ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL095493

Key Points:

- Uncertainty in the surface climate response to sudden stratospheric warmings is assessed from bootstrapped composites of 39 observed events
- The bootstrapped composites show robust but highly variable patterns over the Northern Hemisphere
- The spread across the composites is due to tropospheric variability that is independent of the stratospheric conditions sampled

Supporting Information:

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

Correspondence to:

J. Oehrlein,
jessica.oehrlein@columbia.edu

Citation:

Oehrlein, J., Polvani, L. M., Sun, L., & Deser, C. (2021). How well do we know the surface impact of sudden stratospheric warmings? *Geophysical Research Letters*, *48*, e2021GL095493. https://doi.org/10.1029/2021GL095493

Received 29 JUL 2021
Accepted 27 OCT 2021

How Well Do We Know the Surface Impact of Sudden Stratospheric Warmings?

Jessica Oehrlein[1,2], Lorenzo M. Polvani[2,3,4], Lantao Sun[5], and Clara Deser[6]

[1]Department of Mathematics, Fitchburg State University, Fitchburg, MA, USA, [2]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA, [3]Department of Earth and Environmental Sciences, Columbia University, New York, NY, USA, [4]Lamont-Doherty Earth Observatory, Palisades, NY, USA, [5]Department of Atmospheric Sciences, Colorado State University, Fort Collins, CO, USA, [6]National Center for Atmospheric Research, Boulder, CO, USA

Abstract Sudden stratospheric warmings (SSWs) are key to understanding and predicting subseasonal Northern Hemisphere winter climate variability. Here we study the uncertainty in the surface response to SSWs in reanalysis data by constructing synthetic composites based on bootstrapping the 39 events observed during the 1958–2019 period. We find that the well-known responses in the North Atlantic and European regions following SSWs are consistently present, but their magnitude and spatial pattern vary considerably across the synthetic composites. We further find that this uncertainty is unrelated to stratospheric polar vortex strength and is instead the result of independent tropospheric variability. Our findings provide a basis for evaluating the fidelity of the surface response to SSWs in models.

Plain Language Summary In winter, the average winds about 30 km above the Arctic are usually west-to-east. When they are disrupted and reverse directions in an event known as a sudden stratospheric warming, particular surface climate patterns tend to develop over the following 60 days, especially in the North Atlantic and European regions. However, there is a great deal of variation or uncertainty in this response, and that variation can be difficult to measure. We study this uncertainty by building composites or averages of different combinations of observed events, assuming they are interchangeable. Using these synthetic composites, we find that the responses in the North Atlantic and European regions are always present, but they vary in magnitude, location, and shape. We further find that this variation is not a result of how strong or weak the 30 km winds are in each synthetic composite; rather, it results from unrelated noise in the atmospheric system. Our results can be used to inform weather and climate forecasts of the surface impacts associated with these high-altitude disruptions of the atmospheric circulation.

1. Introduction

The state of the stratospheric polar vortex is an important driver of wintertime climate variability in the Northern Hemisphere troposphere. In particular, the extreme weak state of the vortex seen during sudden stratospheric warmings (SSWs) has been connected to negative phases of the Northern Annular Mode (NAM) and North Atlantic Oscillation (NAO) with effects at the surface for two months after the SSW (Baldwin & Dunkerton, 2001). Effects on temperature include below-normal values in Northern Europe and the Eastern United States and above-normal values in North Africa, Central Asia, and Eastern Canada in the aftermath of SSWs (e.g., Butler et al., 2017; Domeisen & Butler, 2020; King et al., 2019; Kolstad et al., 2010; Scaife et al., 2008; D. W. J. Thompson & Wallace, 2001). Common precipitation anomalies following SSWs include dry spells in northern Europe and increased precipitation in southern Europe (e.g., Ayarzagüena et al., 2018; Butler et al., 2017; Domeisen & Butler, 2020; King et al., 2019).

However, there is a great deal of uncertainty in this response, and in observational studies, we do not have the luxury of a large ensemble to isolate the forced response from unrelated noise. The record of SSW observations is under 70 years long (Baldwin et al., 2021), and the typical surface response is not found in all events. This raises the question of whether the set of SSWs we have observed is representative and why a surface signal is seen following some events and not others. Studies of this uncertainty have focused on variability across individual SSW events or types of events. Only two-thirds of SSWs propagate downward to the surface and are followed by a negative NAO (Afargan-Gerstman & Domeisen, 2020; Butler et al., 2020; Domeisen, 2019; Karpechko et al., 2017). Suggested stratospheric causes for the spread in surface response include lower stratospheric anomalies and magnitude of wave activity following the central date (Karpechko et al., 2017), persistence of these anomalies (Runde et al., 2016), and differences in type of SSW event (i.e., split/displacement, absorbing/reflecting) (Kodera et al., 2016; Mitchell et al., 2013; Seviour et al., 2016). However, these may not determine the following surface responses (Karpechko et al., 2017; Maycock & Hitchcock, 2015; White et al., 2019). Suggested tropospheric causes for the uncertainty in the surface response following SSWs include the state of the jet or North Atlantic prior to the event (Chan & Plumb, 2009; Charlton-Perez et al., 2018; Domeisen et al., 2020; Garfinkel et al., 2013) or other phenomena affecting the troposphere, such as ENSO and the MJO (Baldwin et al., 2021, and references therein).

One possible approach to studying SSWs with relatively few observed events is to use large-ensemble models, as is done in Wang et al. (2020) for Southern Hemisphere SSWs. Here, we instead use the observed set of SSWs that we have and follow Deser et al. (2017, 2018), which addressed similar challenges in understanding the extratropical circulation response to the El Niño-Southern Oscillation (ENSO). Using a bootstrap resampling method, they constructed synthetic, observationally based El Niño and La Niña composites comparable to the observed composite. Because these synthetic composites were built of resampled observed events, it is plausible that they could have occurred given different atmospheric variability unrelated to ENSO. This approach captures the uncertainty in both spatial pattern and magnitude of impacts of ENSO. They found that sea level pressure (SLP), temperature, and precipitation anomalies in some regions were robust across the synthetic composites but nevertheless varied in magnitude by up to a factor of 2; other regions showed less robust responses across the composites. The spread in the circulation responses in all regions was found to be largely unrelated to ENSO diversity, and instead to be due to internal atmospheric noise.

The goal of this study, using the method of Deser et al. (2017), is to answer two questions related to uncertainty in the tropospheric response to SSWs. First, how robust to sampling variability are the observed composite surface responses to SSWs? Second, is the spread that we see in the composite surface response a result of differences in the SSWs that make up each synthetic composite, or is it due to unrelated tropospheric variability? Our analysis proceeds as follows. After describing our methods (Section 2), we examine a subset of the observationally based synthetic composites, as well as the observed composite, to qualitatively illustrate the spread in both pattern and amplitude in the mean surface response following SSWs (Section 3a). Then, focusing on particular regions identified from those composites, we confirm that the well-known observed responses are robust and distinct from what is seen in a climatological winter composite (Section 3b). Finally, we attempt to relate the spread in surface anomalies to the spread in stratospheric anomalies across the 2,000 synthetic composites (Section 3c). We find that there is little relationship between the composite stratospheric anomalies and the magnitude of anomalies at the surface, and we deduce that the uncertainty in the surface response is largely due to unrelated internal tropospheric variability. We conclude with a brief discussion of the use of these results for model evaluation (Section 4).

2. Data and Methods

To study the anomalies following sudden stratosphere warmings, we use data from the Japanese 55-Year Reanalysis (JRA-55) (Japan Meteorological Agency, Japan, 2013; Kobayashi et al., 2015), chosen for a top above the stratopause (0.1 hPa), fine vertical resolution (60 levels) (Fujiwara et al., 2017), and suitability for use in studying SSWs (Gerber et al., 2021). We analyze winds, SLPs, temperatures, precipitation, and geopotential heights from this data set over the 1958–2019 period, calculating daily anomalies by removing from daily mean fields a climatology calculated as the mean value of each calendar day over the full period.

We detect SSWs using the definition of Charlton and Polvani (2007) (see the corrigendum Charlton-Perez & Polvani, 2011). An event is considered an SSW if the zonal mean zonal winds at 10 hPa and 60°N reverse from westerly to easterly during extended boreal winter (NDJFM). The first date when the daily zonal mean zonal winds are easterly is defined as the "central date," and no day within 20 days following the central date is considered a separate SSW. If the daily zonal mean zonal winds do not return to westerly for at least 10

10.1029/2021GL095493

consecutive days before April 30th, the event is classified as a final stratospheric warming and is excluded. This definition is among those described in Butler and Gerber (2018) as optimal for identifying SSWs. This procedure identifies 39 SSWs, listed in the leftmost column of Table S1 in Supporting Information S1, in JRA-55 over the 1958–2019 period.

Following Deser et al. (2017), we form synthetic SSW composites by randomly sampling with replacement (bootstrapping) from the 39 SSW events to form new sets of 39 events. With this procedure, we generate 2,000 synthetic composites. This bootstrap distribution allows us to study variability across SSW composites as opposed to event-to-event SSW variability. To confirm that the results of this process are in agreement with probabilistic predictions, we examine two characteristics: the distribution of the number of unique SSW events across the 2,000 synthetic composites, and the distribution of the maximum number of times a single event is repeated in a composite. These are shown in Figure S1 in Supporting Information S1 and indeed correspond to what is expected of a multinomial process.

We compare the distributions of composite responses to SSWs to distributions of these fields over comparable climatologies. We construct these 2,000 climatology composites by randomly choosing 39 60-day periods of the year, each of which corresponds to 60-day periods of an SSW in the reanalysis, and separately, randomly choosing a year from the 1958–2019 period for each of these periods. This preserves seasonality effects by sampling from winter periods according to the seasonal distribution of SSWs but forms a climatology by choosing from all years without regard for vortex state.

We calculate the NAM, following Oehrlein et al. (2020), at each pressure level as a deseasonalized and detrended daily mean of geopotential height, which is then averaged over 65°–90°N. This quantity is normalized to have unit variance with a sign convention such that a negative stratospheric NAM indicates a weak polar vortex.

Throughout the paper, we focus on six regional surface responses. Region boundaries for these quantities were chosen to capture variability across composites. The results are robust to changes in the exact boundaries of the region. These climate indices are computed as below:

1. NAO: The difference between normalized, area-weighted averages of SLP anomalies over 62.5°–90°N, 45°W–10°E and 35°–50°N, 45°W–10°E.
2. North Atlantic Precipitation: The area-weighted average over 30°–50°N, 40°W–10°E.
3. North Pacific SLP: The area-weighted average over 30°–60°N, 175°E–135°W.
4. Northern Eurasian Surface Temperature (T_s): The area-weighted average over 60°–75°N, 30°–120°E (Polvani et al., 2017).
5. Eastern Canadian T_s: The area-weighted average over 45°–70°N, 45°–90°W.
6. Eastern United States T_s: The area-weighted average over 25°–42.5°N, 65°–90°W.

3. Results

Figure 1 shows SLP, T_s, and precipitation anomalies for the 60 days following SSW central dates both for the observed composite (a–c) and for six of the 2,000 synthetic composites (a1–a6, b1–b6, c1–c6); the same synthetic composites are shown for all fields. These composites were selected as a qualitative illustration of the spread in anomaly patterns and magnitudes across the entire bootstrapped sample. A systematic quantification of the spread across the entire bootstrapped sample will also be given.

Let us first consider the SLP anomalies (Figures 1a and a1–a6). While a negative NAO is present in all of these composites, it varies from strong (a2) to much weaker (a1) by a factor of two in both centers of action. The spatial pattern also varies significantly, with the southern lobe sometimes centered over the North Atlantic (a4) and sometimes shifted toward western Europe (a5). The other region of interest in these composites is the North Pacific. The observed composite and many of the synthetic composites show a high-pressure anomaly in this region, but it is often not statistically significant at the 95% level and is much weaker than the NAO-related anomalies.

Turning to the corresponding T_s anomalies (Figures 1b and b1–b6), we again see features common across all seven composites: northern Eurasian cooling, Central Asian and Middle Eastern warming, and East

10.1029/2021GL095493

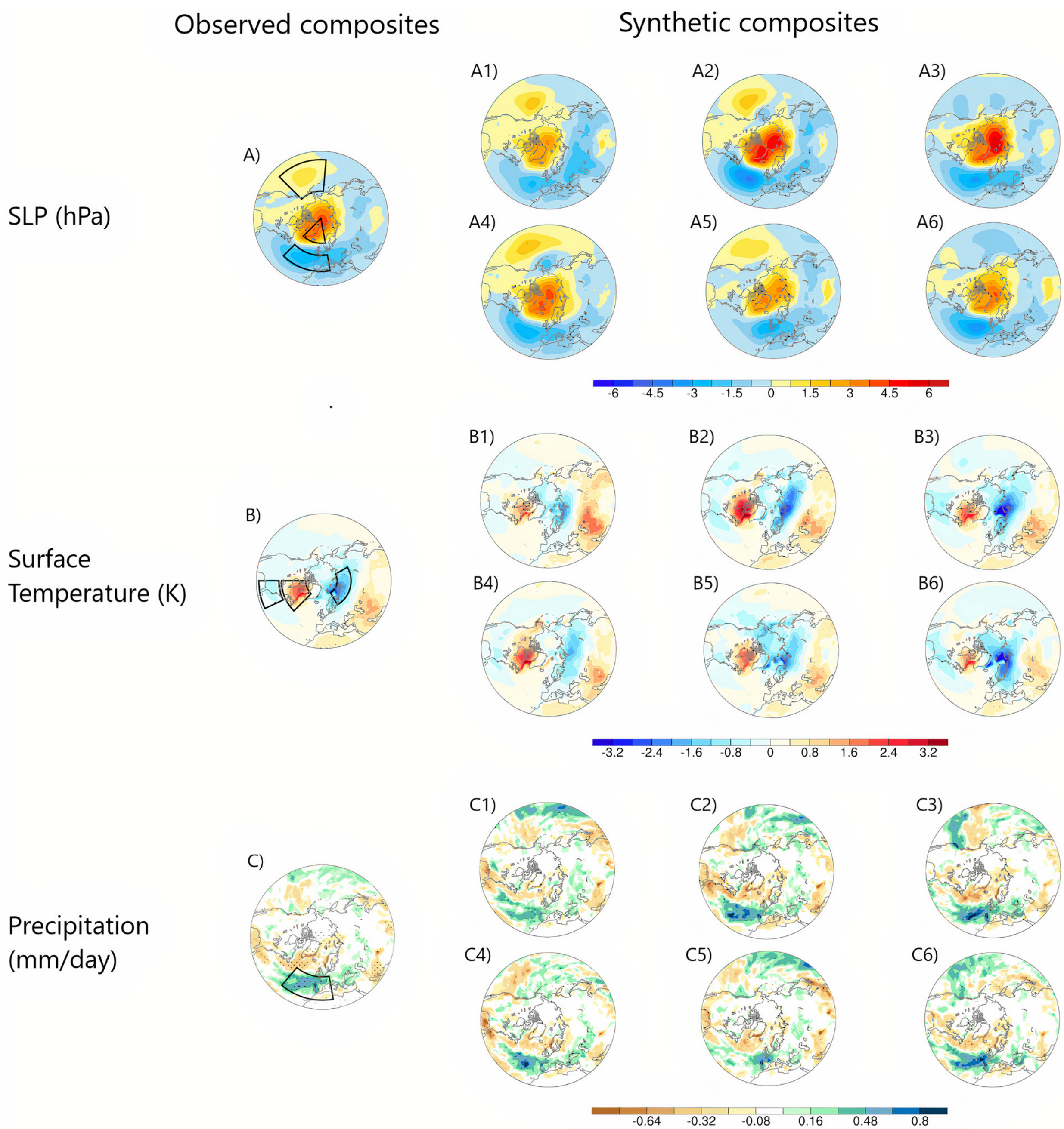

Figure 1. The observed composite and six synthetic composites for sea level pressure (SLP) (a, a1–a6), T_s (b, b1–b6), and precipitation (c, c1–c6) in the 60 days following the sudden stratospheric warming central date, with stippling for significance at the 95% level based on a two-tailed Student's *t*-test. Black boxes on the observed composites show regions used to define the climate indices.

Canadian warming. However, as with SLP, there is large spread in magnitude and pattern of these anomalies. For example, the northern Eurasian cooling varies greatly in strength (b3 vs. b4) and extent (b1 vs. b5). We also note that the observed composite and five synthetic composites show statistically significant cooling in the Eastern United States, sometimes confined to the coast (b5) and sometimes stretching to the US Midwest (b6).

Finally, let us examine the associated precipitation anomalies (Figures 1c and c1–c6). Following SSWs, we consistently see increased precipitation over the North Atlantic and western and southern Europe, with

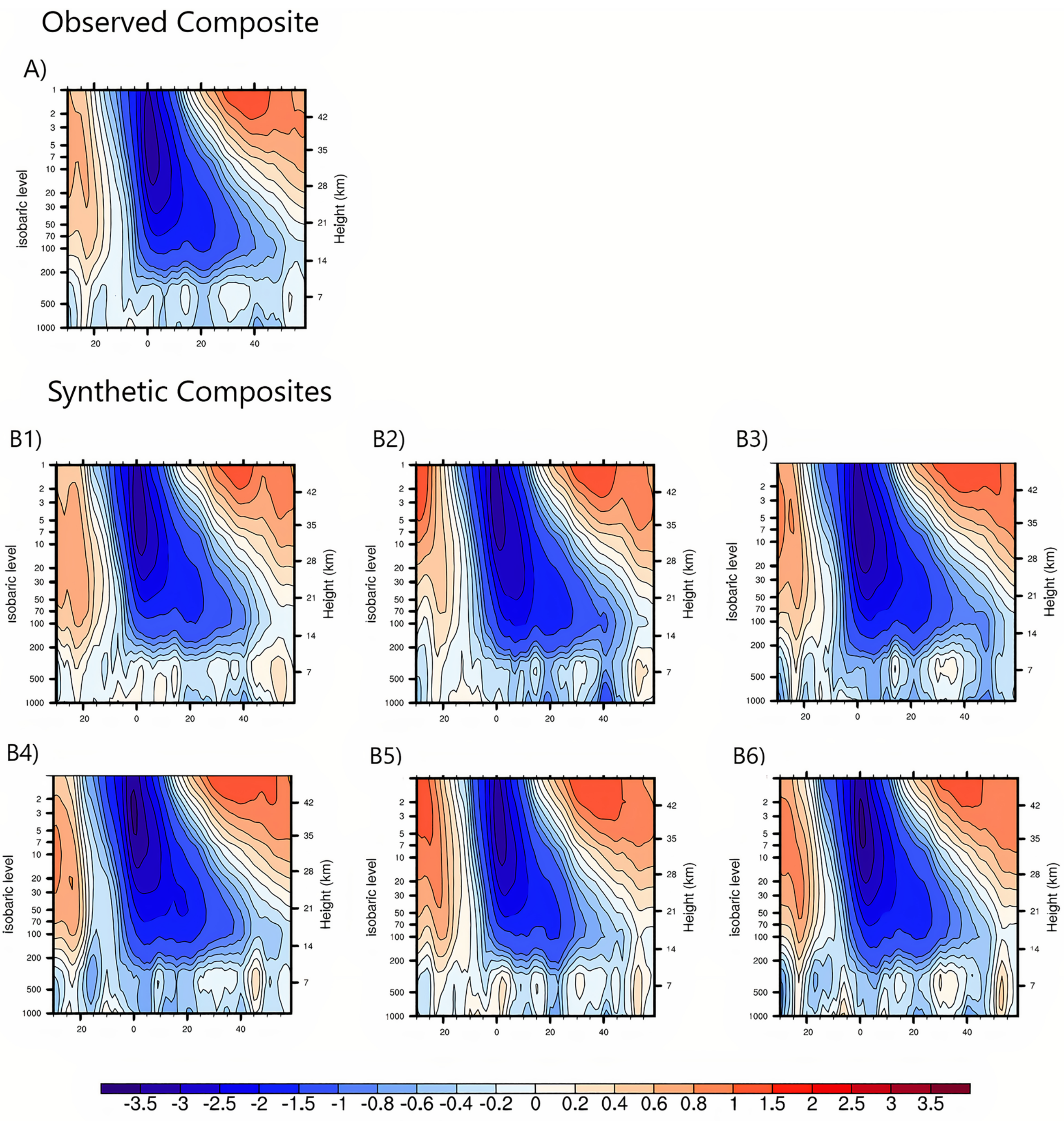

Figure 2. The observed composite and six synthetic composites of the Northern Annular Mode, from 30 days before to 60 days after the sudden stratospheric warming central date.

spread in magnitude and pattern generally following those of the associated negative SLP anomaly. This is often accompanied by a dry anomaly in northern Europe and eastern North America.

Together with the surface patterns following SSWs, we now consider the corresponding composite stratospheric conditions. The descent of anomalies from the upper stratosphere to the troposphere is commonly examined using "dripping paint" plots of the NAM, following Baldwin and Dunkerton (2001). We note a wide range of NAM indices in the stratosphere and troposphere in the 30 days preceding and 60 days following the central date. This is illustrated in Figure 2, showing the same synthetic composites as in Figure 1.

Some composites have a more negative NAM at 10 hPa (b4 and b6) or over a longer period of time and greater range of levels (b3). These differences amplify as the anomalies descend. For example, the duration of a strong negative NAM at 100 hPa varies substantially (b1 vs. b3), and while all composites show some descent of the negative NAM to the surface, this also varies in strength (b1 vs. b2) and longevity (b5 vs. b2).

We now address the key question of this study: is the spread in surface response across the synthetic composites explained by the spread in the stratospheric conditions? To answer this, we make use of the entire set of 2,000 synthetic composites. For each of the regional indices listed in Section 2, we identify the composites that correspond to the 10th percentile and the 90th percentile values of the index. In this way, we can quantify the 10th-to-90th percentile range of patterns and amplitudes in the synthetic composites that occurs as a result of internal variability and (potentially) differences in the stratospheric conditions sampled. Figure 3 shows the SLP and NAM anomaly fields for the synthetic composites corresponding to the 10th and 90th percentile values of the NAO (Figures 3a–3d) and East Canadian T_s (Figures 3e–3h) indices. The SSW events included in each composite here are listed in Table S1 in Supporting Information S1, and results from other regional indices are shown in Figures S2 and S3 in Supporting Information S1. For the regions here, we see two opposite relationships between the negative NAM index in the stratosphere and the anomaly at the surface. The stronger NAO at the surface in Figure 3a is associated with a stronger negative NAM in the upper stratosphere (Figure 3b), compared to the weaker NAO associated with the weaker NAM (Figures 3c and 3d). However, the opposite relationship holds for East Canadian T_s (Figures 3e–3h). This suggests that the spread in the composite stratospheric NAM due to the different constituent SSW events does not explain the spread of the composite surface anomalies.

We now consider the full distributions of 2,000 bootstrapped composites. We begin by showing the uncertainty in the composites for our surface climate indices, comparing the bootstrapped composites to a baseline of 2,000 climatological composites (Figure 4). In all cases except that of North Pacific SLP (Figure 4c), there are large shifts in anomalies in these regions following composite SSWs, with little overlap with the baseline distributions. Further, for all composite SSW distributions except the North Pacific SLP and the Eastern US T_s (Figures 4c and 4f), the anomalies across all composites are of the same sign. The Eastern US T_s anomaly is positive in only 10 SSW composites out of 2,000. The North Pacific anomaly shows both less separation from the baseline and a less consistent sign across the composites, with 20% showing negative values.

To investigate the North Pacific region further, we separate the observed events by ENSO phase (NOAA (National Oceanic and Atmospheric Administration), n.d.) due to the influence of ENSO in the region and known interactions between ENSO and the stratospheric polar vortex (e.g., Butler & Polvani, 2011; Domeisen et al., 2019; Polvani et al., 2017). We use a similar bootstrapping process as above, forming composites of 10 SSW events for each ENSO phase (El Niño, La Niña, and neutral); the number of SSW events is reduced due to the sampling available for each ENSO phase. In El Niño and La Niña, North Pacific SLP anomalies (Figure S4 in Supporting Information S1) are shifted positively following SSW composites compared to the baseline composites (+1.3 hPa and +0.59 hPa respectively), but we see the opposite in neutral-ENSO (−0.71 hPa). These results do not suggest a clear influence of SSWs modulated by ENSO in the North Pacific.

Unlike the clear shifts in the mean, there is little difference in the width and shape of the distributions between the climatological and SSW composites. This implies that most of the spread is not a result of differences in composite SSW strength. To demonstrate this, we directly consider the relationship between the surface climate indices and vortex strength as measured by the 10 hPa polar cap (65°–90°N) geopotential height anomaly in the first 5 days after the SSW central date, denoted z10-5 day (Figure 5). This period is chosen to capture the strongest anomaly at 10 hPa. We highlight in blue and red respectively the 10th and 90th percentile composites (spatial patterns shown in Figures 3, S2 and S3 in Supporting Information S1). In all cases, there is no sizable correlation between the surface anomaly and z10-5 day (correlation coefficients ranging from 0.0 to 0.26 in absolute value). Thus, the spread in the composite surface responses is not the result of spread in the composite strength of SSWs as measured by z10-5 day. There is a stronger relationship (correlation coefficients ranging from 0.25 to 0.49 in absolute value) between the surface anomalies and the stratospheric anomalies at 100 hPa in the 5 days following the central date (Figure S5 in Supporting Information S1), suggesting that strong and rapid descent of the NAM signal to the lower troposphere is associated with larger anomalies at the surface. However, 100 hPa is too low to measure the strength of the

10.1029/2021GL095493

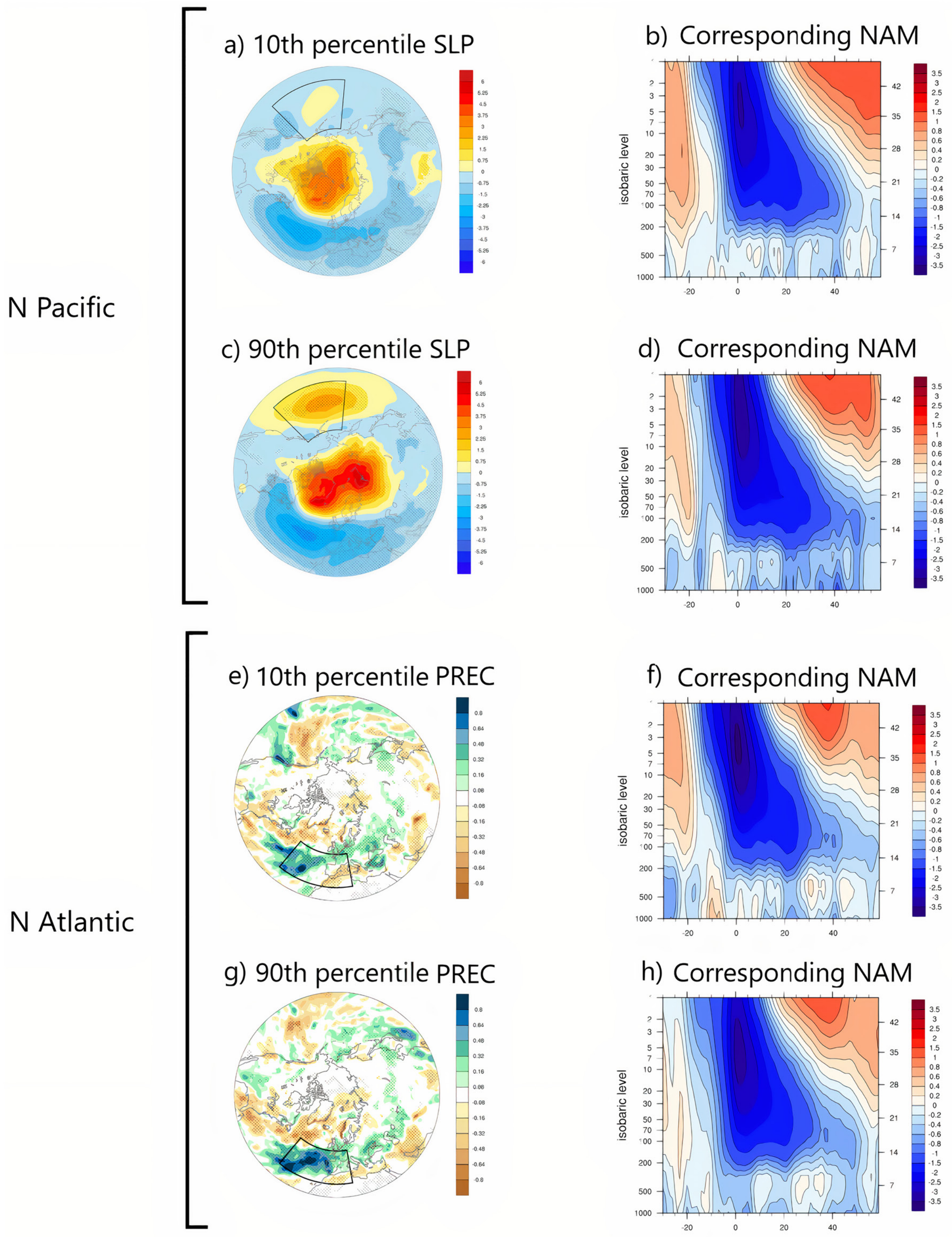

Figure 3. Surface anomaly and Northern Annular Mode (NAM) fields for days 0–60 following the sudden stratospheric warming (SSW) central date for the synthetic SSW composites corresponding to the 10th and 90th percentile values of the North Atlantic Oscillation (NAO) (a–d) and East Canadian T_s (e–h) indices. SLP, sea level pressure.

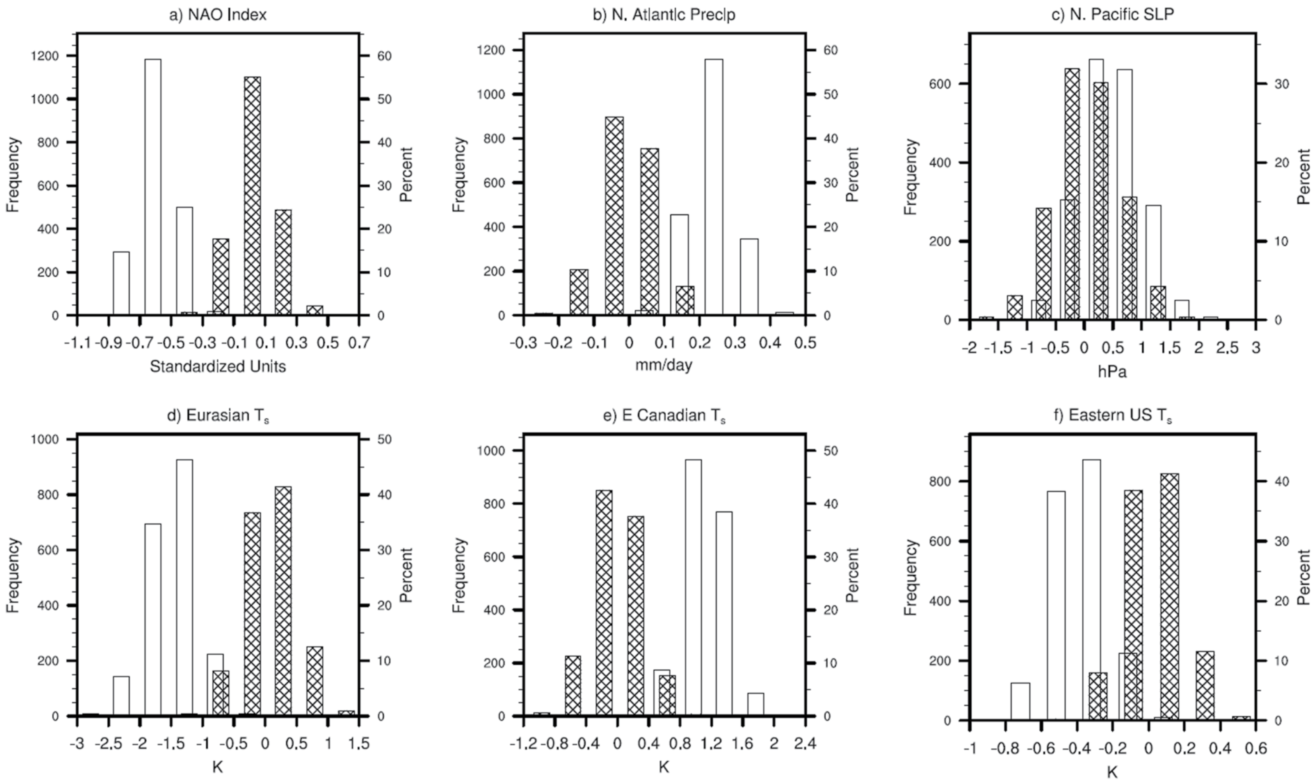

Figure 4. Unfilled: histograms of the composite surface responses in the 60 days following the sudden stratospheric warming central date for (a) North Atlantic Oscillation (NAO), (b) North Atlantic precipitation (mm/day), (c) North Pacific sea level pressure (SLP) (hPa), (d) Eurasian T_s (K), (e) Eastern Canadian T_s (K), and (f) Eastern United States T_s (K), from the 2,000 synthetic composites. Hatched: histograms from the corresponding 2,000 climatological synthetic composites.

main stratospheric vortex; further, the composite NAM anomaly at 100 hPa explains less than 25% of the variance in the composite surface climate indices. Correlations between the 60-day surface anomalies and sliding windows of z-5 day across pressure levels and lag (Figure S6 in Supporting Information S1) show that persistence of lower stratospheric anomalies to days 40–50 may be related to the strength of surface anomalies. However, there are no instances in which the stratospheric spread explains more than 25% of the surface variability. Therefore, we conclude that the vast majority of the spread in the surface composite responses is a result of tropospheric internal variability, independent of the stratosphere.

4. Conclusions

Using over 60 years of data comprising 39 SSW events and applying a bootstrapping procedure to construct 2,000 synthetic SSW composites, we find that the Northern Hemisphere composite surface climate anomalies following a composite SSW exhibit considerable uncertainty in both pattern and magnitude. Well-known SSW responses such as a negative NAO and cooling across Northern Eurasia are robust, as are temperature anomalies in Eastern Canada and the Eastern United States. However, these responses vary by a factor of 3 in magnitude, and the spatial extent of the anomalies also varies widely.

The key finding of this study is that, though the sign of the response is robust, the uncertainty in surface response to SSWs is largely unrelated to polar vortex conditions; that is, a more disrupted polar vortex in a given composite of SSW events does not correspond to stronger-magnitude surface anomalies in general. This suggests that the range of patterns and amplitudes seen at the surface across the bootstrapped SSW composites is the result of unrelated tropospheric variability. There is some relationship between descent and persistence of geopotential height anomalies to the lower stratosphere and the strength of anomalies at the surface, in agreement with previous studies on variability across SSW events (Baldwin et al., 2003; Christiansen, 2005; Gerber et al., 2009; Karpechko et al., 2017; Rao et al., 2020; Runde et al., 2016;

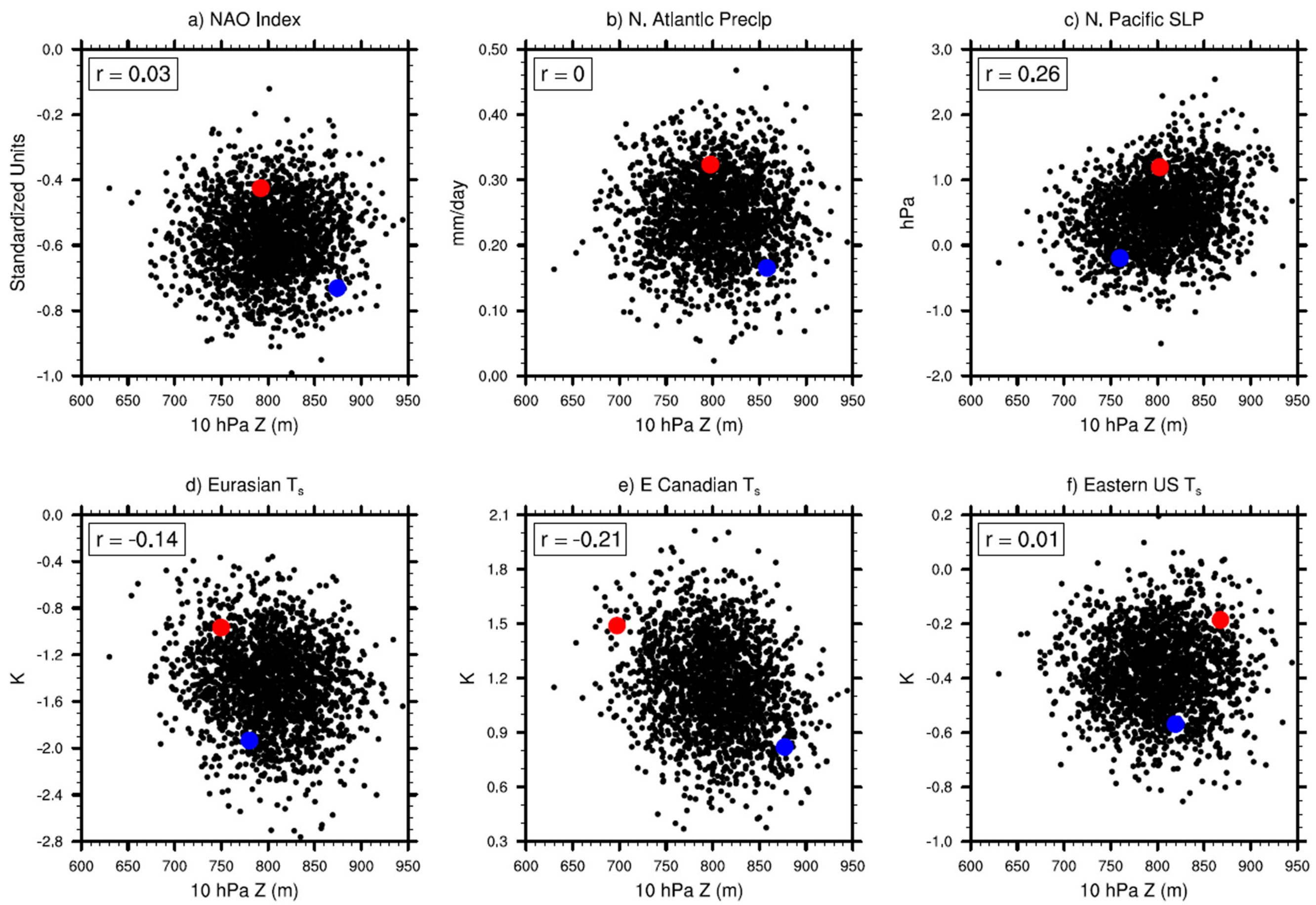

Figure 5. Scatterplots of the composite anomalies of (a) North Atlantic Oscillation (NAO), (b) North Atlantic precipitation, (c) North Pacific sea level pressure (SLP), (d) Eurasian T_s, (e) Eastern Canadian T_s, and (f) Eastern United States T_s in the 0–60 days following sudden stratospheric warmings versus the strength of the composite stratospheric polar vortex in days 0–5 (z10-5 day), for each of the 2,000 synthetic composites. Blue and red dots denote the 10th and 90th percentile composites respectively, for each surface climate index. The value r shown in each panel is the linear correlation coefficient between the two quantities.

Siegmund, 2005). However, we find that this descent to the lower stratosphere makes only a minor contribution to the variability at the surface, leaving 75% or more of the spread across the synthetic SSW composites to independent tropospheric sources. This is also in agreement with previous work (Baldwin et al., 2021; Chan & Plumb, 2009; Charlton-Perez et al., 2018; Domeisen et al., 2020; Garfinkel et al., 2013).

Large ensembles of model simulations are often used to study phenomena with few observed events (i.e., V. Thompson et al., 2017; Wang et al., 2020). The observational results shown in this study can be used to benchmark such climate model simulations of SSW responses. In models for which a large number of simulations under the same radiative forcing scenario are available ("initial-condition Large Ensembles" Deser et al., 2020), the bootstrapping procedure can be bypassed and the SSW composites can be derived directly for each ensemble member. Such an analysis will be helpful for distinguishing between true model biases and apparent biases due to sampling different tropospheric variability unrelated to SSWs. This approach was applied to the evaluation of ENSO composite responses simulated by three climate model Large Ensembles by Deser et al. (2017, 2018). Some models overpredict the strength or persistence of the negative NAO response after SSWs (Kolstad et al., 2020), hampering their effective usage in NAO prediction for government, industry, and health applications in Europe (Charlton-Perez et al., 2021; Domeisen & Butler, 2020). Thus, a careful evaluation of model response to SSWs that accounts for sampling fluctuations due to independent tropospheric variability would be of societal benefit.

Data Availability Statement

Japanese 55-Year Reanalysis (JRA-55) data are available from the Research Data Archive at the National Center for Atmospheric Research (Japan Meteorological Agency, Japan, 2013).

Acknowledgments
The authors thank two anonymous reviewers for their constructive comments and suggestions. J. Oehrlein is funded by National Science Foundation (NSF) grant DGE 16-44869. L. M. Polvani is funded by NSF grant 1914569 to Columbia University. This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under cooperative agreement 1852977.

References

Afargan-Gerstman, H., & Domeisen, D. I. V. (2020). Pacific modulation of the North Atlantic storm track response to sudden stratospheric warming events. *Geophysical Research Letters*, *47*(2). https://doi.org/10.1029/2019GL085007

Ayarzagüena, B., Barriopedro, D., Garrido-Perez, J. M., Abalos, M., Cámara, A., García-Herrera, R., et al. (2018). Stratospheric connection to the abrupt end of the 2016/2017 Iberian drought. *Geophysical Research Letters*, *45*(22), 12639–12646. https://doi.org/10.1029/2018gl079802

Baldwin, M. P., Ayarzagüena, B., Birner, T., Butchart, N., Butler, A. H., Charlton-Perez, A. J., et al. (2021). Sudden stratospheric warmings. *Reviews of Geophysics*, *59*(1). https://doi.org/10.1029/2020rg000708

Baldwin, M. P., & Dunkerton, T. J. (2001). Stratospheric harbingers of anomalous weather regimes. *Science*, *294*(5542), 581–584. https://doi.org/10.1126/science.1063315

Baldwin, M. P., Stephenson, D. B., Thompson, D. W. J., Dunkerton, T. J., Charlton, A. J., & O'Neill, A. (2003). Stratospheric memory and skill of extended-range weather forecasts. *Science*, *301*(5633), 636–640. https://doi.org/10.1126/science.1087143

Butler, A. H., & Gerber, E. P. (2018). Optimizing the definition of a sudden stratospheric warming. *Journal of Climate*, *31*(6), 2337–2344. https://doi.org/10.1175/jcli-d-17-0648.1

Butler, A. H., Lawrence, Z. D., Lee, S. H., Lillo, S. P., & Long, C. S. (2020). Differences between the 2018 and 2019 stratospheric polar vortex split events. *Quarterly Journal of the Royal Meteorological Society*, *146*(732), 3503–3521. https://doi.org/10.1002/qj.3858

Butler, A. H., & Polvani, L. M. (2011). El Niño, La Niña, and stratospheric sudden warmings: A reevaluation in light of the observational record: EL NIÑO, LA NIÑA, AND SSWS. *Geophysical Research Letters*, *38*(13). https://doi.org/10.1029/2011gl048084

Butler, A. H., Sjoberg, J. P., Seidel, D. J., & Rosenlof, K. H. (2017). A sudden stratospheric warming compendium. *Earth System Science Data*, *14*. https://doi.org/10.5194/essd-9-63-2017

Chan, C. J., & Plumb, R. A. (2009). The response to stratospheric forcing and its dependence on the state of the troposphere. *Journal of the Atmospheric Sciences*, *66*(7), 2107–2115. https://doi.org/10.1175/2009jas2937.1

Charlton, A. J., & Polvani, L. M. (2007). A new look at stratospheric sudden warmings. Part I: Climatology and modeling benchmarks. *Journal of Climate*, *20*(3), 449–469. https://doi.org/10.1175/jcli3996.1

Charlton-Perez, A. J., Ferranti, L., & Lee, R. W. (2018). The influence of the stratospheric state on North Atlantic weather regimes. *Quarterly Journal of the Royal Meteorological Society*, *144*(713), 1140–1151. https://doi.org/10.1002/qj.3280

Charlton-Perez, A. J., Huang, W. T. K., & Lee, S. H. (2021). Impact of sudden stratospheric warmings on United Kingdom mortality. *Atmospheric Science Letters*, *22*(2).

Charlton-Perez, A. J., & Polvani, L. M. (2011). Corrigendum. *Journal of Climate*, *24*(22), 5951–5951. https://doi.org/10.1175/jcli-d-11-00348.1

Christiansen, B. (2005). Downward propagation and statistical forecast of the near-surface weather: Downward propagation in weather forecast. *Journal of Geophysical Research*, *110*(D14). https://doi.org/10.1029/2004jd005431

Deser, C., Lehner, F., Rodgers, K., Ault, T., Delworth, T. L., DiNezio, P. N., et al. (2020). Insights from earth system model initial-condition large ensembles and future prospects. *Nature Climate Change*, *10*, 277–286. https://doi.org/10.1038/s41558-020-0731-2

Deser, C., Simpson, I. R., McKinnon, K. A., & Phillips, A. S. (2017). The northern hemisphere extratropical atmospheric circulation response to ENSO: How well do we know it and how do we evaluate models accordingly? *Journal of Climate*, *30*(13), 5059–5082. https://doi.org/10.1175/jcli-d-16-0844.1

Deser, C., Simpson, I. R., Phillips, A. S., & McKinnon, K. A. (2018). How well do we know ENSO's climate impacts over North America, and how do we evaluate models accordingly? *Journal of Climate*, *31*(13), 4991–5014. https://doi.org/10.1175/jcli-d-17-0783.1

Domeisen, D. I. V. (2019). Estimating the frequency of sudden stratospheric warming events from surface observations of the North Atlantic Oscillation. *Journal of Geophysical Research: Atmospheres*, *124*(6), 3180–3194. https://doi.org/10.1029/2018jd030077

Domeisen, D. I. V., & Butler, A. H. (2020). Stratospheric drivers of extreme events at the Earth's surface. *Communications Earth & Environment*, *1*(1), 59. https://doi.org/10.1038/s43247-020-00060-z

Domeisen, D. I. V., Garfinkel, C. I., & Butler, A. H. (2019). The teleconnection of El Niño Southern Oscillation to the stratosphere. *Reviews of Geophysics*, *57*(1), 5–47. https://doi.org/10.1029/2018rg000596

Domeisen, D. I. V., Grams, C. M., & Papritz, L. (2020). The role of North Atlantic–European weather regimes in the surface impact of sudden stratospheric warming events. *Weather and Climate Dynamics*, *1*(2), 373–388. https://doi.org/10.5194/wcd-1-373-2020

Fujiwara, M., Wright, J. S., Manney, G. L., Gray, L. J., Anstey, J., Birner, T., et al. (2017). Introduction to the SPARC Reanalysis Intercomparison Project (S-RIP) and overview of the reanalysis systems. *Atmospheric Chemistry and Physics*, *17*(2), 1417–1452. https://doi.org/10.5194/acp-17-1417-2017

Garfinkel, C. I., Waugh, D. W., & Gerber, E. P. (2013). The effect of tropospheric jet latitude on coupling between the stratospheric polar vortex and the troposphere. *Journal of Climate*, *26*(6), 2077–2095. https://doi.org/10.1175/jcli-d-12-00301.1

Gerber, E. P., Martineau, P., Ayarzagüena, B., Barriopedro, D., Bracegirdle, T. J., Butler, A. H., et al. (2021). Extratropical stratosphere-troposphere coupling. In M. Fujiwara, G. L. Manney, L. J. Gray, & J. S. Wright (Eds.), *SPARC Reanalysis Intercomparison Project (S-RIP) final report* (Chap. 6, SPARC Report No. 10, WCRP-6/2021). https://doi.org/10.17874/800dee57d13

Gerber, E. P., Orbe, C., & Polvani, L. M. (2009). Stratospheric influence on the tropospheric circulation revealed by idealized ensemble forecasts. *Geophysical Research Letters*, *36*(24), L24801. https://doi.org/10.1029/2009gl040913

Japan Meteorological Agency, Japan. (2013). *JRA-55: Japanese 55-year reanalysis, daily 3-hourly and 6-hourly data*. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6HH6H41

Karpechko, A. Y., Hitchcock, P., Peters, D. H. W., & Schneidereit, A. (2017). Predictability of downward propagation of major sudden stratospheric warmings: Downward propagation of SSWs. *Quarterly Journal of the Royal Meteorological Society*, *143*(704), 1459–1470. https://doi.org/10.1002/qj.3017

King, A. D., Butler, A. H., Jucker, M., Earl, N. O., & Rudeva, I. (2019). Observed relationships between sudden stratospheric warmings and European climate extremes. *Journal of Geophysical Research: Atmospheres*, *19*. https://doi.org/10.1029/2019jd030480

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., et al. (2015). The JRA-55 reanalysis: General specifications and basic characteristics. *Journal of the Meteorological Society of Japan. Series II*, *93*(1), 5–48. https://doi.org/10.2151/jmsj.2015-001

Kodera, K., Mukougawa, H., Maury, P., Ueda, M., & Claud, C. (2016). Absorbing and reflecting sudden stratospheric warming events and their relationship with tropospheric circulation: Absorbing and reflecting sudden warmings. *Journal of Geophysical Research: Atmospheres*, *121*(1), 80–94. https://doi.org/10.1002/2015jd023359

Kolstad, E. W., Breiteig, T., & Scaife, A. A. (2010). The association between stratospheric weak polar vortex events and cold air outbreaks in the Northern Hemisphere. *Quarterly Journal of the Royal Meteorological Society*, *8*. https://doi.org/10.1002/qj.620

Kolstad, E. W., Wulff, C. O., Domeisen, D. I. V., & Woollings, T. (2020). Tracing North Atlantic Oscillation forecast errors to stratospheric origins. *Journal of Climate*, *33*(21), 9145–9157. https://doi.org/10.1175/jcli-d-20-0270.1

Maycock, A. C., & Hitchcock, P. (2015). Do split and displacement sudden stratospheric warmings have different annular mode signatures?: Annular mode signatures of SSWs. *Geophysical Research Letters*, *42*(24), 10943–10951. https://doi.org/10.1002/2015gl066754

Mitchell, D. M., Gray, L. J., Anstey, J., Baldwin, M. P., & Charlton-Perez, A. J. (2013). The influence of stratospheric vortex displacements and splits on surface climate. *Journal of Climate*, *26*(8), 2668–2682. https://doi.org/10.1175/jcli-d-12-00030.1

NOAA (National Oceanic and Atmospheric Administration). (n.d.). *Cold & warm episodes by season*. Retrieved from https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

Oehrlein, J., Chiodo, G., & Polvani, L. M. (2020). The effect of interactive ozone chemistry on weak and strong stratospheric polar vortex events. *Atmospheric Chemistry and Physics*, *20*(17), 10531–10544. https://doi.org/10.5194/acp-20-10531-2020

Polvani, L. M., Sun, L., Butler, A. H., Richter, J. H., & Deser, C. (2017). Distinguishing stratospheric sudden warmings from ENSO as key drivers of wintertime climate variability over the North Atlantic and Eurasia. *Journal of Climate*, *30*(6), 1959–1969. https://doi.org/10.1175/jcli-d-16-0277.1

Rao, J., Garfinkel, C. I., & White, I. P. (2020). Predicting the downward and surface influence of the February 2018 and January 2019 sudden stratospheric warming events in subseasonal to seasonal (S2S) models. *Journal of Geophysical Research: Atmospheres*, *125*(2). https://doi.org/10.1029/2019jd031919

Runde, T., Dameris, M., Garny, H., & Kinnison, D. E. (2016). Classification of stratospheric extreme events according to their downward propagation to the troposphere. *Geophysical Research Letters*, *43*(12), 6665–6672. https://doi.org/10.1002/2016GL069569

Scaife, A. A., Folland, C. K., Alexander, L. V., Moberg, A., & Knight, J. R. (2008). European climate extremes and the North Atlantic Oscillation. *Journal of Climate*, *21*(1), 72–83. https://doi.org/10.1175/2007jcli1631.1

Seviour, W. J. M., Gray, L. J., & Mitchell, D. M. (2016). Stratospheric polar vortex splits and displacements in the high-top CMIP5 climate models: Vortex splits and displacements in CMIP5. *Journal of Geophysical Research: Atmospheres*, *121*(4), 1400–1413. https://doi.org/10.1002/2015jd024178

Siegmund, P. (2005). Stratospheric polar cap mean height and temperature as extended-range weather predictors. *Monthly Weather Review*, *133*(8), 2436–2448. https://doi.org/10.1175/mwr2985.1

Thompson, D. W. J., & Wallace, J. M. (2001). Regional climate impacts of the northern hemisphere annular mode. *Science*, *293*(5527), 85–89. https://doi.org/10.1126/science.1058958

Thompson, V., Dunstone, N. J., Scaife, A. A., Smith, D. M., Slingo, J. M., Brown, S., & Blecher, S. E. (2017). High risk of unprecedented UK rainfall in the current climate. *Nature Communications*, *8*(107). https://doi.org/10.1038/s41467-017-00275-3

Wang, L., Hardiman, S. C., Bett, P. E., Comer, R. E., Kent, C., & Scaife, A. A. (2020). What chance of a sudden stratospheric warming in the southern hemisphere? *Environmental Research Letters*, *15*, 104038. https://doi.org/10.1088/1748-9326/aba8c1

White, I., Garfinkel, C. I., Gerber, E. P., & Jucker, M. (2019). The downward influence of sudden stratospheric warmings: Association with tropospheric precursors. *Journal of Climate*, *32*, 24. https://doi.org/10.1175/jcli-d-18-0053.1