SSWs in both ENSO phases compared to non-SSW winters (Figures 3i and 3l), consistent with a more negative NAO pattern. A concurrent reduction in cold extremes is also found over Greenland. Moreover, we find as in Figure 2 that the differences between SSW and non-SSW winters are generally larger for El Niño in the multi-model mean. However, this does not hold up in every model (not shown).

Finally, regional differences between El Niño and La Niña in the extremes associated to SSWs appear over the eastern United States (Figures 3c,3f, 3i, and 3l). In this region, SSWs during El Niño are associated with an increased likelihood of both extreme precipitation and cold temperatures. This is consistent with the 500 hPa geopotential height composites in Figure 2, which show that the tropospheric response during El Niño extends further westward compared to La Niña. These features suggest the existence of certain nonlinearities in the atmospheric response. Other differences observed across the Pacific sector may also be linked to such nonlinear interactions.

4. Conclusions

SSWs induce sub-seasonal to seasonal changes in the North Atlantic circulation, including a negative NAO, an equatorward shift of the eddy-driven jet, and increased precipitation over southern Europe (Butler et al., 2017). However, because of the stratospheric variability and the partial masking of the surface response to SSWs by other sources of tropospheric variability (Hitchcock & Simpson, 2014), about one third of the SSWs in reanalysis are followed by a non-canonical poleward-shifted tropospheric jet (Afargan-Gerstman & Domeisen, 2020; Martínez-Andradas et al., 2023).

Our analysis shows that a similar proportion of non-canonical poleward shifts following SSWs occurs in the C3S seasonal forecast ensemble, which includes a much larger sample of SSW events than the reanalysis. The likelihood of a poleward-shifted jet following SSWs increases during La Niña winters, suggesting an ENSO modulation of the North Atlantic circulation response to SSWs. We further show that after SSWs, the probability of an equatorward-shifted jet in the North Atlantic and negative NAO increases compared to non-SSW winter days no matter the ENSO phase, these being features of the response to SSWs. This supports earlier findings from a large ensemble of a global circulation model (Polvani et al., 2017) that the response to SSWs is distinguishable from the ENSO signal.

A simple explanation of this behavior is that while the late-winter El Niño tropospheric teleconnection favors a negative phase of the NAO and an equatorward North Atlantic jet shift (Brönnimann, 2007; Iza et al., 2016; Jiménez-Esteve & Domeisen, 2020), the La Niña teleconnection tends to promote the opposite pattern. Therefore, the tropospheric teleconnection of La Niña in the North Atlantic destructively interferes with the SSW signal, leading to much weaker tropospheric anomalies after SSWs. Indeed, the composite of geopotential height anomalies at 500 hPa in the aftermath of SSWs during La Niña shows very weak anomalies in the North Atlantic.

Most forecast systems agree on a reduced SSW impact in the North Atlantic in La Niña compared to El Niño, a signal that would be difficult to robustly detect in observations due to sampling variability, demonstrating the benefits of leveraging ensemble seasonal forecast simulations that have many more SSW events. A similar behavior is apparent in the climate model results of Polvani et al. (2017), although it is not directly addressed in the discussion. One possible reason is that lower stratospheric NAM anomalies tend to be less negative during La Niña. We argue that these weaker magnitude anomalies are not due to a weaker dynamical response to SSWs, but rather to a background contribution of La Niña at seasonal timescales to a more positive NAM in the lower stratosphere. This results in a reduced stratospheric contribution to the tropospheric signal, adding to the reduced SSW impact in the North Atlantic during La Niña. Furthermore, the presence of nonlinearities in the downstream propagation from the Pacific of the ENSO tropospheric wavetrain (Jiménez-Esteve & Domeisen, 2020) could be relevant, although this is beyond the scope of this article.

These findings contribute to our understanding of seasonal forecasts. In practice, ENSO is typically well predicted at seasonal lead times (Brönnimann, 2007), so initializations at the beginning of winter accurately capture the ENSO phase, while the stratospheric evolution remains much more uncertain. Though seasonal forecast models can reasonably estimate the probability of a SSW occurring at some point in a given winter (Portal et al., 2022), the exact timing of the SSW is generally only predictable on deterministic timescales (10–14 days, Domeisen, Butler, et al., 2020). Our study reveals marked differences in the North Atlantic predictions by comparing forecast members with at least one SSW to those without. For instance, in El Niño winters, SSW members show a negative NAO, while non-SSW members show a near-neutral NAO. In contrast, during La Niña, SSW members exhibit near-neutral NAO anomalies, while non-SSW members present a positive NAO. These dynamical differences, in addition to thermodynamic factors such as moisture availability, then contribute to complex regional shifts in extreme event probabilities that need to be carefully considered, in the event that an SSW actually occurs.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The C3S seasonal forecast database (Copernicus Climate Change Service, 2018) and ERA5 reanalysis (Copernicus Climate Change Service, 2023) are available online through the Copernicus Climate Data Store.

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