AGU ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL106288

Identifying Perturbations That Tipped the Stratosphere Into a Sudden Warming During January 2013

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Key Points:

- We identify key atmospheric features over the North Atlantic in "correct" forecasts of the January 2013 Sudden Stratospheric Warming (SSW)
- Transplanting these conditions between ensemble members can systematically increase or decrease the SSW forecast probability
- The proposed methodology can demonstrate the causality of specific atmospheric features and their role in medium and long-range forecasts

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Citation:

Kent, C., Scaife, A. A., Seviour, W. J. M., Dunstone, N., Smith, D., & Smout-Day, K. (2023). Identifying perturbations that tipped the stratosphere into a sudden warming during January 2013. *Geophysical Research Letters*, *50*, e2023GL106288. https://doi.org/10.1029/2023GL106288

Received 12 SEP 2023
Accepted 6 DEC 2023

Abstract

We present a new methodology demonstrating that specific small-magnitude regional perturbations can cause large systematic responses in subseasonal predictions. We show this with ensemble forecasts of the January 2013 Sudden Stratospheric Warming (SSW) from an operational long-range global prediction system. In forecast members which predict the SSW, tropospheric ridging over the North Atlantic is strengthened 10 days prior to the event. This subsequently enhances planetary wave forcing and weakens the stratospheric polar vortex. Transplanting tropospheric conditions in this region from "correct" to "incorrect" forecasts (and vice versa) significantly alters the SSW forecast probability. The occurrence of this SSW is therefore strongly controlled by the troposphere several days prior. Tipping more members into a sudden warming also significantly affects surface predictions the following month. Despite chaotic behavior of the climate system, small-magnitude synoptic-scale perturbations can drive different dynamical states and systematically impact medium and long-range predictions.

Plain Language Summary

Subseasonal forecast ensembles exhibit a large spread in conditions after several days. Some ensemble members go on to produce "correct" forecasts whilst others do not: is this unorganized chaotic noise, or can specific perturbations drive systematic responses? We investigate this with forecasts of the January 2013 Sudden Stratospheric Warming (SSW). Comparing "correct" and "incorrect" SSW forecasts we identify key differences developing over the North Atlantic shortly after initialization. To demonstrate causality, we take atmospheric conditions for this region from a "correct" forecast member and insert them into all other forecast members. This change significantly increases the number of "correct" forecasts of the SSW 10 days later. The reverse experiment, taking conditions from an "incorrect" member, significantly decreases the SSW forecast probability. These results demonstrate how specific atmospheric features can systematically influence predictions at medium and long-range time scales, potentially providing additional skill at times of uncertainty.

1. Introduction

Ensembles of subseasonal forecasts diverge due to chaotic noise and can be used to provide probabilities of different outcomes. In a chaotic system nearby trajectories rapidly separate and after 1–2 weeks the ensemble contains a wide variety of atmospheric conditions, implying an intrinsic limit of deterministic predictability in the midlatitudes (Lorenz, 1969; Selz et al., 2022). Beyond this timescale some ensemble members can produce "correct" forecasts, as demonstrated for example, in the lead up to the record-breaking heatwave in the UK during July 2022 (Holley & Lee, 2022), whilst other forecast members do not. In this study we investigate whether this is the result of unorganized chaotic noise throughout the forecast, or, whether specific perturbations can lead to a systematic and predictable impact on the forecast outcome. If systematic perturbations can be isolated, this information could improve our understanding of the atmosphere as well as real-time forecasts. We use the January 2013 Sudden Stratospheric Warming (SSW) as a case study.

Skillful predictions of SSWs (Butler et al., 2017; Charlton & Polvani, 2007) are a major source of extended-range predictability for the northern hemisphere winter (Scaife et al., 2016) as they can affect surface conditions for the following 30–60 days (Baldwin & Dunkerton, 2001; Domeisen & Butler, 2020; Domeisen et al., 2020b; Kolstad et al., 2010). During an SSW the westerly polar stratospheric winds weaken and easterlies descend throughout the stratosphere (Baldwin et al., 2021). The deterministic lead time for predicting this reversal is approximately 2 weeks (Butler et al., 2019; Domeisen et al., 2020a; Karpechko et al., 2018; Marshall & Scaife, 2010; Taguchi, 2020).

SSWs are driven by the rapid amplification and breaking of upward propagating Rossby waves (Baldwin et al., 2021; Matsuno, 1971) associated with both tropospheric wave activity (Bao et al., 2017; Garfinkel et al., 2010; Martius et al., 2009; Matsuno, 1971) and internal stratospheric conditions (Christiansen, 1999; Holton & Mass, 1976; Matthewman & Esler, 2011; Scaife & James, 2000). There can be a high sensitivity to stratospheric conditions when the tropospheric flow is constrained (de la Cámara et al., 2017), as well as a critical role from wave generation by extratropical cyclones (Cho et al., 2022). Historical analysis suggest at least one third of SSWs immediately follow anomalous tropospheric wave activity, with the longer-term accumulation of upward wave activity also important (Birner & Albers, 2017; de la Cámara et al., 2019; Polvani & Waugh, 2004). Understanding the roles of these different processes within subseasonal forecasts is an active area of research (Hitchcock et al., 2022).

Here we focus on the 2012–2013 major SSW (Butler et al., 2017). Following two pronounced decelerations in December the polar vortex zonal-mean zonal wind became easterly on 7 January. This event was associated with cold air outbreaks across Europe and North Asia during January 2013 (Liu & Zhang, 2014; Nath et al., 2016). Studies suggest that tropospheric precursors, including blocking and an explosively developing extratropical cyclone, and pre-conditioning of the stratosphere, played a role in its development (Attard et al., 2016; Coy & Pawson, 2015; Vargin & Medvedeva, 2015). A multi-model comparison indicates the SSW was predictable up to 2 weeks ahead, with the development of planetary wave activity in the troposphere being a key component (Tripathi et al., 2016).

We investigate if "correct" predictions of the event depend upon tropospheric perturbations at specific locations and lead times. We build on previous analyses using a large ensemble (200 members) initialized on 25 December 2013 (13-day lead time) from a fully-coupled ocean-atmosphere operational prediction system (Section 2). We classify ensemble members based on deterministic criteria, that is, those which do and do not forecast the SSW onset date. Comparing these two subsets we identify physically coherent differences associated with the SSW (Section 3). To demonstrate causality we transplant conditions from one member into all other members and assess the resulting change in forecast probability and long-range prediction (Section 4). We explore regional sensitivity of transplanting in Section 4 and discuss the implications in Section 5.

2. Data Sets and Experimental Design

2.1. Data Sets

Observed windspeed, mean sea level pressure (MSLP) and temperature conditions during December 2012 through to January 2013 were taken from the ERA5 reanalysis data set (Hersbach et al., 2020). Hourly data were extracted from https://cds.climate.copernicus.eu/ and bilinearly interpolated to the dynamical model grid.

Subseasonal forecasts are taken from the Met Office operational long-range prediction system GloSea (MacLachlan et al., 2015) with the GC3.2 configuration (Williams et al., 2018). It is a fully-coupled (ocean-atmosphere) global climate model with a resolution of approximately 60 km in the atmosphere and 0.25° in the ocean. Identical initial conditions are used and ensemble spread between members is generated by stochastic physics schemes, which aim to reflect uncertainties due to sub-grid processes (Sánchez et al., 2016).

2.2. Experimental Design

To explore causality of atmospheric perturbations we make use of a "transplant" function, allowing geographical sections of atmospheric fields for each model member to be independently modified. In this case atmospheric fields for specific regions are transplanted from a selected ensemble member into all others. Unlike nudging techniques (e.g., Jung et al., 2008; Maidens et al., 2019) there is no transition function or smoothing and the transplanting is performed at only one time step during the forecast, which then continues running without further intervention. We transplant zonal and meridional winds, density, humidity and potential temperature for model levels 1–47 (surface to approximately 100 hPa). Restricting the vertical extent to 200 hPa does not affect our findings.

The "control" ensemble comprises 200 members initialized on 25 December 0000z (13 days prior to the SSW) with a forecast period of 3 months. For additional experiments we transplant tropospheric conditions (see Section 3

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10.1029/2023GL106288

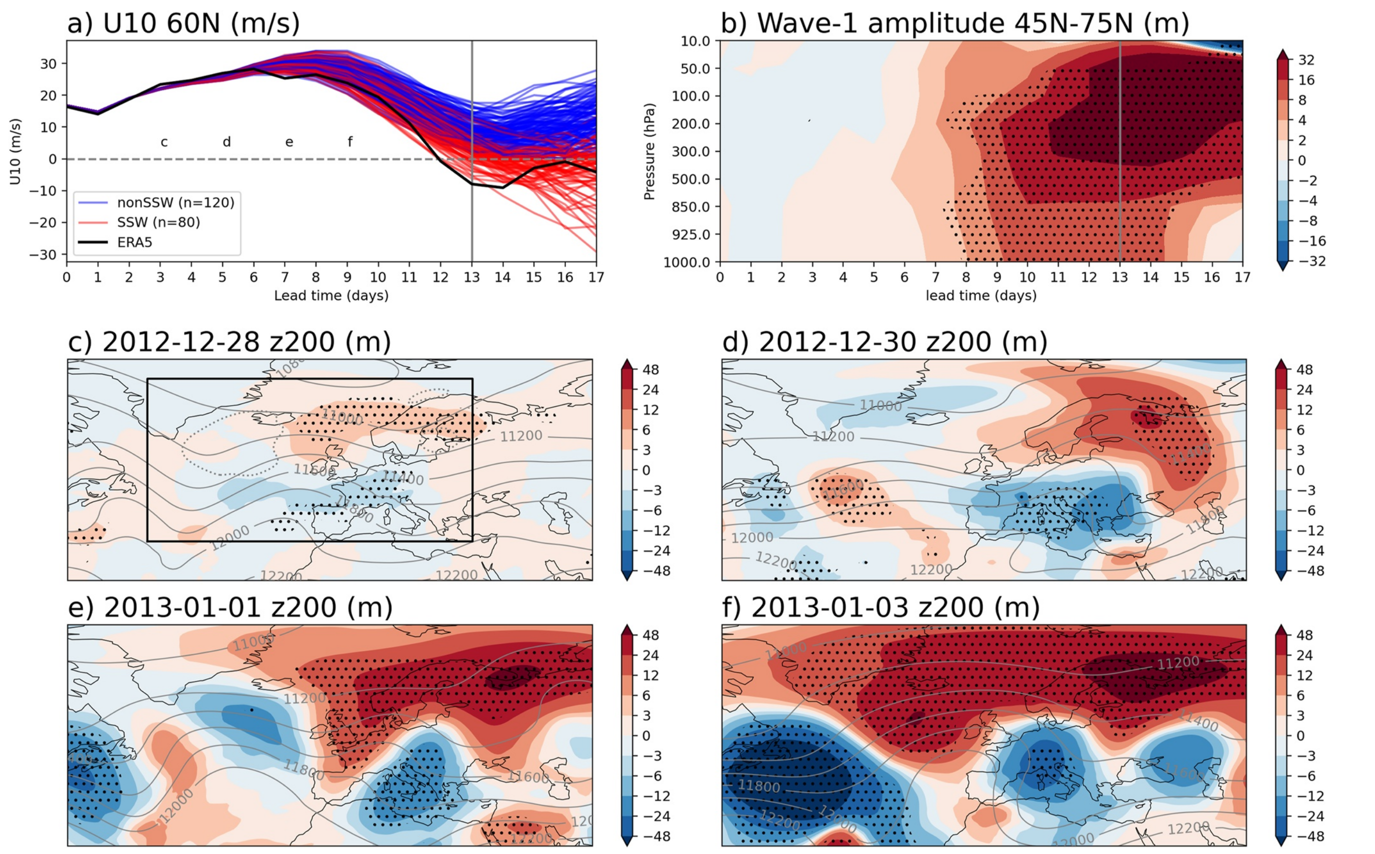

Figure 1. Differences between "correct" ($n = 80$) and "incorrect" ($n = 120$) forecasts initialized on 25 December 2012. (a) Zonal mean zonal wind at 10 hPa and 60°N (red = "correct," blue = "incorrect"), the ERA5 reanalysis in black (gray indicates Sudden Stratospheric Warming onset date), and letters indicate timing of panels (c)–(f). (b) Difference in geopotential wave-1 amplitudes as a function of lead time. (c–) Differences in geopotential height at 200 hPa (z200). Ensemble mean ($n = 200$) z200 shown in gray contours. Stippling indicates significant differences (*T*-test, 95% confidence level). Black box in (c) is the chosen region for transplanting. Gray dashed contours in (c) show the 990 mb mean sea level pressure. Units are m for all except (a) m s^{-1}.

below) from one member into all other 199 members at a specific forecast time and then allow the simulations to continue. Using conditions extracted from a member which correctly predicts the SSW forms the "SSWplus" ensemble. An identical setup with an ensemble member that does not predict the SSW forms the "SSWminus" ensemble. Importantly, as GloSea is bit-reproducible, the difference between these two 200-member ensembles and the control is solely due to the transplanting.

For each ensemble member we assess the deterministic skill of the SSW onset date. Specifically, we classify a "correct" forecast if the zonal mean zonal wind at 10 hPa and 60°N becomes negative (easterly) between 6 and 12 January 2013. A stricter time window does not alter the conclusions of our study.

3. Perturbations Associated With "Correct" SSW Forecasts

Within the control ensemble 80 of the 200 ensemble members (40%) correctly predict the zonal mean zonal wind reversal at 10 hPa and 60°N (Figure 1a), 54 of which are within a stricter ±2 days window. In general, the model predicts the SSW onset to occur slightly later than seen in ERA5, although the onset date is within the ensemble spread.

In the lower and mid-troposphere, planetary wave-1 amplitudes (45–75°N) are found to be significantly larger approximately 7 days prior to the event in members with "correct" SSW forecasts (Figure 1b). This signal grows and propagates up into the stratosphere over several days, a time scale consistent with that of an upward propagating planetary-scale Rossby wave. This indicates that the perturbations which project positively onto the tropospheric wave-1 forcing may be linked to a systematic response in the ensemble. Geopotential height composites show this signal to be primarily located over the North Atlantic and Scandinavian region and not the North Pacific (not shown).

Within 24 hr of initialization we find little evidence of spatially coherent anomalies within the 80 SSW members (not shown). After 72 hr an extratropical cyclone develops in all members in the North Atlantic (Figure 1c, dashed gray contour) and undergoes explosive cyclogenesis (Sanders & Gyakum, 1980). The cyclone intensity is slightly deeper, but not significantly so, in "correct" ensemble members. However, the associated downstream high located over the United Kingdom is significantly enhanced and corresponds to a dipole structure in the developing upper-tropospheric ridge (Figure 1c). These composite differences are relatively small in magnitude ($\pm$5 m geopotential height at 200 hPa) and all members show similar synoptic conditions in absolute terms.

Over the next 2 days the ridge continues to strengthen and leads to upper-level anticyclonic wave-breaking (Figure 1d, gray contours). Ensemble members which predict the SSW show a greater reversal of tropospheric potential vorticity gradient over eastern Europe representing a significantly stronger wave breaking event (Figure 1d, shading). Following this, blocking over northern Russia and Scandinavia is enhanced and the zonal wind is reduced across northern Europe 6 days prior to the SSW. The geopotential height anomalies (Figure 1e, shading) correspond to significantly weaker upper-tropospheric winds in "correct" forecasts.

A Rossby wave propagating over North America enters the Atlantic basin and encounters the weakened flow around the 3 January 2013 (Vargin & Medvedeva, 2015). A ridge develops across the Atlantic sector (Figure 1f, gray contours) which is significantly stronger in "correct" members (Figure 1f, shading) and projects positively onto the tropospheric planetary wave-1 forcing (Figure 1b).

The deepening extra-tropical cyclone and North Atlantic blocking correspond well with previous analyses of this event, as well as tropospheric precursor locations for SSWs (Coy & Pawson, 2015; Garfinkel et al., 2010; Kolstad et al., 2010; Lee et al., 2019; Martius et al., 2009; Tripathi et al., 2016; Vargin & Medvedeva, 2015). However, these studies do not demonstrate causality, that is, if changing these features impacts the prediction of the SSW, which is our aim.

To test causality we focus on conditions 72 hr after initialization (Figure 1c, shading) and select the ensemble member which exhibits the strongest 200 mb geopotential height dipole ([9°W–15°E, 43°N–49°N] minus [12°W–28°E, 60°N–68°N]). This member predicts the SSW onset on 8 January 2013 (1 day after the observed) and also exhibits the strongest spatial correlation with the ensemble composites shown in Figure 1c. The SSWplus experiment is generated by transplanting conditions (black box Figure 1c) from this member into all other 199 members at 0000z on 28 December 2012. All members are then restarted and continue without further modification.

The reverse experiment, SSWminus, is identical except that conditions are transplanted from the ensemble member with the weakest upper-level dipole and which does not predict the SSW. We select the strongest and weakest dipole members to help isolate the impact this pattern has on the ensemble. Importantly, the average magnitude of the transplanted anomalies across members ($\pm$25 m in 200 hPa geopotential height) is small compared to the model's climatological variability in this region ($\sim$200 m, daily standard deviation from 1993 to 2016). We do not find any significant spurious features due to discontinuities at the boundaries of the transplanted region.

4. Results

4.1. Transplanting Perturbations Systematically Impacts SSW Forecasts

Remarkably, within the SSWplus ensemble the SSW forecast probability is significantly increased from 40% (in the control) up to 66.5%. In addition, the reverse experiment (SSWminus) significantly decreases the probability down to 27.5%. The probability of the SSW in the ensemble therefore depends systematically on the small perturbations from the transplanted conditions (Figure 1c).

In terms of the polar vortex strength on 7 January 2013, the transplanting experiments are associated with a decrease (SSWplus) or increase (SSWminus) of approximately 5 m s^{-1} (Figure 2a). Furthermore, for all 200 members the polar vortex is systematically weakened (negative wind anomalies) for at least 10 days following the transplanting (Figure 2b). These results demonstrate that small-magnitude perturbations 10 days prior to the event can systematically alter the polar vortex and tip the stratosphere toward a greatly increased likelihood of a sudden warming.

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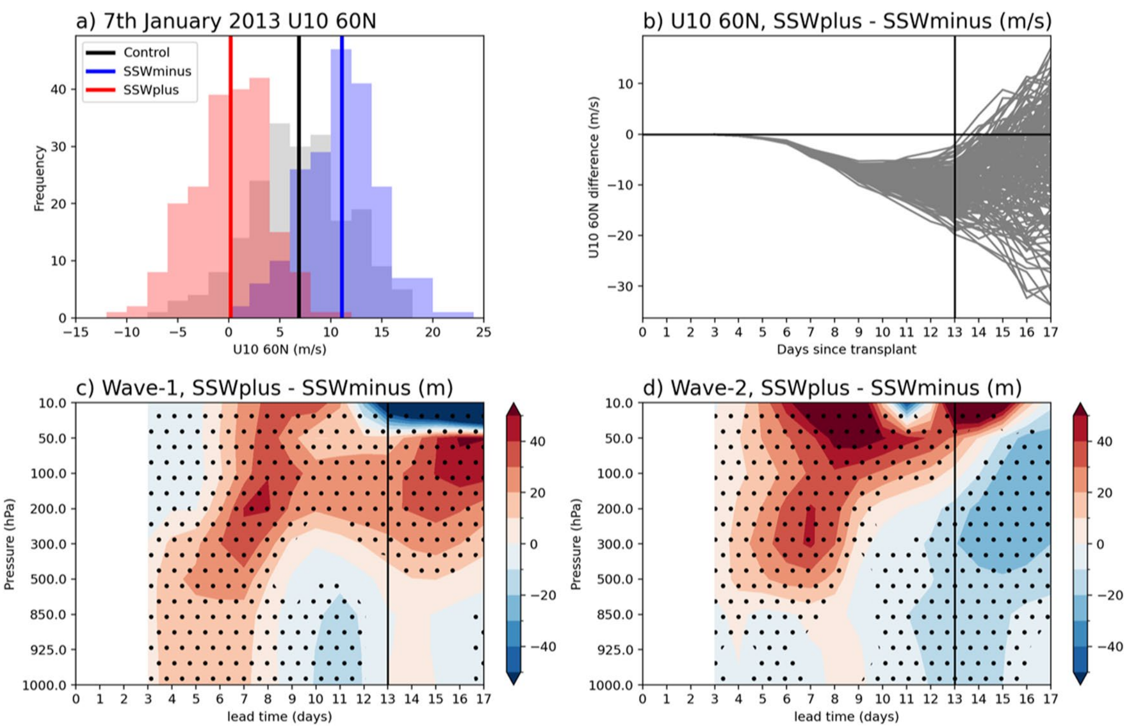

Figure 2. Transplanting systematically impacts Sudden Stratospheric Warming (SSW) forecasts. (a) Polar vortex strength (zonal mean zonal wind at 10 hPa, 60°N) in the control, SSWplus and SSWminus ensembles on 7 January 2013. Solid lines indicate ensemble mean. Impact on polar vortex strength (b) due to transplanting for each member (SSWplus—SSWminus) and planetary wave amplitudes (45–75°N) for wave number 1 (c) and 2 (d). Stippling indicates significant differences (95% confidence level). Transplanting occurs on day 3 and the SSW day 13 (vertical black line in bcd). Units are m s^{-1} (ab) and m (cd).

The geopotential height wave amplitude anomalies (Figures 2c and 2d) show that the transplanting significantly affects the tropospheric flow. Planetary wave amplitudes are increased and propagate upwards into the stratosphere as seen within the control ensemble (Figure 1b), although now for wavenumbers 1 and 2. Significant differences are observed within the stratosphere directly after transplanting due to the model adjusting to the inserted tropospheric conditions. The primary signal however develops within the troposphere in which the anticyclonic Rossby wave breaking on 30 December is strengthened (greater potential vorticity inversion), the zonal wind is reduced across northern Europe on 1 January, and enhanced ridging occurs over the North Atlantic. The impact of the transplanting aligns well with the dynamical mechanism identified within the control ensemble leading up to the SSW.

Performing identical experiments but restricting the vertical extent of the transplanting to ~200 hPa, or extending it to include all model levels, did not alter the ensemble forecast further, indicating that for this region and event it appears to be primarily tropospheric perturbations which are key.

4.2. Influence on Subseasonal Predictions for January 2013

Analysis of the polar cap (60–90°N) geopotential height differences (SSWplus—SSWminus) show a rapid increase in high latitudes due to the increased number of members tipping into a sudden warming (Figure 3a). This signal persists for several weeks throughout January 2013.

Composite differences for the surface response during January 2013 (Figure 3b) show that the transplanting leads to significant increases in MSLP across the northernmost Atlantic and Arctic. The ensemble mean North Atlantic Oscillation (regional definition of Dunstone et al., 2016) is significantly reduced, in line with canonical SSW responses (e.g., Baldwin & Dunkerton, 2001; Bett et al., 2023; Hall et al., 2023; Kidston et al., 2015), and results in reduced MSLP forecast errors over Iceland and northern United Kingdom (Figure 3c). Forecast improvements are also seen across the Arctic and Eurasia, but not directly over the Atlantic indicating that the observed tropospheric coupling and regional influence is not fully captured, a limitation seen in other events and models (Karpechko et al., 2018).

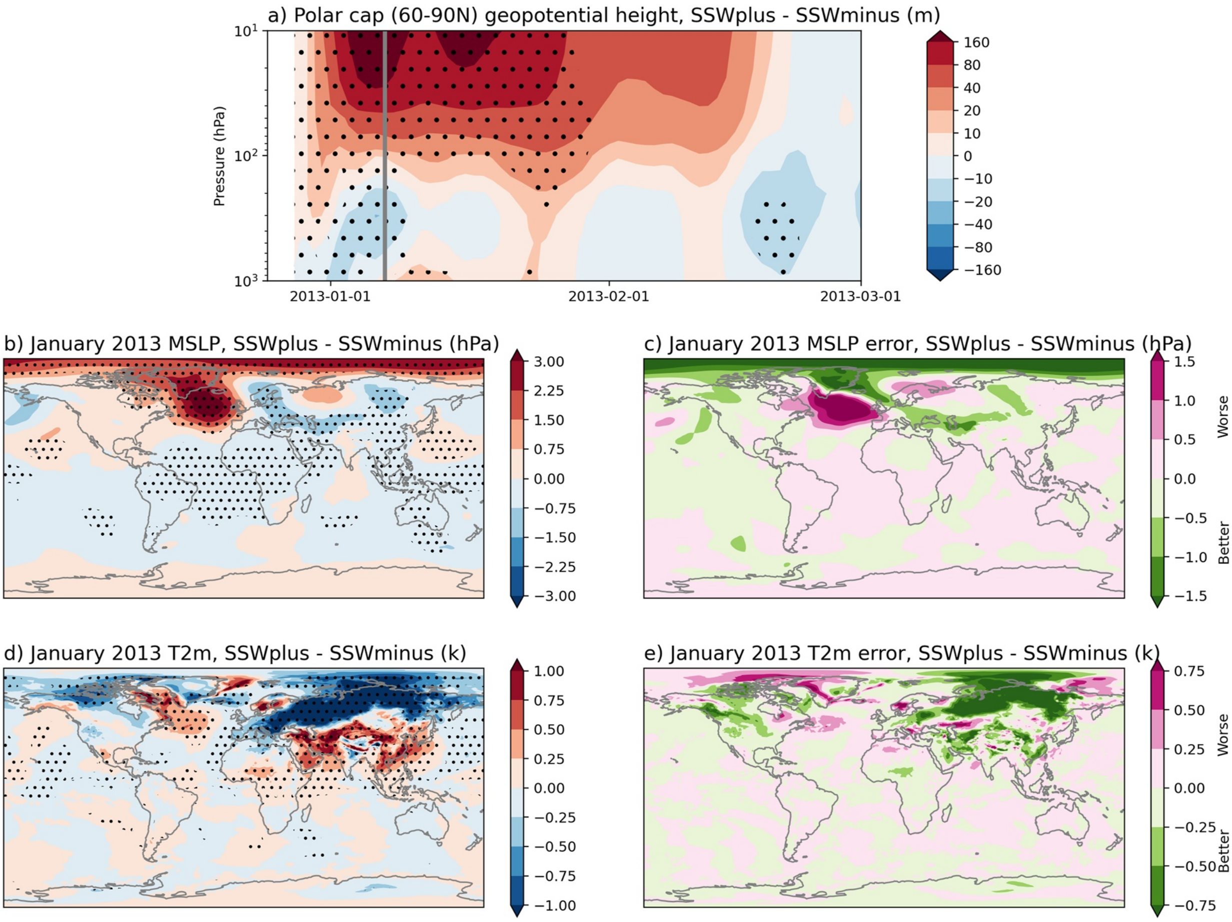

Figure 3. Impact of transplanting (SSWplus—SSWminus) on subseasonal predictions during January 2013. (a) Daily polar cap (60–90°N) geopotential height differences (m), (b) monthly mean sea level pressure (MSLP) (hPa), (c) monthly MSLP Root Mean Square Error (RMSE) difference (hPa), (c) monthly 2 m temperature (k), and (d) monthly 2 m temperature RMSE difference. Stippling indicates significant differences (95% confidence level). The lead-time dependent bias is removed.

Large parts of the northern hemisphere also exhibit significant differences in forecast surface temperature (Figure 3d). In particular, the transplanting drives a dipole response with cooling (warming) across much of Europe and North Asia (South and East Asia). These are associated with reduced forecast errors (Figure 3e), suggesting that the cold conditions experienced were linked to the SSW, and that tipping more members into a sudden warming strengthens this signal.

We note that the zonal mean signal (Figure 3a) is generally weaker than expected when compared to other SSW events (Baldwin & Dunkerton, 2001; Karpechko et al., 2018). This is likely due to the overall weakened state of the polar vortex even in the SSWminus experiment. Thus the differences largely reflect a comparison between major and minor SSW forecasts. The large ensemble size helps to reduce noise, however we cannot completely rule out that the surface changes seen result from tropospheric dynamics. Nevertheless, the perturbations identified shortly after initialization in December 2012 lead to significantly different and improved surface predictions across much of the northern hemisphere for January 2013.

4.3. Regional Sensitivity of Transplanting Tropospheric Conditions

To understand the potential limit of the transplanting methodology we repeat the SSWplus experiment transplanting the whole tropical and northern hemisphere region (20°S–90°N). Tropospheric perturbations which could systematically influence the stratosphere over the 10-day lead time are expected to be located within this region, hence this experiment can be regarded as an "upper limit" test. Transplanting this large area significantly increases the SSW forecast probability from 40% in the control up to 82.5% (165 out of 200 members). The

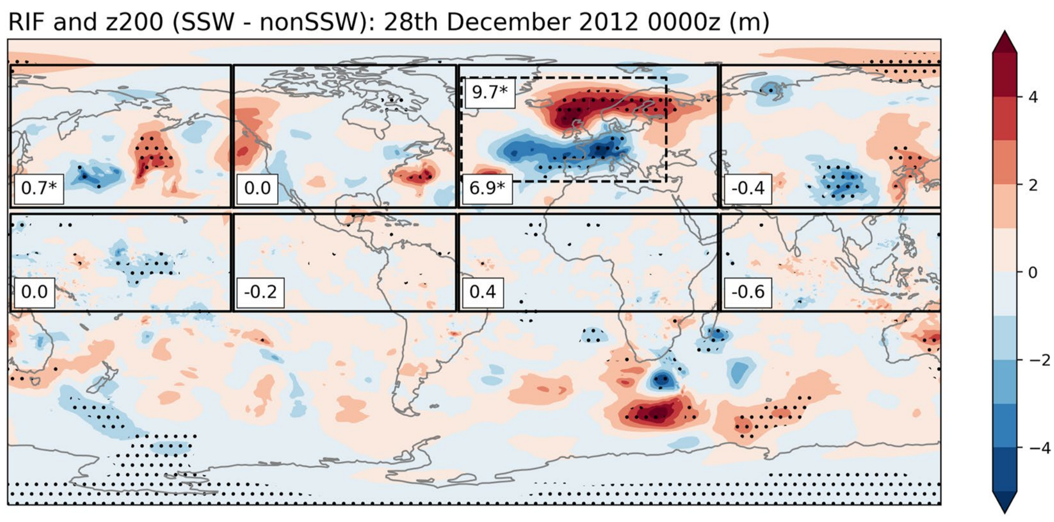

Figure 4. Regional sensitivity of transplanting on 28 December 2012. (a) Difference in z200 (m) between Sudden Stratospheric Warming (SSW) and non-SSW members within Control, stippling indicates significance at 95% confidence level. Solid black boxes show regional transplanting locations with Regional Importance Factor (RIF) score in lower left corner (* indicates significant change in SSW frequency). Dashed box represents SSWplus and SSWminus transplant locations.

reverse experiment, based on SSWminus, decreases the probability to 11%. The North Atlantic transplant region in the SSWplus experiment therefore provides over half of the potential increase in SSW frequency but uses approximately 6% of the area.

To explore the geographic sensitivity of the transplanting we perform new experiments across the northern hemisphere and define the Regional Importance Factor (RIF), for region, r, as

$$\mathrm{RIF}_r = \left(\frac{S_r - S_{\mathrm{control}}}{S_{\mathrm{upper}} - S_{\mathrm{control}}}\right) \bigg/ \left(\frac{A_r}{A_{\mathrm{upper}}}\right)$$

where S is the number of "correct" ensemble members, A is the spatial area (km^2), and "control" and "upper" subscripts are the control and northern hemisphere experiment results. RIF relates the magnitude of any changes to that expected if the signal was evenly distributed across the northern hemisphere.

When repeating the transplant experiment independently for 8 approximately equal area regions (Figure 4) the North Atlantic sector exhibits a sensitivity approximately 10 times greater than that of other similar sized regions globally. The sensitivity increases to almost 10 when restricting the transplant region to that over the North Atlantic (dashed box, Figure 4). However, transplanting only one node of the dipole (i.e., upper or lower regions) did not produce a systematic response. A significant increase in SSW probability is observed when transplanting over the North Pacific, however, this is much smaller than the North Atlantic and the RIF is less than 1. These two regions exhibit significantly reduced forecast errors (compared with ERA5), suggesting they could be identified shortly after initialization, providing a new avenue for interpreting forecasts at times of heightened ensemble uncertainty. For all other regions (solid boxes, Figure 4) the SSW probability exhibits no systematic response despite some containing significant differences between "correct" and "incorrect" members.

5. Discussion and Conclusions

Tipping elements and bifurcations of the climate system are present in many contexts, but most commonly discussed in relation to a changing climate (Lenton et al., 2008). Here we have demonstrated their importance within subseasonal predictions and how they can be driven by small-magnitude regional perturbations. Our work extends empirical analyses of SSW forecasts (Karpechko et al., 2018; Kolstad et al., 2010; Lee et al., 2019; Tripathi et al., 2016) by presenting a methodology which can demonstrate causality of specific atmospheric features and their role in tipping the stratosphere into a sudden warming.

Focusing on the January 2013 SSW, with a lead time of 10 days, we identify perturbations over the North Atlantic which strengthen an anticyclonic Rossby wave breaking event and systematically change the probability of an SSW. In turn this impacts the long-range predictions for January 2013, significantly improving surface predictions across large parts of Eurasia. Our results show that tropospheric conditions exhibited a strong control during this event and highlights high sensitivity of sudden warmings to the strength, and not just occurrence, of tropospheric blocking events.

Given that the polar vortex is weakened leading up to the event, it is possible that any perturbations may effect the SSW probability. However, our results show a systematic influence. Transplanting from a correct forecast member significantly increased the SSW forecast probability, whilst the reverse experiment produced a significant decrease. The imposed perturbations physically relate to strengthening (or weakening) the dynamical mechanism associated with driving the SSW. Furthermore, in all 200 ensemble members there is a systematic weakening of the polar vortex for at least 10 days due to the transplanting (SSWplus—SSWminus). When increasing the SSW forecast probability, the sensitivity found in the North Atlantic region is order 10 times greater than other geographic areas. Finally, the identified signal aligns well with previously identified SSW precursors and relates to reduced forecast errors. These factors provide confidence of a systematic link with the SSW.

Interestingly, we find greater sensitivity to transplanting over the Atlantic than the Pacific despite both regions being important sources of planetary wave activity prior to SSWs (Martius et al., 2009). We speculate that this is due to two factors; (a) planetary waves 1 and 2 overlap constructively over the eastern North Atlantic & North Europe region, and (b) it is the area of largest ensemble spread at time of transplanting. Thus it can provide the largest relative differences between "correct" and "incorrect" forecasts and the subsequent blocking projects positively onto the planetary wave forcing. This potentially indicates a link between subseasonal predictions and so-called "predictability barriers" (González-Alemán et al., 2022; Sánchez et al., 2020). The method here allows identification of critical regional perturbations which may of course differ from event to event. A key research extension is therefore to explore the regional sensitivity for other SSWs.

In our experiments mesoscale (or smaller) perturbations could not systematically influence the SSW forecast probability. An additional investigation to find the specific source (e.g., grid cell) of the North Atlantic dipole perturbations also proved unsuccessful. At short lead times (<24 hr) differences between members exhibit considerable noise, and transplanting mesoscale conditions had no effect on the ensemble's SSW prediction. Instead, a small (but significant) increase could be achieved by transplanting conditions over synoptic (or larger) scales. This provides further evidence that small-magnitude synoptic-scale perturbations can dominate over small-scale "butterflies" in terms of the ensemble spread and error growth (Durran & Gingrich, 2014; Durran & Weyn, 2016; Rodwell & Wernli, 2023).

We have demonstrated the power of large ensembles to identify spatially coherent perturbations shortly after initialization, which can significantly influence medium- and long-range forecasts, potentially providing additional skill at times of uncertainty. The results raise several interesting questions for future research, including how common such atmospheric features are across other events or lead times, to what extent other perturbations can influence forecasts of extreme events such as this, and how transplanting can be utilized to better understand and update ensemble forecasts prior to extreme events.

Data Availability Statement

The ERA5 reanalysis data is available through the Copernicus Climate Data Store (Hersbach et al., 2023). Model data utilized to create the figures are available via Zenodo (Kent, 2023).

Acknowledgments

This work was supported by the Met Office Hadley Centre Climate Programme (HCCP) funded by the UK Department for Science, Innovation and Technology (DSIT) and the UK Public Weather Service. We also thank two expert reviewers.

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