Received: 7 April 2022 | Revised: 22 July 2022 | Accepted: 27 July 2022
DOI: 10.1002/asl.1126

Atmospheric Science Letters RMetS

RESEARCH ARTICLE

Predictability of European winter 2020/2021: Influence of a mid-winter sudden stratospheric warming

Julia F. Lockwood[1] | **Nicky Stringer**[1] | **Hazel E. Thornton**[1] | **Adam A. Scaife**[1,2] | **Philip E. Bett**[1] | **Tamara Collier**[1] | **Ruth Comer**[1] | **Nick Dunstone**[1] | **Margaret Gordon**[1] | **Leon Hermanson**[1] | **Sarah Ineson**[1] | **Jamie Kettleborough**[1] | **Jeff Knight**[1] | **Joseph Mancell**[1] | **Peter McLean**[1] | **Doug Smith**[1] | **Tony Wardle**[1] | **Prince Xavier**[1] | **Ben Youngman**[2]

[1]Met Office Hadley Centre, Exeter, UK
[2]College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK

Correspondence
Julia F. Lockwood, Met Office Hadley Centre, FitzRoy Road, Exeter, EX1 3PB, UK.
Email: julia.lockwood@metoffice.gov.uk

Funding information
Met Office Hadley Centre Climate Programme funded by BEIS and Defra; UK Public Weather Service

Abstract

Boreal winter (December–February) 2020/2021 in the North Atlantic/European region was characterised by a negative North Atlantic Oscillation (NAO) index. Although this was captured within the ensemble spread of predictions from the Met Office Global Seasonal forecast system (GloSea5), with 17% of ensemble members predicting an NAO less than zero, the forecast ensemble mean was shifted towards a positive NAO phase. The observed monthly NAO anomalies were particularly negative in January and February, following an early January sudden stratospheric warming (SSW), and a prolonged period of Phase 6 or 7 of the Madden Julian Oscillation (MJO) in late January/early February. In contrast, predictions showed the expected teleconnection from the observed La Niña, with a positive NAO signal resulting from a weakening of the Aleutian Low leading to a reduction in tropospheric wave activity, an increase in polar vortex strength and a reduced chance of an SSW. Forecasts initialised later in the winter season successfully predicted the negative NAO in January and February once the SSW and MJO were within the medium range timescale. GloSea5 likely over-predicted the strength of the La Niña which we estimate caused a small negative bias in the SSW probability. However, this error is smaller than the uncertainty in SSW probability from the finite forecast ensemble size, emphasising the need for large forecast ensembles. This case study also demonstrates the advantage of continuously updated lagged ensemble forecasts over a 'burst' ensemble started on a fixed date, since a change in forecast signal due to events within the season can be detected early and promptly communicated to users.

KEYWORDS
European winter, North Atlantic Oscillation, Seasonal forecasting, stratosphere, teleconnections

1 | INTRODUCTION

The North Atlantic Oscillation (NAO) is the dominant pattern of atmospheric circulation variability in the North Atlantic (Wallace & Gutzler, 1981), with positive phases associated with stormy, mild and wet conditions over north-west Europe and eastern United States, and negative phases associated with dry, cold conditions (and vice versa for southwest Europe and eastern Canada). Recently, the surface winter mean (December–February [DJF]) NAO has been demonstrated to be predictable 1 month ahead (Athanasiadis et al., 2017; Scaife et al., 2014), and this has been followed by real time operational predictions from the Met Office's seasonal prediction system, GloSea5, where the model ensemble mean has consistently predicted the correct sign of the anomaly (Dunstone et al., 2018; Hardiman et al., 2020; Knight et al., 2021; Scaife et al., 2017), aiding decision makers in sectors such as transport (Palin et al., 2016), energy (Clark et al., 2017; Thornton et al., 2019) and water management (Stringer et al., 2020; Svensson et al., 2015).

Winter 2020/2021 saw a moderate amplitude La Niña, that is, a cool phase of the El Niño Southern Oscillation (ENSO), which was over-predicted by GloSea5. The ensemble mean of GloSea5, along with all other seasonal forecast systems on the C3S Climate Datastore (https://climate.copernicus.eu/charts/c3s_seasonal/), showed a clear signal for a strong polar vortex, positive phase NAO and higher than average temperatures in northern Europe. This is consistent with current understanding of the ENSO-NAO teleconnection via the stratospheric pathway (Hardiman et al., 2019; Ineson & Scaife, 2009; Moron & Gouirand, 2003). Tropospheric teleconnection pathways between ENSO and the North Atlantic have also been documented, for example, via the propagation from the Pacific to Atlantic of quasi-stationary Rossby wave trains and/or transient eddies (e.g., Jiménez-Esteve & Domeisen, 2018), as well as excitation of Rossby waves in the North Atlantic itself (e.g., Ayarzagüena et al., 2018). Here, however, we focus on the stratospheric pathway because strong anomalies in the forecast polar vortex imply that it was the dominant mechanism operating in the model.

For the stratospheric pathway, tropical rainfall anomalies associated with La Niña excite a Rossby wave emanating from the tropical Pacific which weakens the Aleutian Low, reducing the amplitude of climatological Wavenumber 1, thus reducing vertical wave activity propagating into the stratosphere (Iza et al., 2016). This allows the polar vortex to remain strong with a reduced chance of a sudden stratospheric warming (SSW), as was indeed indicated by GloSea5 in advance of the winter season. The resulting positive stratospheric westerly wind anomalies subsequently propagate towards the surface and increase the chance of a positive NAO (Baldwin & Dunkerton, 2001; Kidston et al., 2015).

On this occasion, however, an SSW occurred on 5 January 2021 (Lee, 2021), with the strength of the stratospheric polar vortex remaining below its climatological strength until mid-February (Rao et al., 2021). The NAO was on average negative for the season (−7.8 hPa; see Section 3.1), with associated cooler-than-average near surface air temperatures over Northern Europe (−0.4 K with respect to the average over the model hindcast period, averaged over 10° W–50° E; 50° N–65° N). The NAO monthly anomalies were particularly low in January (−13.4 hPa) and February (−9.3 hPa). A prolonged period of the Madden Julian Oscillation (MJO) in Phases 6 and 7 (defined by the multivariate MJO index; Wheeler & Hendon, 2004) from mid-January to mid-February 2021, may have also played a role in amplifying and extending the negative NAO (Cassou, 2008).

In this paper we examine the predictability and impact of the SSW and MJO on the NAO, and by analysing the La Niña-Aleutian Low-SSW teleconnection in GloSea5 we assess whether the observed outcome was indeed a low probability event (within the ensemble spread but towards the tail of the distribution), or whether there is any evidence for forecast error.

The paper is structured as follows. Section 2 describes the GloSea5 forecast system and the observational datasets used. In the Results (Section 3) we compare the forecast to observations (Section 3.1) and examine the predictability and impact of the SSW and Phase 6 or 7 MJO (Section 3.2). The relationship between La Niña, the Aleutian Low and SSWs in GloSea5 and observations is explored in Section 3.3 to examine whether the teleconnection in model and observations are consistent, and to estimate the impact of the over-forecast La Niña on SSW probability. The discussion and conclusions are given in Section 4.

2 | SEASONAL FORECAST SYSTEM AND OBSERVATIONAL DATASETS

We use the real-time seasonal forecasts produced by the Met Office GloSea5 seasonal prediction system (MacLachlan et al., 2015), which initialises two forecast members each day using current daily atmospheric and oceanic analysis data. The forecasts for DJF were initialised on 2–22 November 2020, giving a lagged forecast ensemble of 42 members. To investigate the predictability of the SSW and Phase 6 or 7 MJO (Section 3.2) we use forecasts initialised later in the season (up to 1 February 2021).

For calculating the GloSea5 climatology we use the 'operational' hindcasts, which are produced concurrently with the forecasts (MacLachlan et al., 2015). These cover the period 1993/1994 to 2016/2017, with seven members initialised on each of the 1, 9 and 17 November each hindcast year, giving 21 hindcast ensemble members. For estimating the hindcast polar vortex and SSW climatology (Figures 2 and 6), we double the hindcast ensemble size to 42 members by including the operational hindcasts produced in 2019. For both the hindcasts and forecasts, ensemble members initialised on the same day differ only via stochastic perturbations (Bowler et al., 2009).

Sea surface temperature (SST) observations are from the HadSST4 dataset (Kennedy et al., 2019). The ENSO index is defined using SST anomalies in the Niño 3.4 region, with errors estimated using the uncertainty information provided with HadSST4 as described in Kennedy et al. (2022). Mean sea level pressure (MSLP) verification data are from the near real time update of the HadSLP2r dataset (Allan & Ansell, 2006). The observed MJO indices are defined using the Wheeler and Hendon (2004) index and were taken from the Bureau of Meteorology (www.bom.gov.au/climate/mjo/graphics/rmm.74toRealtime.txt). All other verification data (referred to as 'observations') are from the ERA5 re-analysis (Hersbach et al., 2020).

The NAO index is defined as the anomaly in the difference between MSLP averaged over a region centred on the Azores (20° W–28° W, 36° N–40° N) and one centred on Iceland (16° W–25° W, 63° N–70° N; Dunstone et al., 2016). Throughout the paper, anomalies are given with respect to the hindcast period (1993/1994 to 2016/2017) for both model and observations.

3 | RESULTS

3.1 | Winter 2020/2021

The forecast predicted a strong La Niña for winter 2020/2021, with an ensemble mean Niño3.4 value of −1.7 K (spread −2.3 to −1.1 K). The observed value was on the upper limit of the forecast ensemble (−1.0 ± 0.4 K). The over-forecasting of ENSO is a known issue with GloSea5 (Scaife et al., 2019), and is a particular issue for La Niña (Hermanson et al., 2018).

Figure 1 shows the observed and forecast ensemble mean MSLP anomalies for DJF and each month separately, with the NAO anomalies given above each panel. The forecast intra-seasonal evolution of MSLP follows that expected for the La Niña teleconnection (Ayarzagüena et al., 2018), with positive anomalies in the North Pacific (weakening the Aleutian Low) and the presence of a North Atlantic ridge in December (Figure 1b), and a positive NAO pattern developing in late winter (Figure 1h,k). The observations show the December North Atlantic ridge in agreement with the forecast. However, in contrast to the forecast, the observed Aleutian Low is deepened in December and January (Figure 1d,g), and a negative NAO developed in January and February, although the southern node of the pattern is shifted northwards in both months compared to the canonical pattern (e.g., Hurrell et al., 2003). Winter 2010/2011 is another recent example of a negative NAO in a La Niña winter, when the negative NAO was likely forced by Atlantic SST re-emergence (Grist et al., 2019; Maidens et al., 2013; Taws et al., 2011). However, examination of the heat content anomalies (not shown) shows this is unlikely to be the case in 2020/2021. Although the outcome was different to the forecast ensemble mean, 17% of ensemble members did predict a negative NAO for DJF. Individual forecast ensemble members were able to capture MSLP patterns similar to those observed, as can be seen by the 'best' example ensemble members shown in Figure 1 (all of which predicted SSWs, where an SSW is defined by the reversal of zonal mean zonal winds at 10 hPa and 60° N). In this sense we cannot reject the null hypothesis that the difference between observed winter 2020/2021 and the typical evolution during La Niña (and the forecast ensemble mean) was simply a product of unpredictable internal atmospheric variability.

Figure 2a shows the evolution of the stratospheric polar vortex in the forecast and observations, and the corresponding fraction of forecast members that have had an SSW by each date is shown in Figure 2b. In Figure 2b, the shading shows the 95% Bayesian credible intervals, $[c_1, c_2]$, defined such that there is a 95% chance that the true SSW probability lies between c_1 and c_2 (Wilks, 2019; more detail is given in Appendix S1). As expected during La Niña (Scaife et al., 2016), the polar vortex was forecast to be stronger than average in the ensemble mean, and the forecast SSW probability remained below climatology throughout the season. The westerly quasi-biennial oscillation and quiescent MJO throughout December (see below) also favoured a low SSW probability (Rao et al., 2021). The forecast probability of an SSW during DJF was 0.33, much lower than the climatological value of 0.55, with only 1 year in the hindcast having a lower probability (the strong positive NAO winter of 2013/2014). It is clear from the credible intervals shown in Figure 2b, however, that the forecast probability calculated from only 42 members is highly uncertain, with a 95% range in SSW probability of nearly 0.3.

In the observations, the strength of the polar vortex was well above the observed climatological values in early December, in agreement with the forecast, but it rapidly decelerated in early January leading to an SSW on 5 January 2021. The disruption of the polar vortex was particularly prolonged (Lu et al., 2021; Rao et al., 2021),

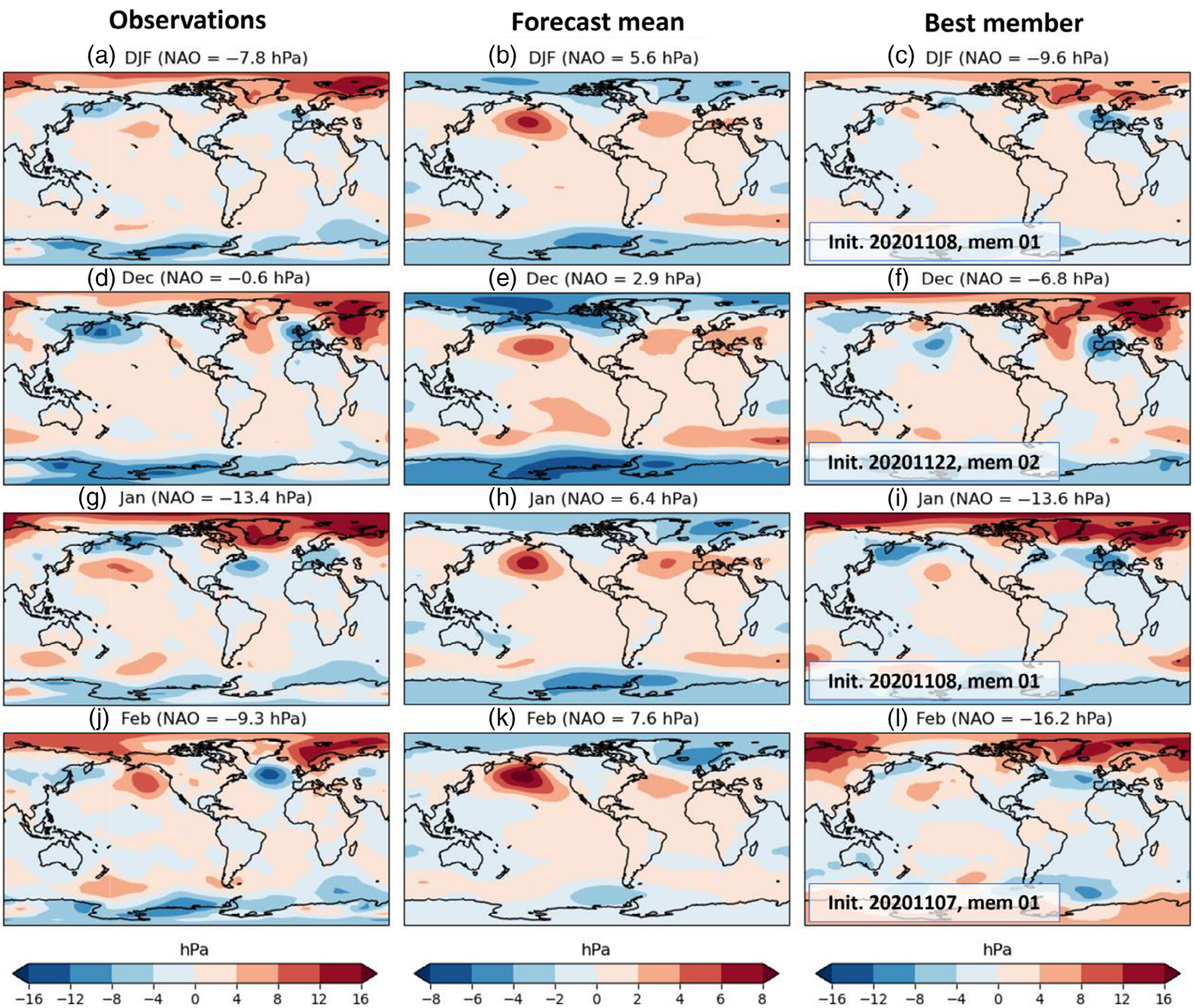

FIGURE 1 Mean sea level pressure anomalies for winter 2020/2021. Observations (a, d, g, j), forecast mean (b, e, h, k) and 'best' individual ensemble members (c, f, i, l). The top row shows the anomalies in DJF, and the remaining rows show the individual months. 'Best' ensemble members in the right hand column are identified by having the highest pattern correlation with observations over the northern hemisphere (selected separately for the DJF average and each individual month; initialisation dates given in each panel). Note the smaller scale used for the forecast mean anomalies in the middle panel.

with its strength remaining below the observed climatological average until 17 February 2021.

Figure 3 shows the timeline of the winter observations in more detail. In late December, just before the SSW onset, the zonal mean zonal winds at 60° N (Figure 3a) show easterly anomalies at the surface and throughout the troposphere and stratosphere, with corresponding negative daily NAO values (Figure 3c) and lower than average temperatures over the United Kingdom and Ireland (Figure 3d). From early January the SSW easterly anomalies appear to propagate downwards, prolonging the negative NAO/cold period at the surface. The MJO (Figure 3b) is relatively inactive until 21st January 2021, when it enters an extended period of Phase 6 or 7. Similar to El Niño, the MJO in these phases can weaken the polar vortex through tropospheric wave forcing (e.g., Jiang et al., 2017), and it has been considered an important influence on SSWs in previous winters (e.g., February 2018; Knight et al., 2021). For winter 2020/2021, although the MJO was not the SSW trigger, it may have been a factor in the prolonging the polar vortex disruption in early 2021.

3.2 | Investigating the predictability and impact of the SSW and MJO

The predictability of the SSW and MJO event are shown in Figure 4. The GloSea5 system produces two new

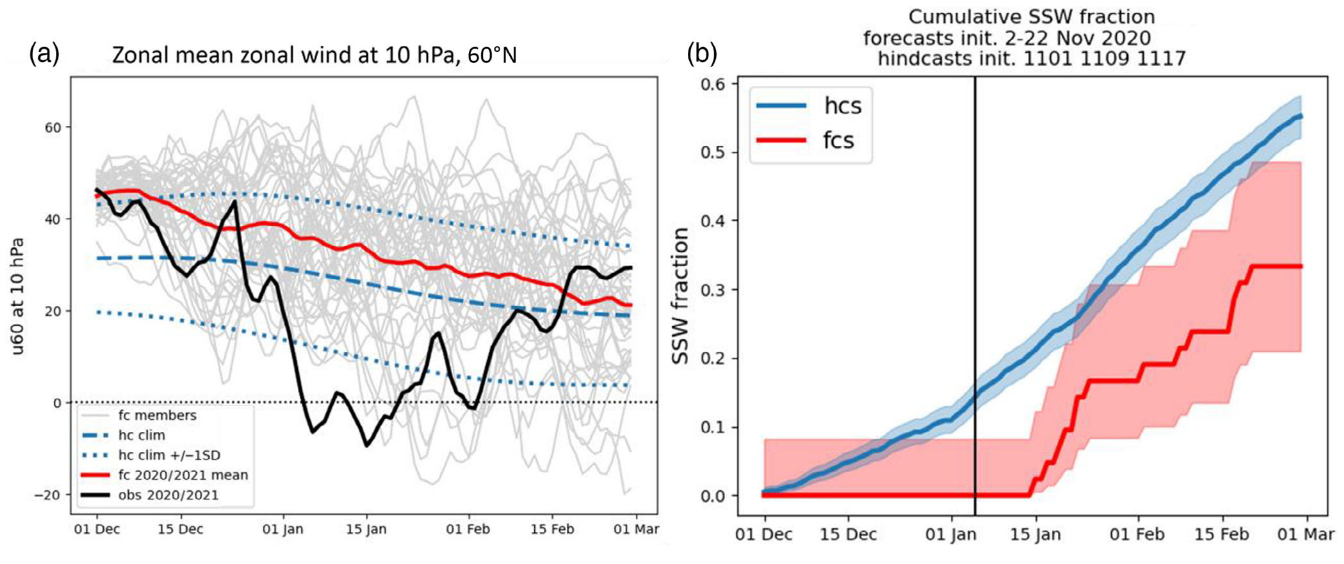

FIGURE 2 The stratospheric polar vortex and SSW probability. (a) Zonal mean zonal winds at 60° N, 10 hPa in observations (black), forecast ensemble members (grey) and the forecast ensemble mean (red). The hindcast climatology (mean ± 1 SD) is shown by the blue dashed and solid lines. (b) Fraction of ensemble members with an SSW by date in forecasts (fcs) (red) and hindcast (hcs) climatology (blue). The shading shows the 95% credible intervals on the SSW fraction (probability) calculated as described in Appendix S1.

forecast members every day, so we split the forecasts into running sub-ensembles of seven consecutive start dates (giving 14 members in each sub-ensemble), and calculate the fraction of members in each sub-ensemble that predicted the 5 January SSW (tolerance ±2 days) and the prolonged mid-to-late winter Phase 6 or 7 MJO (defined by having at least 15 days with Phase 6 or 7 MJO between 15 January and 28 February 2021, with an amplitude greater than 1). Note that in this section we use forecasts initialised throughout the winter, as opposed to the November start dates in Figure 1.

Figure 4 shows that by 25 December 2020, the SSW is predicted by the majority of ensemble members, giving a predictability lead time of approximately 11 days. This is in line with typical SSW predictability (Domeisen et al., 2020; Taguchi, 2016), and a similar result for this winter holds for other models in the subseasonal-to-seasonal prediction project (Rao et al., 2021). The long MJO event is predicted by the majority of ensemble members from just 2 days before the onset. This is because of the strict duration criteria used which requires the forecasts to correctly predict the MJO for 15 days, which is approximately the typical predictability lead time of daily MJO (12–36 days; e.g., Lim et al., 2018).

The impact of the SSW in the forecasts is shown in Figure 5, which shows the difference in MSLP composites between ensemble members that predicted an early January SSW and those that did not. The impact of the SSW is largest in January, when the difference in NAO between the ensemble members with and without the SSW is −9.5 hPa ($p \leq 0.05$). The difference reduces to −3.8 hPa in February, and even the composite for members with the SSW reverts to a neutral NAO (+1.61 hPa), indicating a waning influence of the SSW in the model in February.

The impact of the MJO in February is estimated in a similar way (Figure 5e, where MJO members are those which satisfy the same criteria as in Figure 4). Both the MJO and non-MJO composites predict negative NAO values for February, as all members are now initialised with a weak stratospheric polar vortex, but members which predicted the long MJO event have an NAO on average 4.6 hPa more negative than those which did not. We conclude that the SSW is likely to have driven a period of negative NAO in January and that the effects of the SSW were enhanced by the MJO, prolonging the negative NAO into February. Neither the SSW nor MJO were predicted in the forecasts initialised in November.

3.3 | La Niña, the Aleutian Low and SSWs

Figure 1 showed that the Aleutian Low deepened in December 2020 and January 2021, opposite to the expected effect of La Niña. This may have contributed to the pulse of planetary Wavenumber 1 activity noted by previous studies (Lu et al., 2021; Rao et al., 2021), making an SSW more likely. However, previous studies have also argued that the observational record shows an increased frequency of SSWs during La Niña winters (e.g., Butler & Polvani, 2011). Garfinkel et al. (2012) suggested this is

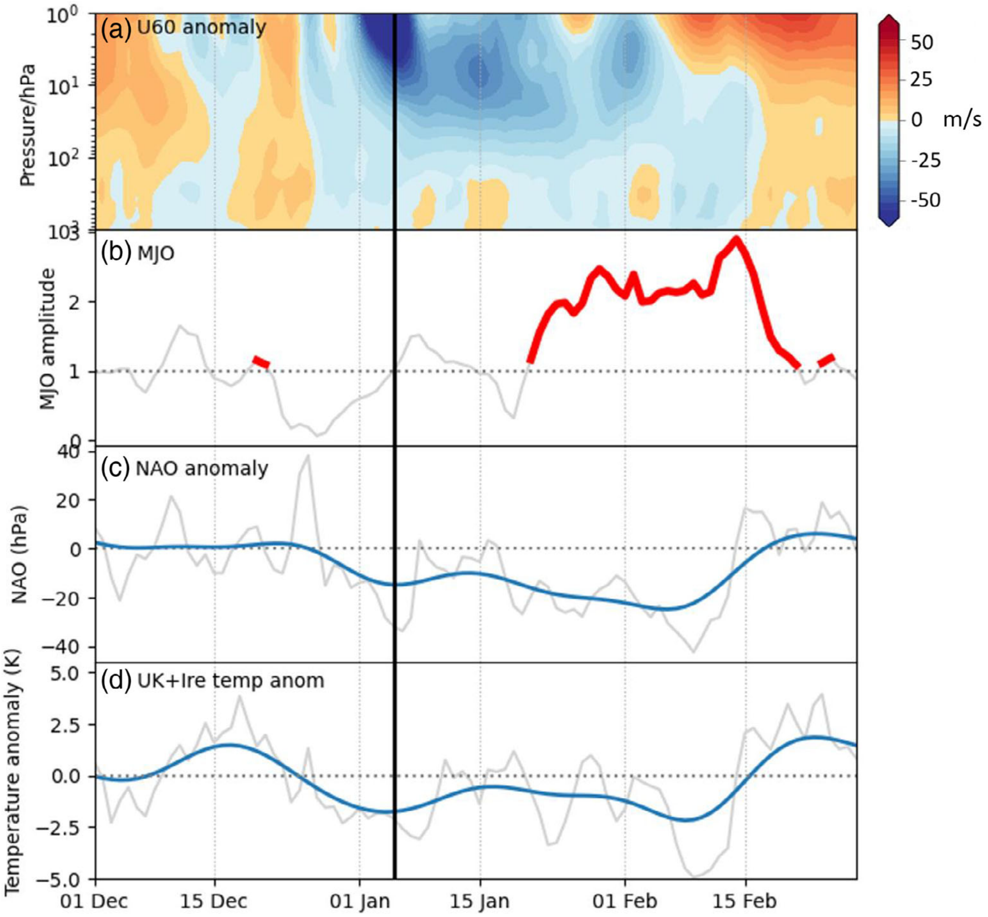

FIGURE 3 Timeline of observed events in winter 2020/2021. (a) Daily zonal mean zonal wind anomalies at 60° N throughout the atmosphere; (b) daily MJO amplitude. The thick red line marks when the MJO enters Phase 6 or 7; (c) daily (grey) and smoothed (blue, using Gaussian smoothing with 5 day SD) NAO anomalies; (d) daily (grey) and smoothed (blue) temperature anomalies averaged over United Kingdom and Ireland (defined by the region 10° W–3° E, 50° N–60° N). In (a), (c) and (d), the daily anomalies are given with respect to the smoothed daily climatology over the hindcast period. The black vertical line marks the date of the SSW (5 January 2021).

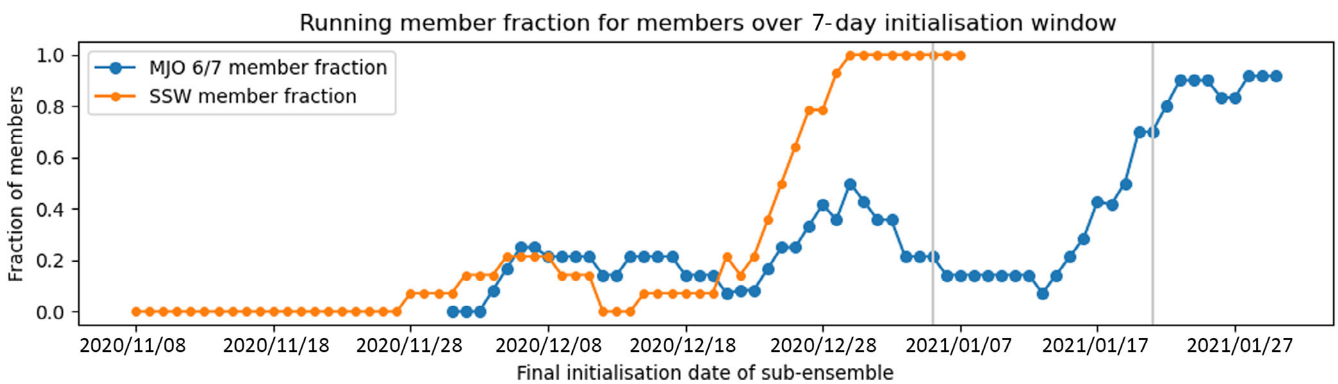

FIGURE 4 Predictability of the SSW and Phase 6 or 7 MJO. Fraction of members with an SSW (orange) and mid-to-late winter Phase 6 or 7 MJO (blue) in running sub-ensembles comprising of seven consecutive start dates (14 members in each sub-ensemble). The *x*-axis label gives the final initialisation date of each sub-ensemble. An ensemble member counts as predicting the SSW if it is forecast to occur on the 5 January 2021 ± 2 days, and predicting a mid-to-late winter MJO if it has at least 15 days with Phase 6 or 7 MJO with an amplitude greater than 1 between 15 January and 28 February 2021. The vertical lines mark the observed SSW (5 January 2021) and onset of the MJO event (21 January 2021).

caused by an asymmetry in the tropospheric geopotential height response to ENSO in the north Pacific, where a La Niña results in a negative geopotential height anomaly in the far north Pacific, coinciding with the negative geopotential height anomaly commonly found preceding SSWs. Indeed, the observed MSLP anomalies in December 2020 and January 2021 (Figure 1) closely resemble the SSW precursor shown in Figure 1 of their paper. The short observational record, however, means that there is considerable uncertainty in this relationship (Domeisen et al., 2019), and it is also sensitive to the definition of La Niña used (Iza et al., 2016; Song & Son, 2018).

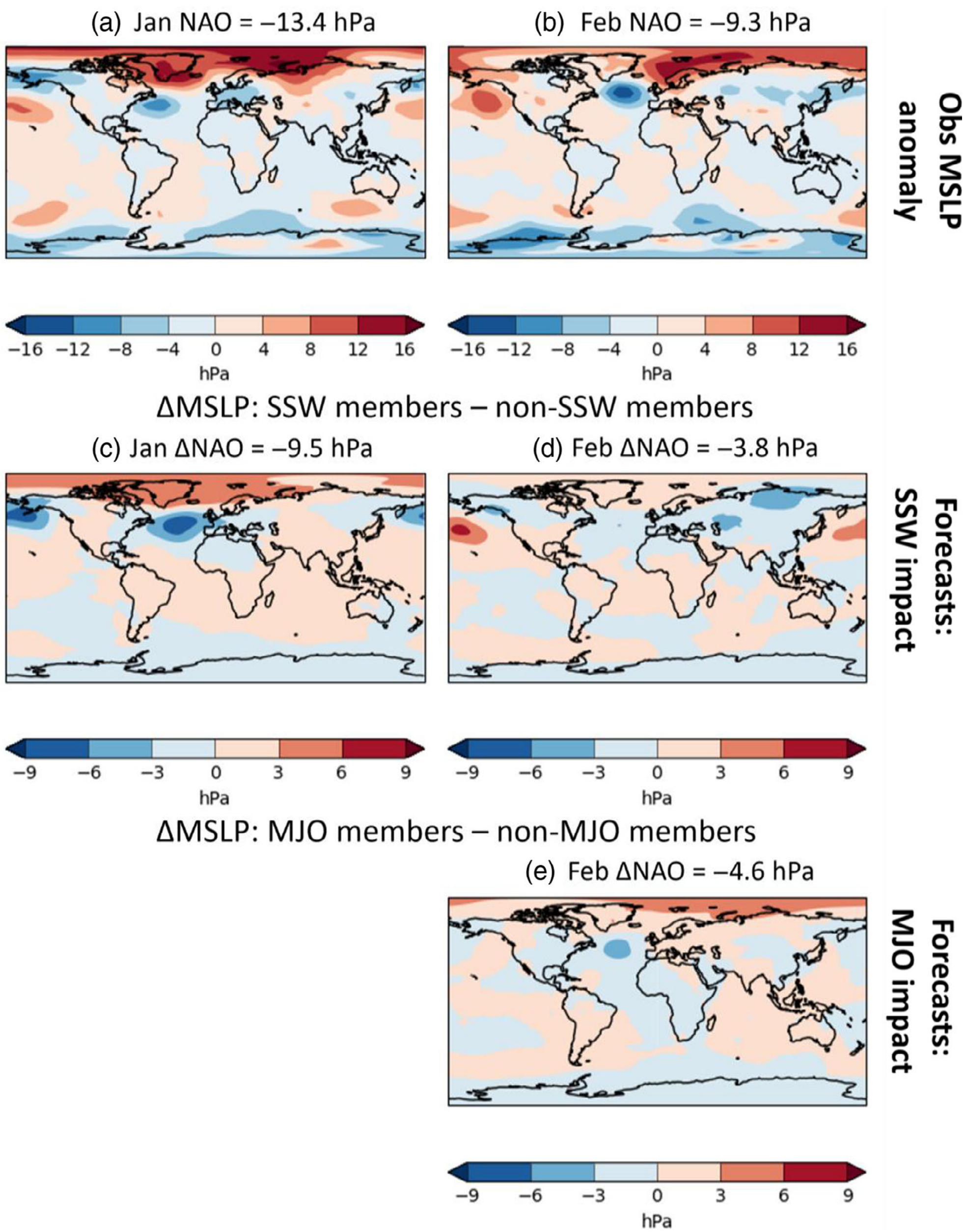

FIGURE 5 The impact of the early January SSW and February Phase 6 or 7 MJO. (a, b) Observed MSLP anomalies in January and February (as in Figure 1c,d). (c and d) Difference in MSLP between composites of forecasts with the early January SSW (17 members) and without (17 members), in January (c) and February (d), for forecasts initialized between 28 November and 27 December 2020. (e) Difference in MSLP in February between composites of forecasts with the Phase 6 or 7 MJO (16 members) and without (22) members, for forecasts initialized between 11 and 29 January 2021. Note the different scales used in (a) and (b) compared to (c) to (e). To isolate the effect of the SSW and MJO as opposed to initial conditions, members used for the composites were selected to ensure similar start dates.

In Figure 6 we examine the relationship between the Niño3.4 index, the Aleutian Low and SSWs to investigate whether there is any inconsistency in this relationship between GloSea5 and observations, and whether the over-forecast La Niña could have contributed to over-confidence in the forecast low SSW probability. The Niño3.4 index is chosen because it covers the central Pacific region which has been shown to have a stronger relationship with positive NAO than east Pacific regions (e.g., Zhang et al., 2019). Over-forecasting in this region in particular may therefore have been a reason for the strong NAO signal.

Figure 6a shows a scatter plot of December 500 hPa geopotential height anomalies in the Aleutian Low (AL) region (shown in Figure 6d) against December Niño3.4 anomalies in observations, the 2020/2021 GloSea5 forecasts, and GloSea5 hindcasts. The anomalies are plotted for December only rather than DJF to reduce any influence of SSWs on the AL, although similar conclusions are reached when DJF anomalies are used.

Both hindcasts and observations show the expected negative relationship between Niño3.4 and the AL (Garfinkel et al., 2013; Zhang et al., 2019), with similar correlations of −0.38 and −0.39 for hindcast ensemble members and observations, respectively (both $p \leq 5\%$), and no evidence for asymmetry in the response to Niño3.4 in the AL region examined here. There is considerable scatter, however, and the observed AL anomaly in winter 2020/2021 (−30 m) is well within the range of the 2020/2021 forecasts. Considerable internal variability of the signature of ENSO in the

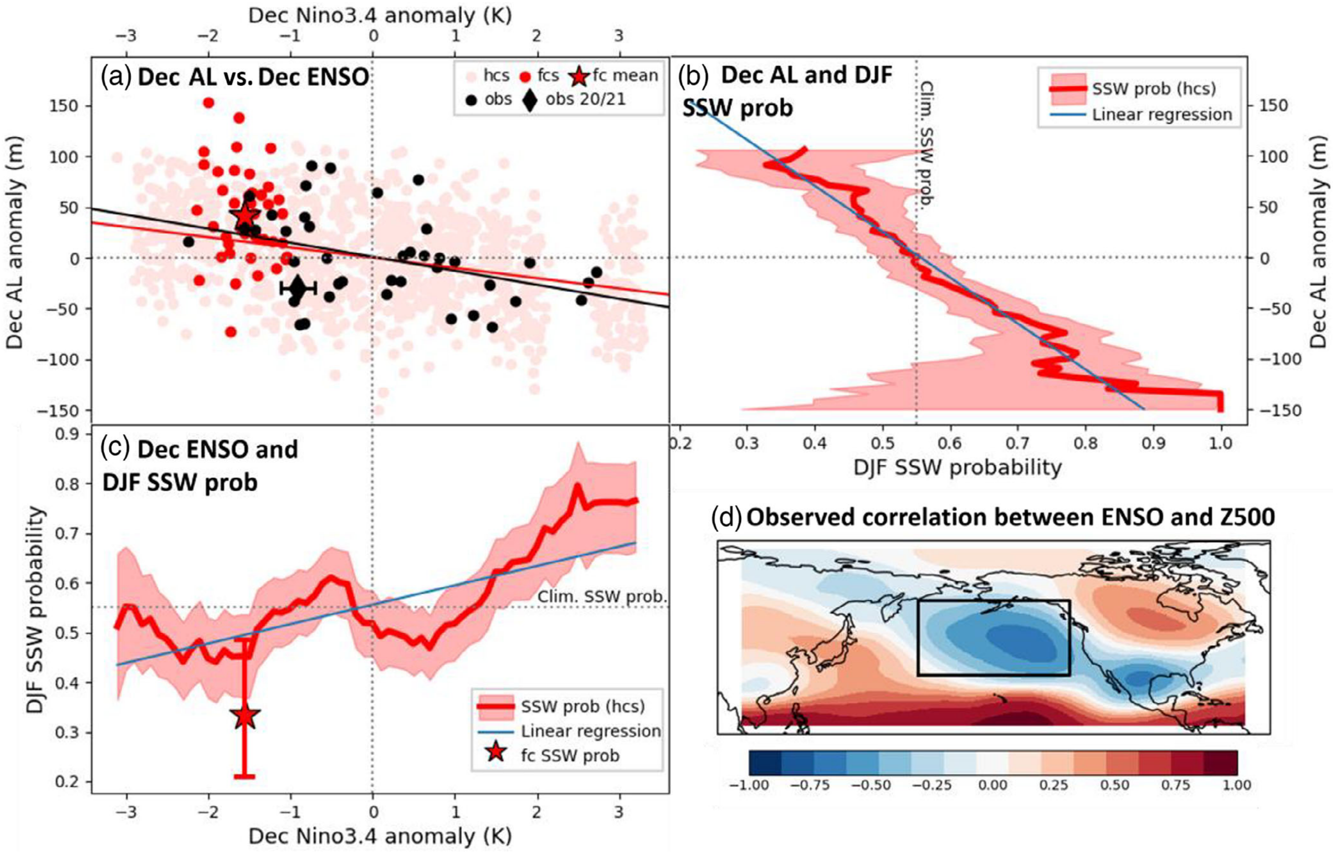

FIGURE 6 The ENSO-Aleutian Low-SSW teleconnection. (a) Scatter plot of December Aleutian Low (AL) and December Niño3.4 anomaly in observations (black), and GloSea5 hindcast members (labelled 'hcs', pink), forecast members ('fcs' red) and forecast mean (red star). Observed data includes all Decembers from 1979 to 2020 (December 2020 data marked by the black diamond, with 95% uncertainty shown by the bars). The solid lines show the linear regression of AL onto Niño3.4 anomaly in observations (black) and in GloSea5 (red). (b) Relationship between probability of an SSW in DJF and December AL anomaly measured in GloSea5 hindcasts, using an AL window of 40 m (red line). The shading shows the 95% credible intervals. The linear regression is shown with the blue line. The vertical dotted line marks the GloSea5 climatological SSW probability of 0.55. (c) As in (b) but showing the relationship between probability of an SSW in DJF and December Niño3.4 measured in GloSea hindcasts, using a Niño3.4 window of 1 K. The red star shows the SSW probability measured from the 2020/2021 forecast ensemble members, with 95% credible intervals shown by the bars. (d) Correlation between 500 hPa geopotential height (Z500) and Niño3.4 in observations. The box marks the region used to calculate the AL anomaly (170° E–230° E; 30° N–60° N).

North Pacific in models and observations was also found by Deser et al. (2017). It is therefore difficult to conclude that there is model error here.

Figures 6b,c show the relationship between the December AL/Niño3.4 in GloSea5 hindcasts and probability of an SSW in DJF. The SSW probabilities are estimated by taking a moving window in AL/Niño3.4 and calculating the fraction of hindcasts in the window with an SSW. The 95% credible intervals are estimated as in Figure 2. Figure 6b shows, consistent with the theory and previous model studies (e.g., Ineson & Scaife, 2009; Matsuno, 1971), there is a strong negative linear relationship between AL anomaly and SSW probability in GloSea5. The observations show a consistent relationship (Figure S2), although the sampling uncertainty is large due to the limited number of observations.

From Figure 6a,b together, we see that even for strong La Niña as in the 2020/2021 forecast ensemble, large variability in the AL can result in individual realisations actually having a higher than average chance of an SSW.[1] In other words, unpredictable variability in the AL can potentially disrupt the stratospheric teleconnection pathway between ENSO and the Euro-Atlantic region.

Figure 6c shows the expected increase in SSW probability with increasing Niño3.4 index. The apparent non-linearity could be a result of the limited number of independent hindcast years in each window used to measure the SSW probability. In observations the relationship is difficult to discern due to the huge sampling uncertainty (Figure S3). The only potentially significant difference between model and observation is for the three observed very strong El Niños which did not result in SSWs in

DJF, and were instead dominated by a wavelike response at mid-latitudes (Hardiman et al., 2019; Toniazzo & Scaife, 2006).

Estimating the SSW probability from the hindcasts at the *forecast* mean December Niño3.4 anomaly (−1.6 K) gives a probability of 0.45 ± 0.08 (using the measured value interpolated from the red curve in Figure 6c). This is somewhat higher than the forecast value of 0.33 (shown by the red star in Figure 6c), and the large intervals on the forecast probability indicate that this exceptionally low probability could well be due to sampling error compounding the over-predicted La Niña.

Had the forecast correctly predicted the observed December Niño3.4 value of -0.9 ± 0.2 K, we estimate the SSW probability would have increased to between 0.47 and 0.63 (taking into account both the uncertainty in observed Niño3.4 and sampling uncertainty in SSW probability). This indicates only a modest reduction in SSW probability (~10%) due to the over-forecast La Niña, which is consistent with it only resulting in a small change in the predictable component of AL depth (see the linear regressions in Figure 6a).

We conclude that the over-forecast La Niña may have slightly contributed to the low forecast SSW probability, but that sampling error in the SSW probability from a 42-member ensemble also played an important role, emphasising the need for large forecast ensembles. This analysis therefore does not reveal any obvious discrepancies between model and observations in the ENSO-Aleutian Low-SSW relationship, but further work is needed to understand the observed La Niña teleconnection and more sensitive tests may yet reveal an error. Unpredictable variability in the Aleutian Low region (Cho et al., 2022), along with variability in other SSW precursor regions such as northern Eurasia (Lu et al., 2021; Rao et al., 2021), resulted in an increased likelihood of an SSW through tropospheric wave forcing. This appears to be unpredictable 1 month in advance with the current seasonal forecast system.

4 | DISCUSSION AND CONCLUSIONS

Boreal winter 2020/2021 in the North Atlantic/European region was characterised by a negative NAO, but the seasonal forecast from GloSea5, along with other leading seasonal prediction systems, predicted a positive NAO signal in the ensemble mean due to the La Niña teleconnection. The observed outcome was, however, captured within the forecast ensemble spread. The observed negative NAO was likely a result of the early January SSW and mid- to late-winter Phase 6 or 7 MJO event. Atmospheric variability in the Aleutian Low region increased the chances of an SSW, but neither the SSW nor the late winter MJO event were predictable from November in initialised forecasts.

The low forecast SSW probability may have been exacerbated by the over-forecast La Niña, but this error is smaller than the uncertainty in SSW probability due to the relatively small forecast ensemble size, emphasising the need for large forecast ensembles. Our analysis has not found evidence for any systematic forecast error in the La Niña-Aleutian Low-SSW teleconnection, although more investigation is needed.

We note that previous studies have highlighted the importance of the particular pattern of SSTs and convection anomalies in the Pacific on the resulting teleconnection to the extra-tropics (e.g., Grimm & Silva Dias, 1995), and that La Niñas can be associated with a negative, rather than positive, NAO when the peak SSTs lie in the eastern rather than central Pacific (Ren et al., 2019; Zhang et al., 2019). Figure S4 shows the observed and forecast SST anomalies for winter 2020/2021 and does reveal errors in the forecast SST anomaly patterns. The forecast peak SSTs actually lie further east than the observations, which should force the forecasts towards a more negative NAO according to the aforementioned references. However, it is difficult to assess any errors in SST or convection that are common to all ensemble members, and a more dedicated study is required to fully understand the implications of these errors on the teleconnection to the extra-tropics.

This case study shows that although SSWs have been shown to add skill to seasonal forecasts (Sigmond et al., 2013; Scaife et al., 2016; Scaife et al., 2022), if one occurs mid-winter in a season with forecast low probability conditions, it can have a large impact on the season ahead, leading to observed conditions very different to the original ensemble mean forecast signal. This demonstrates the advantage of continuously updated lagged ensembles, over a 'burst' ensemble with all members initialised at the same time, since changes in the forecast signal due to phenomena with sub-seasonal predictability, such as SSWs and the MJO, can be promptly communicated to users.

AUTHOR CONTRIBUTIONS

Julia F. Lockwood: Formal analysis; investigation; methodology; writing – original draft. **Nicky Stringer:** Formal analysis; investigation; methodology; writing – original draft. **Hazel E. Thornton:** Methodology; supervision; writing – review and editing. **Adam A. Scaife:** Conceptualization; funding acquisition; methodology; supervision; writing – review and editing. **Philip E. Bett:** Writing – review and editing. **Tamara Collier:** Data

curation; software. **Ruth Comer:** Data curation; software. **Nick Dunstone:** Writing – review and editing. **Margaret Gordon:** Data curation; software. **Leon Hermanson:** Writing – review and editing. **Sarah Ineson:** Conceptualization; writing – review and editing. **Jamie Kettleborough:** Data curation; software; writing – review and editing. **Jeff Knight:** Conceptualization; writing – review and editing. **Joseph Mancell:** Data curation; software. **Peter McLean:** Data curation; software. **Doug Smith:** Supervision; writing – review and editing. **Tony Wardle:** Data curation; writing – review and editing. **Dr. Prince Xavier:** Data curation; writing – review and editing. **Ben Youngman:** Validation; writing – review and editing.

ACKNOWLEDGEMENTS

The authors received support from the United Kingdom Public Weather Service (https://www.metoffice.gov.uk/about-us/what/pws) and the Met Office Hadley Centre Climate Programme funded by the United Kingdom Government Department of Business, Energy and Industrial Strategy (BEIS) and the Department of Environment, Food, and Rural Affairs (Defra).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The GloSea5 and ERA5 data used in the paper are available from the C3S Climate data store (https://cds.climate.copernicus.eu/#!/home). HadSST4 is available from https://www.metoffice.gov.uk/hadobs/hadsst4/, and HadSLP2r is available from https://www.metoffice.gov.uk/hadobs/hadslp2/.

ORCID

Julia F. Lockwood https://orcid.org/0000-0003-2596-7341
Adam A. Scaife https://orcid.org/0000-0002-5189-7538
Nick Dunstone https://orcid.org/0000-0001-6859-6814
Jeff Knight https://orcid.org/0000-0003-1868-0852

ENDNOTE

[1] This is assuming that the ENSO-SSW teleconnection acts only through the AL, so the relationship between SSW probability and AL anomaly is independent of ENSO state.

REFERENCES

Allan, R. & Ansell, T. (2006) A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850–2004. *Journal of Climate*, 19(22), 5816–5842. https://doi.org/10.1175/JCLI3937.1

Athanasiadis, P.J., Bellucci, A., Scaife, A.A., Hermanson, L., Materia, S., Sanna, A. et al. (2017) A multisystem view of wintertime NAO seasonal predictions. *Journal of Climate*, 30, 1461–1475. https://doi.org/10.1175/JCLI-D-16-0153.1

Ayarzagüena, B., Ineson, S., Dunstone, N.J., Baldwin, M.P. & Scaife, A.A. (2018) Intraseasonal effects of El Niño–Southern Oscillation on North Atlantic climate. *Journal of Climate*, 31(21), 8861–8873.

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

Bowler, N., Arribas, A., Beare, S., Mylne, K.E. & Shutts, G. (2009) The local ETKF and SKEB: upgrades to the MOGREPS short-range ensemble prediction system. *Quarterly Journal of the Royal Meteorological Society*, 135, 767–776.

Butler, A.H. & Polvani, L.M. (2011) El Niño, La Niña, and stratospheric sudden warmings: a reevaluation in light of the observational record. *Geophysical Research Letters*, 38, L13807. https://doi.org/10.1029/2011GL048084

Cassou, C. (2008) Intraseasonal interaction between the Madden–Julian oscillation and the North Atlantic oscillation. *Nature*, 455, 523–552. https://doi.org/10.1038/nature07286

Cho, H.-O., Kang, M.-J., Son, S.-W., Hong, D.-C. & Kang, J.M. (2022) A critical role of the North Pacific bomb cyclones in the onset of the 2021 sudden stratospheric warming. *Geophysical Research Letters*, 49, e2022GL099245. https://doi.org/10.1029/2022GL099245

Clark, R.T., Bett, P.E., Thornton, H.E. & Scaife, A.A. (2017) Skilful seasonal predictions for the European energy industry. *Environmental Research Letters*, 12, 024002. https://doi.org/10.1088/1748-9326/aa57ab

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

Domeisen, D.I.V., Butler, A.H., Charlton-Perez, A.J., Ayarzagüena, B., Baldwin, M.P., Dunn-Sigouin, E. et al. (2020) The role of the stratosphere in subseasonal to seasonal prediction: 1. Predictability of the stratosphere. *Journal of Geophysical Research: Atmospheres*, 125, e2019JD030920. https://doi.org/10.1029/2019JD030920

Domeisen, D.I., Garfinkel, C.I. & Butler, A.H. (2019) The teleconnection of El Niño Southern Oscillation to the stratosphere. *Reviews of Geophysics*, 57, 5–47. https://doi.org/10.1029/2018RG000596

Dunstone, N., Scaife, A.A., MacLachlan, C., Knight, J., Ineson, S., Smith, D. et al. (2018) Predictability of European winter 2016/2017. *Atmospheric Science Letters*, 19, e868. https://doi.org/10.1002/asl.868

Dunstone, N., Smith, D., Scaife, A.A., Hermanson, L., Eade, R., Robinson, N. et al. (2016) Skilful predictions of the winter North Atlantic oscillation one year ahead. *Nature Geoscience*, 9, 809–814. https://doi.org/10.1038/ngeo2824

Garfinkel, C.I., Butler, A.H., Waugh, D.W., Hurwitz, M.M. & Polvani, L.M. (2012) Why might stratospheric sudden warmings occur with similar frequency in El Niño and La Niña winters? *Journal of Geophysical Research*, 117, D19106. https://doi.org/10.1029/2012JD017777

Garfinkel, C.I., Hurwitz, M.M., Waugh, D.W. & Butler, A.H. (2013) Are the teleconnections of Central Pacific and Eastern Pacific El Niño distinct in boreal wintertime? *Climate Dynamics*, 41, 1835–1852. https://doi.org/10.1007/s00382-012-1570-2

Grimm, A.M. & Silva Dias, P.L. (1995) Analysis of tropical–extratropical interactions with influence functions of a barotropic model. *Journal of Atmospheric Sciences*, 52(20), 3538–3555. https://doi.org/10.1175/1520-0469(1995)052<3538:AOTIWI>2.0.CO;2

Grist, J.P., Sinha, B., Hewitt, H.T., Duchez, A., MacLachlan, C., Hyder, P. et al. (2019) Re-emergence of North Atlantic subsurface ocean temperature anomalies in a seasonal forecast system. *Climate Dynamics*, 53, 4799–4820. https://doi.org/10.1007/s00382-019-04826-w

Hardiman, S.C., Dunstone, N.J., Scaife, A.A., Smith, D.M., Ineson, S., Lim, J. et al. (2019) The impact of strong El Nino and La Nina events on the North Atlantic. *Geophysical Research Letters*, 46, 2874–2883. https://doi.org/10.1029/2018GL081776

Hardiman, S.C., Dunstone, N.J., Scaife, A.A., Smith, D.M., Knight, J.R., Davies, P. et al. (2020) Predictability of European winter 2019/20: Indian Ocean dipole impacts on the NAO. *Atmospheric Science Letters*, 21, e1005. https://doi.org/10.1002/asl.1005

Hermanson, L., Ren, H.-L., Vellinga, M., Dunstone, N.D., Hyder, P., Ineson, S. et al. (2018) Different types of drifts in two seasonal forecast systems and their dependence on ENSO. *Climate Dynamics*, 51, 1411–1426. https://doi.org/10.1007/s00382-017-3962-9

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J. et al. (2020) The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049. https://doi.org/10.1002/qj.3803

Hurrell, J.W., Kushnir, Y., Ottersen, G. & Visbeck, M. (2003) An overview of the North Atlantic oscillation. In: Hurrell, J.W., Kushnir, Y., Ottersen, G. & Visbeck, M. (Eds.) *The North Atlantic oscillation: climatic significance and environmental impact*. Washington, DC: American Geophysical Union, pp. 1–37. https://doi.org/10.1029/134GM01

Ineson, S. & Scaife, A.A. (2009) The role of the stratosphere in the European climate response to El Niño. *Nature Geoscience*, 2, 32–36. 10. doi:10.1038/ngeo381

Iza, M., Calvo, N. & Manzini, E. (2016) The stratospheric pathway of La Niña. *Journal of Climate*, 29(24), 8899–8914. https://doi.org/10.1175/JCLI-D-16-0230.1

Jiang, Z., Feldstein, S.B. & Lee, S. (2017) The relationship between the Madden–Julian oscillation and the North Atlantic oscillation. *Quarterly Journal of the Royal Meteorological Society*, 143, 240–250. https://doi.org/10.1002/qj.2917

Jiménez-Esteve, B. & Domeisen, D.I. (2018) The tropospheric pathway of the ENSO-North Atlantic teleconnection. *Journal of Climate*, 31, 4563–4584. https://doi.org/10.1175/JCLI-D-17-0716.1

Kennedy, J.J., Rayner, N.A., Atkinson, C.P. & Killick, R.E. (2019) An ensemble data set of sea-surface temperature change from 1850: the Met Office Hadley Centre HadSST.4.0.0.0 data set. *Journal of Geophysical Research: Atmospheres*, 124, 7719–7763. https://doi.org/10.1029/2018JD029867

Kennedy, J. J., Rayner, N. A., Atkinson, C. P. & Killick, R. E. (2022) *HadSST.4.0.1.0 product user guide*. Technical Report, Met Office. Available at: https://www.metoffice.gov.uk/hadobs/hadsst4/HadSST.4.0.1.0_Product_User_Guide.pdf. Accessed May 2022.

Kidston, J., Scaife, A., Hardiman, S., Mitchell, D.M., Butchart, N., Baldwin, M.P. et al. (2015) Stratospheric influence on tropospheric jet streams, storm tracks and surface weather. *Nature Geoscience*, 8, 433–440. https://doi.org/10.1038/ngeo2424

Knight, J., Scaife, A.A., Bett, P.E., Collier, T., Dunstone, N., Gordon, M. et al. (2021) Predictability of European winters 2017/2018 and 2018/2019: contrasting influences from the Tropics and stratosphere. *Atmospheric Science Letters*, 22, e1009. https://doi.org/10.1002/asl.1009

Lee, S.H. (2021) The January 2021 sudden stratospheric warming. *Weather*, 76, 135–136.

Lim, Y., Son, S. & Kim, D. (2018) MJO prediction skill of the subseasonal-to-seasonal prediction models. *Journal of Climate*, 31(10), 4075–4094. https://doi.org/10.1175/JCLI-D-17-0545.1

Lu, Q., Rao, J., Liang, Z., Guo, D., Luo, J., Liu, S. et al. (2021) The sudden stratospheric warming in January 2021. *Environmental Research Letters*, 16, 084029. https://doi.org/10.1088/1748-9326/ac12f4

MacLachlan, C., Arribas, A., Peterson, K.A., Maidens, A., Fereday, D., Scaife, A.A. et al. (2015) Global seasonal forecast system version 5 (GloSea5): a high-resolution seasonal forecast system. *Quarterly Journal of the Royal Meteorological Society*, 141, 1072–1084. https://doi.org/10.1002/qj.2396

Maidens, A., Arribas, A., Scaife, A.A., MacLachlan, C., Peterson, D. & Knight, J. (2013) The influence of surface forcings on prediction of the North Atlantic oscillation regime of winter 2010/11. *Monthly Weather Review*, 141(11), 3801–3813.

Matsuno, T. (1971) A dynamical model of the stratospheric sudden warming. *Journal of Atmospheric Sciences*, 28(8), 1479–1494. https://doi.org/10.1175/1520-0469(1971)028<1479:ADMOTS>2.0.CO;2

Moron, V. & Gouirand, I. (2003) Seasonal modulation of the El Niño–Southern Oscillation relationship with sea level pressure anomalies over the North Atlantic in October–March 1873–1996. *International Journal of Climatology*, 23, 143–155. https://doi.org/10.1002/joc.868

Palin, E.J., Scaife, A.A., Wallace, E., Pope, E.C.D., Arribas, A. & Brookshaw, A. (2016) Skillful seasonal forecasts of winter disruption to the U.K. transport system. *Journal of Applied Meteorology and Climatology*, 55(2), 325–344. https://doi.org/10.1175/JAMC-D-15-0102.1

Rao, J., Garfinkel, C.I., Wu, T., Lu, Y., Lu, Q. & Liang, Z. (2021) The January 2021 sudden stratospheric warming and its prediction in subseasonal to seasonal models. *Journal of Geophysical Research: Atmospheres*, 126, e2021JD035057. https://doi.org/10.1029/2021JD035057

Ren, H.-L., Scaife, A.A., Dunstone, N., Tian, B., Liu, Y., Ineson, S. et al. (2019) Seasonal predictability of winter ENSO types in operational dynamical model predictions. *Climate Dynamics*, 52, 3869–3890. https://doi.org/10.1007/s00382-018-4366-1

Scaife, A.A., Arribas, A., Blockley, E., Brookshaw, A., Clark, R.T., Dunstone, N. et al. (2014) Skillful long-range prediction of European and North American winters. *Geophysical Research Letters*, 41, 2514–2519. https://doi.org/10.1002/2014GL059637

Scaife, A.A., Baldwin, M.P., Butler, A.H., Charlton-Perez, A.J., Domeisen, D.I.V., Garfinkel, C.I. et al. (2022) Long-range prediction and the stratosphere. *Atmospheric Chemistry and Physics*, 22, 2601–2623. https://doi.org/10.5194/acp-22-2601-2022

Scaife, A.A., Camp, J., Comer, R., Davis, P., Dunstone, N., Gordon, M. et al. (2019) Does increased atmospheric resolution improve seasonal climate predictions? *Atmospheric Science Letters*, 20, e922. https://doi.org/10.1002/asl.922

Scaife, A.A., Comer, R., Dunstone, N., Fereday, D., Folland, C., Good, E. et al. (2017) Predictability of European winter 2015/2016. *Atmospheric Science Letters*, 18, 38–44. https://doi.org/10.1002/asl.721

Scaife, A.A., Karpechko, A.Y., Baldwin, M.P., Brookshaw, A., Butler, A.H., Eade, R. et al. (2016) Seasonal winter forecasts and the stratosphere. *Atmospheric Science Letters*, 17, 51–56. https://doi.org/10.1002/asl.598

Sigmond, M., Scinocca, J., Kharin, V. & Shepherd, T.G. (2013) Enhanced seasonal forecast skill following stratospheric sudden warmings. *Nature Geoscience*, 6, 98–102. https://doi.org/10.1038/ngeo1698

Song, K. & Son, S. (2018) Revisiting the ENSO–SSW relationship. *Journal of Climate*, 31(6), 2133–2143. https://doi.org/10.1175/JCLI-D-17-0078.1

Stringer, N., Knight, J. & Thornton, H. (2020) Improving meteorological seasonal forecasts for hydrological modeling in European winter. *Journal of Applied Meteorology and Climatology*, 59(2), 317–332. https://doi.org/10.1175/JAMC-D-19-0094.1

Svensson, C., Brookshaw, A., Scaife, A.A., Bell, V.A., Mackay, J.D., Jackson, C.R. et al. (2015) Long range forecasts of UK winter hydrology. *Environmental Research Letters*, 10, 064006. https://doi.org/10.1088/1748-9326/10/6/064006

Taguchi, M. (2016) Predictability of major stratospheric sudden warmings: analysis results from JMA operational 1-month ensemble predictions from 2001/02 to 2012/13. *Journal of the Atmospheric Sciences*, 73(2), 789–806.

Taws, S.L., Marsh, R., Wells, N.C. & Hirschi, J. (2011) Re-emerging ocean temperature anomalies in late-2010 associated with a repeat negative NAO. *Geophysical Research Letters*, 38(20), L20601. https://doi.org/10.1029/2011GL048978

Thornton, H.E., Scaife, A.A., Hoskins, B.J., Brayshaw, D.J., Smith, D.M., Dunstone, N. et al. (2019) Skilful seasonal prediction of winter gas demand. *Environmental Research Letters*, 14, 024009. https://doi.org/10.1088/1748-9326/aaf338

Toniazzo, T. & Scaife, A.A. (2006) The influence of ENSO on winter North Atlantic climate. *Geophysical Research Letters*, 33, L24704. https://doi.org/10.1029/2006GL027881

Wallace, J.M. & Gutzler, D.S. (1981) Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Monthly Weather Review*, 109(4), 784–812. https://doi.org/10.1175/1520-0493(1981)109<0784:TITGHF>2.0.CO;2

Wheeler, M.C. & Hendon, H.H. (2004) An all-season real-time multivariate MJO index: development of an index for monitoring and prediction. *Monthly Weather Review*, 132(8), 1917–1932.

Wilks, D.S. (2019) Bayesian inference. In: *Statistical methods in the atmospheric sciences*, Fourth edition. MA, USA: Elsevier, pp. 209-234. https://doi.org/10.1016/B978-0-12-815823-4.00006-7

Zhang, W., Wang, Z., Stuecker, M.F., Turner, A.G., Jin, F.F. & Geng, X. (2019) Impact of ENSO longitudinal position on teleconnections to the NAO. *Climate Dynamics*, 52, 257–274. https://doi.org/10.1007/s00382-018-4135-1

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Lockwood, J. F., Stringer, N., Thornton, H. E., Scaife, A. A., Bett, P. E., Collier, T., Comer, R., Dunstone, N., Gordon, M., Hermanson, L., Ineson, S., Kettleborough, J., Knight, J., Mancell, J., McLean, P., Smith, D., Wardle, T., Xavier, P., & Youngman, B. (2022). Predictability of European winter 2020/2021: Influence of a mid-winter sudden stratospheric warming. *Atmospheric Science Letters*, e1126. https://doi.org/10.1002/asl.1126