Geophysical Research Letters

RESEARCH LETTER
10.1029/2024GL111717

Key Points:

- The meridional wind in the midlatitude upper stratosphere in October contains significant seasonal predictability for the winter NAO
- The strength of the meridional wind in this region also predicts changes in the occurrence of midwinter SSWs
- The winter surface impact of the October upper stratospheric wind occurs partly, but not entirely, via changes to the polar vortex

Supporting Information:

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

Correspondence to:

E. Collingwood,
elcoll56@bas.ac.uk

Citation:

Collingwood, E., Scaife, A. A., Lu, H., Sinha, B., King, J., Marsh, R., & Marshall, G. (2024). Meridional wind in the upper stratosphere: A source of winter NAO predictability. *Geophysical Research Letters*, *51*, e2024GL111717. https://doi.org/10.1029/2024GL111717

Received 8 AUG 2024
Accepted 27 NOV 2024

Meridional Wind in the Upper Stratosphere: A Source of Winter NAO Predictability

Elizabeth Collingwood[1,2], Adam A. Scaife[3,4], Hua Lu[1], Bablu Sinha[5], John King[1], Robert Marsh[2], and Gareth Marshall[1]

[1]British Antarctic Survey, Cambridge, UK, [2]School of Ocean and Earth Science, University of Southampton, Southampton, UK, [3]Met Office Hadley Centre, Exeter, UK, [4]Department of Mathematics and Statistics, University of Exeter, Exeter, UK, [5]National Oceanography Centre, Southampton, UK

Abstract Improvement of subseasonal to seasonal North Atlantic winter forecasting requires better prediction of the North Atlantic Oscillation (NAO), the dominant mode of variability in the Northern Hemisphere. Despite recent research demonstrating the importance of stratosphere-troposphere coupling for NAO predictability, the driving mechanisms and implications are not fully understood. This study reveals that the October upper stratosphere is highly relevant to polar vortex development and predictability of winter NAO. We derive a simple index based on the strength of meridional wind in the upper stratospheric surf zone and find that anomalously poleward motion is associated with a significantly stronger polar vortex, which predicts the subsequent winter surface NAO with a correlation coefficient of $r = 0.40$.

Plain Language Summary The North Atlantic Oscillation (NAO) is a large-scale atmospheric system that significantly affects the weather and climate in the North Atlantic basin, especially in winter. Accurately forecasting the NAO 1–3 months ahead is challenging. However, on these timescales, more predictable factors like the stratosphere play a crucial role in modulating the NAO. The upper stratosphere plays a significant role in stratospheric dynamics, however it remains poorly understood and its potential to improve winter NAO predictions is largely untapped. Here, we create a simple index to measure the north-south winds in the upper stratosphere during October and find that a positive index predicts a stronger winter polar vortex, leading to a more positive NAO. This results in warmer, wetter, and stormier conditions in northern Europe and the eastern US, and colder, drier conditions in southern Europe and Canada. Conversely, a negative index indicates a weaker winter polar vortex and an increased likelihood of sudden stratospheric warming events, which can often lead to extreme and prolonged cold conditions at the surface. Our findings highlight the importance of monitoring the upper stratosphere in October to improve winter NAO predictions and better understand stratosphere-troposphere coupling.

1. Introduction

Variability of North Atlantic winter climate is dominated by the North Atlantic Oscillation (NAO; e.g., Hurrell et al., 2001). The NAO is a large-scale atmospheric pressure dipole situated over the North Atlantic with centers located in the subtropics (the Azores high) and the Arctic (the Iceland low). While this pattern is present throughout the year, the NAO is most prominent in winter and explains over one-third of sea level pressure variance in the North Atlantic (Hurrell & Deser, 2010). Its phases are associated with the strength and location of the jet-stream (Woollings et al., 2010), which affect changes in surface temperature, precipitation, and storm track behavior in the North Atlantic basin (e.g., Degenhardt et al., 2024; Hurrell et al., 2003; Rogers, 1997; Scaife et al., 2008; Vallis & Gerber, 2008), emphasizing the importance of skilful subseasonal to seasonal (S2S) NAO forecasts. While accurate S2S forecasting of the surface NAO presents challenges, previous studies have demonstrated significant predictability on seasonal timescales and indicate that further untapped predictability still exists (Athanasiadis et al., 2017; Baker et al., 2018; Riddle et al., 2013; Scaife et al., 2014).

The mechanisms that generate and maintain the NAO are not fully understood. While it is considered to be primarily maintained by internal eddy-mean flow interactions (e.g., Barnes & Hartmann, 2010; Benedict et al., 2004; Feldstein, 2003; Franzke et al., 2004; Lorenz & Hartmann, 2003), it is clear that external sources of S2S predictability exist (Deser et al., 2007; Smith et al., 2020). The NAO has known links to tropical rainfall (Fereday et al., 2020; Molteni et al., 2015), which is notably influenced by the El Niño-Southern Oscillation (Bell et al., 2009), North Atlantic sea surface temperature anomalies (Czaja & Frankignoul, 2002; Deser et al., 2007;

Rodwell et al., 1999), Arctic sea ice cover (Strong & Magnusdottir, 2011), Eurasian snow cover (Cohen et al., 2014), solar variability (Ineson et al., 2011; Lu et al., 2017), and stratospheric forcing (O'Reilly et al., 2019; Scaife et al., 2016).

A better understanding of stratosphere-troposphere coupling is increasingly being recognised as essential for improvements in S2S winter NAO forecasting and the prediction of extreme meteorological events (e.g., Baldwin & Dunkerton, 2001; Domeisen et al., 2020; Garfinkel et al., 2020; Scaife et al., 2022). In a forecasting context, recent research is also beginning to appreciate the dynamical influence of the upper stratosphere (1-5 hPa) on downward coupling with the troposphere (e.g., Hitchcock & Haynes, 2016; Nie et al., 2019).

Extratropical stratospheric circulation is primarily driven by planetary-scale Rossby waves (e.g., Charney & Drazin, 1961), the breaking of which is largely confined to the winter stratosphere in the midlatitude "surf zone" (McIntyre & Palmer, 1983). Disturbances in the early winter upper stratosphere can therefore strongly influence stratospheric dynamics by manipulating the waveguide, which can affect subsequent wave breaking and absorption throughout the stratosphere and lead to disparate polar vortex regimes (Gray et al., 2003; Lu et al., 2021) as well as changes to sudden stratospheric warming (SSW) occurrence (Gray et al., 2020, 2022; Greer et al., 2013; O'Neill & Pope, 1988). In particular, Gray et al. (2022) demonstrate that polar vortex development and SSW timing are sensitive to equinoctial upper stratospheric zonal winds, suggesting that anomalous dynamical behavior as early as October may provide insight into seasonal stratospheric development. Despite the promising recent improvements in our understanding of the upper stratosphere and their contributions to S2S winter forecasting (Koushik et al., 2022; Lindgren & Sheshadri, 2020; Lu et al., 2021), it remains a region that is often overlooked with its dynamics poorly understood.

An important feature of winter stratospheric circulation is the extratropical "downward control" effect (Haynes et al., 1991). This global-scale wave-driven circulation is a quasi-instantaneous response arising from the applied forcing of eddy motions in the upper stratosphere. Under the steady-state and quasi-geostrophic assumptions, the residual mean meridional wind, $\bar{v}^*$, is related to the divergence of the Eliassen-Palm (EP) flux, $\mathbf{F}$, a measure of overall wave forcing, by

$$\bar{v}^* \equiv -\frac{1}{\rho_0 f_0} \nabla \cdot \mathbf{F}, \qquad (1)$$

where f_0 is the reference Coriolis parameter and ρ_0 the basic density. Enhanced wave forcing in the upper stratospheric surf zone therefore induces a meridional circulation at and beneath this region (Holton et al., 1995). The Eulerian circulation, however, responds differently to wave forcing. Substituting the quasi-geostrophic definition of $\bar{v}^*$ into Equation 1 yields the relationship

$$f_0 \bar{v}_a \equiv -\rho_0^{-1} F_\phi^{(\phi)}, \qquad (2)$$

for which $\bar{v}_a$ represents the ageostrophic component of the Eulerian mean meridional wind which is approximately equal to zonally averaged meridional wind $\bar{v}$ over monthly averages and $F_\phi^{(\phi)} = -\left(\rho_0 \overline{v' u'}\right)_y$ is the divergence of the meridional component of EP flux. In essence, enhanced eddy momentum flux divergence in the upper stratosphere induces more poleward flow. It is known that anomalous eddy momentum flux divergence in the upper stratosphere generates a response in the ageostrophic winds (Greer et al., 2013; Thayer et al., 2010), however the induced meridional circulation suggested by Equation 2 and the associated impacts on stratosphere-troposphere coupling and the winter surface are unknown.

In this study we propose a simple index that uses the anomalous monthly mean zonally averaged meridional wind in the upper stratospheric surf zone in October, as a proxy for this Eulerian-mean meridional circulation. This index is significantly correlated with the subsequent winter NAO and determines two distinct regimes in which the frequency of SSWs is significantly altered. This study reveals the relevance of not just the upper stratospheric surf zone, but also the often overlooked meridional wind field, to S2S winter prediction and our understanding of stratosphere-troposphere dynamical coupling in the Northern Hemisphere. Details of the data and methods used can be found in Section 2, the results of the analysis in Section 3, and in Section 4 we summarize and briefly discuss potential mechanisms involved.

2. Methodology

2.1. Data

This analysis uses the European Center of Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis sea level pressure, temperature, and zonal mean wind data sets for the period 1979–2024 (inclusive), providing data for 45 complete winters. ERA5 has a horizontal resolution of 0.25° latitude by 0.25° longitude and 137 atmospheric levels from the surface to 80 km above sea level including 60 levels between 0.01 and 100 hPa (Hersbach et al., 2023). 6-hourly grid-based data was used throughout this study. The pressure level data (temperature and zonal and meridional wind) used in the analysis is of a coarser resolution (0.5° latitude by 0.5° longitude), due to storage limitations. The index, however, was calculated using the full resolution data for accuracy.

This analysis was repeated using the Modern-Era Retrospective Analysis for Research and Application Version 2 (MERRA-2) reanalysis data set from NASA's Global Monitoring and Assimilation Office (GMAO) (Gelaro et al., 2017). MERRA-2 confirms the significance of all key results presented in this paper.

2.2. Index Calculation

Winters are separated into two groups determined by the sign of an index in October. The index is the standardised zonally averaged meridional wind speed over the upper stratospheric surf zone (40°N–60°N and 1–3 hPa; mass-weighted). This region is sufficiently far poleward to evade the influence of the Quasi-Biennial Oscillation (QBO)-induced mean meridional circulation, which extends to approximately 40°N in the upper stratosphere.

The ability of this October index to predict the December-January-February (DJF) surface NAO is examined. We take the NAO as being the reanalysis mean sea level pressure (MSLP) difference between the Azores (38°N, 27°W) and Iceland (65°N, 23°W) as in (Dunstone et al., 2016). The specific definition of the NAO index is not critical to the results of this study, as the results remain significant for the NAO index described above and the station- and principal component-based NAO indices (NCAR, 2003).

3. Results

3.1. Polar Vortex Evolution

To understand how the index affects the seasonal development of zonal winds in the stratosphere, Figure 1a illustrates the composite (positive index winters minus negative index winters) of zonal wind $\bar{u}$ at 60°N, taken to be the latitude of the strongest polar vortex winds. The plot demonstrates an initial negative anomaly in the mid to upper stratosphere followed by the downward propagation of a positive anomaly appearing in the December upper stratosphere, which subsequently descends over the following 1–2 months. This feature strongly resembles that of zonal wind composites in other contexts such as SSWs (e.g., Baldwin & Dunkerton, 2001; Karpechko et al., 2017; Kuroda, 2008), strong and weak vortex events (Baldwin & Dunkerton, 2005; Limpasuvan et al., 2005), upper stratospheric anomalies (Baldwin & Dunkerton, 1999; Kodera et al., 1990; Nie et al., 2019), and the QBO (Ebdon & Veryard, 1961; Taguchi, 2018).

Figure 1b shows the 1–3 hPa poleward propagation of the positive anomaly beginning in the October subtropics. This anomaly strengthens as it migrates poleward, reaching values of over 16 ms^{-1} in the midlatitudes, before finally terminating in the polar region in late January. This is indicative of an initially wide upper stratospheric vortex that strengthens and narrows around the pole over the following 2 months. Following the positive anomaly, a negative anomaly originating in the late November subtropics propagates poleward and leads to a weakening of the upper stratospheric vortex in February.

The generation of the subtropical and midlatitude anomalies in early winter upper stratosphere is likely a result of the anomalous meridional wind over the index region evoking an “Eliassen response” to maintain thermal-wind balance (Eliassen, 1951). The early winter anomalies appear to be qualitatively consistent with those depicting the Eliassen response in Figure 3 of Plumb (2010).

Together Figures 1a and 1b suggest that positive index winters are associated with a stronger and more stable polar vortex, until late winter when it is more rapidly destroyed by dynamical processes in the upper stratosphere compared with negative index winters. Mean winter (DJF) polar vortex strength ($\bar{u}$ at 60°N, 10 hPa) shares a correlation coefficient with the October index of $r = 0.36$, which is significant at a p-value ≤ 0.016.

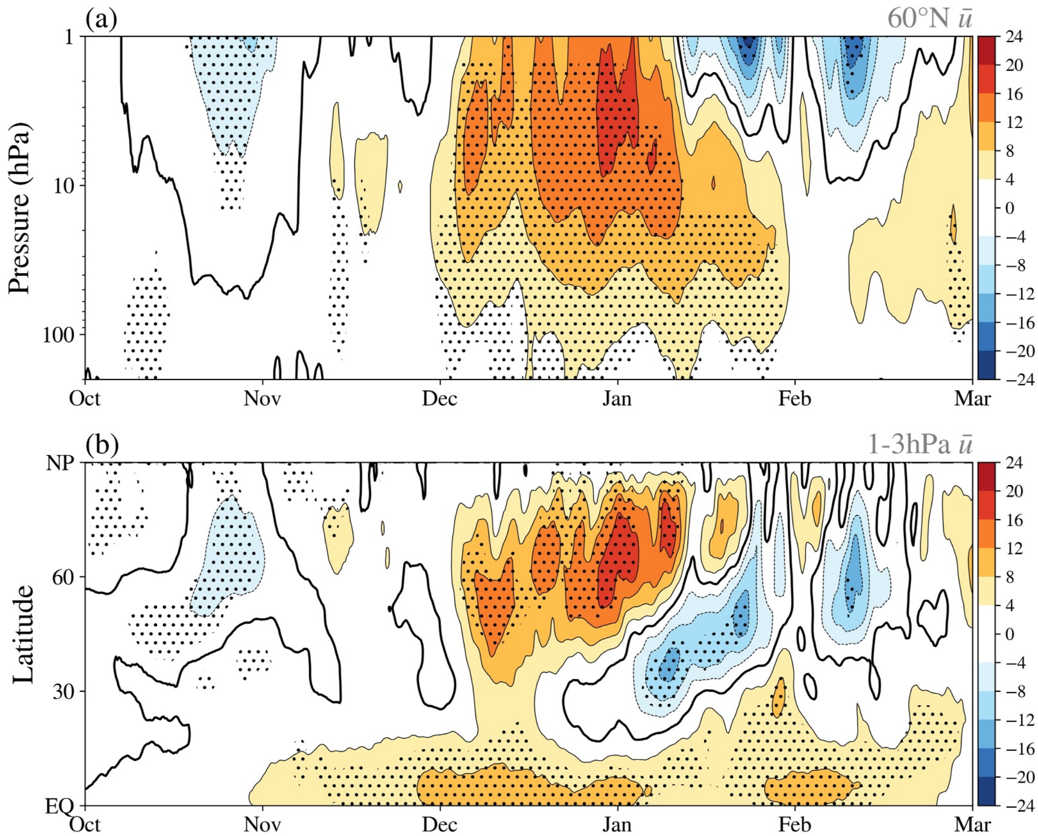

Figure 1. Winter evolution of anomalous zonal wind $\bar{u}$. (a) Moving daily average vertical profile of composite (positive minus negative index) stratospheric zonal winds at 60°N over October-March. (b) As in (a) but showing instead the latitudinal profile of mass-weighted composite zonal winds at 1–3 hPa in the Northern Hemisphere. Contours occur at intervals of 4 ms^{-1} and stippling indicates 5% significance using a Student's *t*-test.

3.2. Sudden Stratospheric Warming Occurrence

Due to the similarities of the downward propagating signal in Figure 1 and that of SSWs, we ask the question: how does the occurrence of SSW events differ across the two winter groups? Figure 2 displays the distribution of SSWs for positive and negative index winters over the months December-March. The SSWs are identified according to the wind reversal criteria posed by Charlton and Polvani (2007).

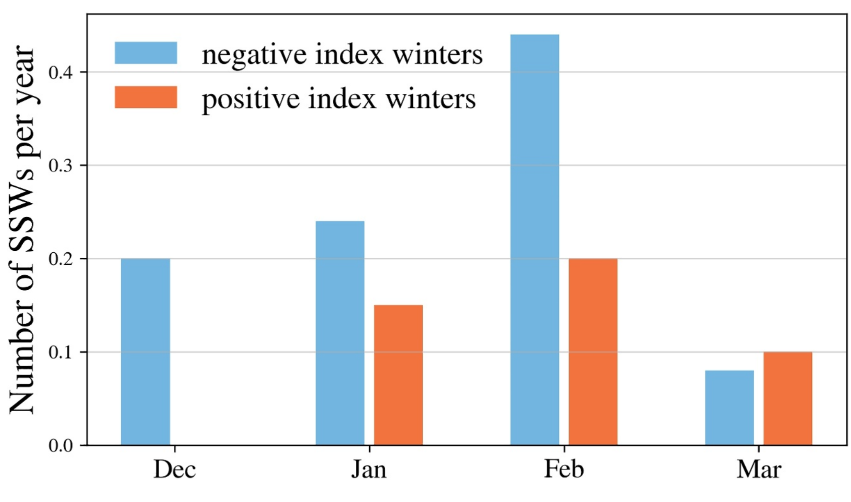

Figure 2. Distribution of SSWs according to the October meridional wind index.

In total, 73% of all SSWs occur in negative index winters, in which they tend to occur earlier in winter (December-February) compared with positive index winters. 80% of negative index winters contain an SSW event compared to only 35% of positive index winters, suggesting the two winter regimes precondition the stratosphere differently such that negative index winters are more predisposed to SSW events compared with positive index winters, which is a significant result at a p-value ≤ 0.006 using both a Chi-square test and a Fisher's exact test, which is more appropriate for smaller sample sizes. This concurs with the stratospheric zonal wind evolution seen in Figure 1 for which positive index winters see a considerably stronger and more stable vortex throughout the subsequent winter period.

The SSW events can be split into two types; downward-propagating, which exhibit significant and persistent annular mode anomalies, and 'non-propagating' that remain in the stratosphere (Karpechko et al., 2017). We find that the proportions of both types of SSWs occurring in positive and negative index winters to be comparable, suggesting that the October index is unable to predict when an SSW will be downward-propagating.

3.3. Surface Impact

In this section, we identify the surface impact of the October index. Figure 3 illustrates the composite MSLP difference between positive and negative index groups for the subsequent winter period (DJF). The spatial pattern features a strong positive NAO signature with an amplitude of 6.52 hPa, which is comparable in magnitude to one interannual standard deviation (8.40 hPa) and is significant at a p-value ≤ 0.005. The October index correlates with the DJF NAO with a coefficient of 0.40, suggesting that 15% of DJF NAO variability can be attributed to the October $\bar{v}$ index. There is a 71% hit rate of the DJF NAO being anomalously positive or negative given a positive or negative October index respectively. It should be noted that this is comparable to, although less than, the skill of current forecast systems and could therefore significantly contribute to forecast skill (Feng et al., 2021; Scaife et al., 2014). A permutation test with 10,000 iterations confirms that the observed correlation is robust at a p-value ≤ 0.008.

The relationship between the October index and DJF NAO may be non-stationary on an approximate decadal timescale. Figure 4 illustrates the 10-year running correlations between the October index and both the DJF NAO and polar vortex strength indices. The plot shows that the October index-DJF NAO teleconnection weakens and actually reverses in the 1990s before then correlating strongly and positively in the years since. There appears to be an association between periods of reduced SSW occurrence with periods with a weaker teleconnection. The 10-year running correlation between the October index and the DJF polar vortex strength appears to be relatively consistent, albeit weaker. Due to the small size of the moving window, sampling variability cannot be ruled out as an explanation for the non-stationary behavior observed here.

4. Discussion

This study measures the relationship that meridional wind in the upper stratospheric surf zone has with the winter polar vortex and surface on a S2S timescale. We construct an index based on the standardised October zonal mean meridional wind speed over the region 40°N–60°N and 1–3 hPa. We find that.

1. The index is significantly positively correlated with subsequent DJF polar vortex strength ($r = 0.36$).
2. The index plays an important role in preconditioning the stratosphere to SSWs. In negative index winters, SSWs are significantly more likely to occur compared with positive index winters.
3. The index is significantly correlated with subsequent DJF NAO ($r = 0.40$).

If the October meridional wind index is a proxy for the Eulerian-mean meridional circulation, then this begs the question; could a measure of the eddy momentum flux divergence, the driver of this effect (Equation 2), serve as a better predictor of DJF NAO and SSW occurrence? Using the standardised divergence of eddy momentum flux calculated over the same region (40°N–60°N, 1–3 hPa) in October as an alternative index, we find that it is similarly skilful in DJF NAO prediction. The strength of its correlation to DJF NAO is significant and similar to that of the meridional wind index ($r = -0.37$), and the magnitude of the DJF NAO response to the alternative October index is 7.57 hPa, which is highly significant ($p \leq 0.006$). This alternative index, however, falls short on SSW prediction. The changes to SSW frequency and occurrence resulting from the alternative index-determined regimes are not significant, suggesting that the divergence of eddy momentum flux may only account for the

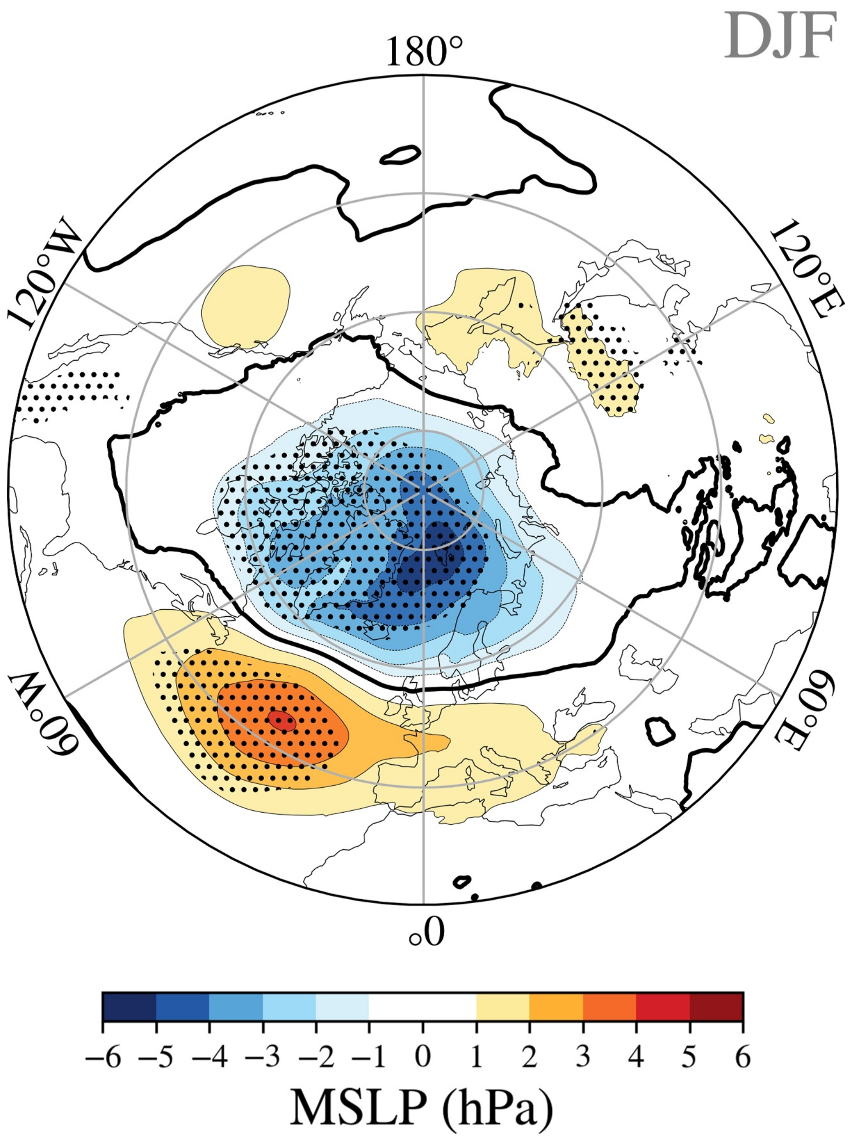

Figure 3. DJF surface response to October stratospheric wind index. Composite difference (positive minus negative index) in mean sea level pressure with contour intervals of 1 hPa. Stippling denotes 5% significance using a Student's *t*-test.

October meridional wind index-DJF NAO teleconnection. The source and mechanism of SSW predictability within the October index are unknown and warrant further investigation.

It is well known that SSW and weak vortex events tend to be followed by a negative NAO response in the following 1–2 months (e.g., Baldwin et al., 2021; Butler et al., 2017; Domeisen, 2019; Domeisen & Butler, 2020), while the North Pacific is less affected. In this study we have established a link between the October index and the DJF polar vortex strength and stability. Figure 1 demonstrates the established downward propagation of the upper stratospheric zonal wind anomaly and the resulting persistent changes to the vortex winds (e.g., Baldwin & Dunkerton, 1999; Kodera et al., 1990). This is corroborated by Figure 2, which demonstrates that negative index winters are significantly more likely to evoke SSWs that weaken and destabilize the vortex. The resulting MSLP response shown in Figure 3 is qualitatively similar to the MSLP response following SSW occurrence (e.g., Figure 3 of Baldwin and Dunkerton (2001), Figure 2 of Kidston et al. (2015), Figure 4 of Butler et al. (2017), and Figure 3 of Bett et al. (2023)). A bootstrapping linear mediation analysis indicates that the DJF polar vortex significantly mediates the teleconnection between the index and DJF NAO, suggesting that the changes to vortex strength and

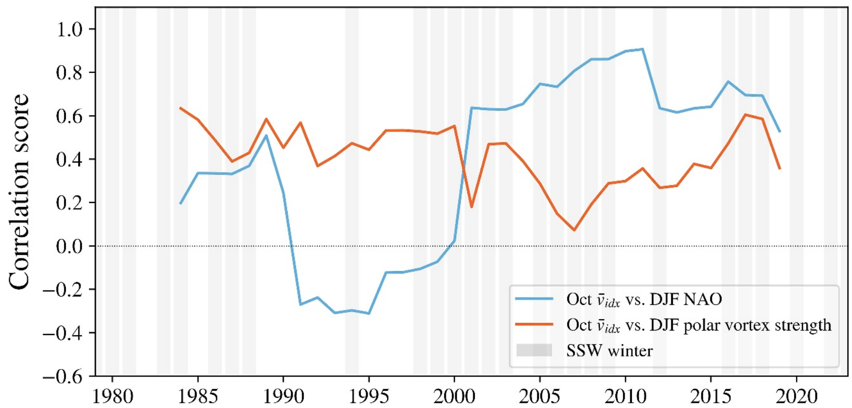

Figure 4. 10-year running correlations between the October meridional wind index, and the DJF NAO and stratospheric polar vortex ($\bar{u}$ at 60°N, 10 hPa) indices. The gray bars signify years in which at least one SSW occurred. The data are centered on the central date of the moving window. The years correspond to the year associated with the December of each winter.

stability are at least partly responsible for the DJF NAO response to the October index. This is supported by Figure 4, which suggests that SSW occurrence may be associated with a strengthened teleconnection.

The mechanisms by which the October index exerts downward influence on the surface can be divided into two parts. The first, is the downward propagation of the upper stratospheric signal along the polar vortex axis we observe in Figure 1a, the driving mechanisms of which involve wave-mean flow interaction with planetary-scale waves, but are not fully understood. A key theory for this downward propagation involves induced changes to planetary-wave propagation, reflection, and breaking (Chen & Robinson, 1992; Hitchcock & Haynes, 2016; Matsuno, 1971; Perlwitz & Harnik, 2003, 2004; Shaw et al., 2010; Shaw & Perlwitz, 2013). The resulting subseasonal vacillation in the winter stratospheric zonal winds is a known feature and we find that the upper stratospheric polar vortex (60°N, 1–3 hPa) correlates with the simple sinusoidal model proposed by Hardiman et al. (2020) with $r = 0.78$.

Gray et al. (2022) highlighted the sensitivity of the initial shape and development of the vortex, and the subsequent changes to stratospheric wave propagation and wave-mean flow interaction, to the Semi-annual Oscillation (SAO). The SAO lies in the equatorial upper stratosphere-lower mesosphere, however despite the difference in latitudinal location, there are important similarities between the influence of the SAO and of the October index on the subsequent development of the polar vortex. The SAO westerlies play a crucial role in defining the conical shape of the vortex in early winter. The October zonal wind anomalies in the Hovmöller composite plot, Figure 1b indicates that the conical shape of the early winter upper stratospheric vortex also varies with the October index. Gray et al. (2022) also found that the early winter equinoctial SAO phase transition had a significant bearing on SSW timing. Similarly the October index is found to determine two winter regimes for which SSW likelihood and timing significantly differ. Despite the apparent similarities, the strength of the SAO in October with 0, ± 1, and ± 2 month lags, and also the timing of the west-to-east phase transition at 0.3 hPa, do not significantly correlate with the October meridional wind index. Despite this, it is possible that the mechanistic response of the polar vortex to the October index is comparable with that of the SAO.

The second component of the mechanism by which the October index imposes downward influence on the surface, involves the receipt of the stratospheric signal by the troposphere whereby a persistent amplification and shift of the subtropical eddy-driven jet is induced (Domeisen et al., 2013; Garfinkel et al., 2013; Hitchcock & Simpson, 2016; Kidston et al., 2015; Limpasuvan et al., 2004; Song & Robinson, 2004). The strength and location of this jet is intrinsically tied to the NAO (e.g., Bordi et al., 2007; Lorenz & Hartmann, 2003; Strommen, 2020; Thompson et al., 2002; Vallis & Gerber, 2008; Woollings et al., 2010). Figure S1 in Supporting Information S1 confirms that the October index is associated with a strong and persistent latitudinal shift in the westerly winds at 200 hPa, indicating a poleward shifted subtropical jet. The 200 hPa westerlies exhibit significant midlatitude anomalies from mid-September, suggesting that the equinoctial troposphere may contribute to the preconditioning of the October upper stratosphere (Charney & Drazin, 1961).

Finally, we address the potential influence of the QBO. A naïve explanation of the meridional wind index could be the QBO-induced mean meridional circulation in the subtropical stratosphere. However, we find the October QBO taken at 50 hPa to be insignificantly correlated with the $\bar{v}$ index ($r = 0.16$). Using partial regression to control for the influence of the QBO, the correlation between the $\bar{v}$ index and DJF NAO remains unchanged ($r = 0.40$), suggesting that the QBO is not involved in the mechanism linking the October index to the winter NAO.

Data Availability Statement

The ERA5 reanalysis hourly pressure level data (Hersbach et al., 2023) used in this study are freely available from https://doi.org/10.24381/cds.bd0915c6. The MERRA-2 reanalysis data (Global Modeling and Assimilation Office (GMAO), 2015) are freely available from https://doi.org/10.5067/IUUF4WB9FT4W. The analysis code is proprietary to Elizabeth Collingwood and is available upon request to elcoll56@bas.ac.uk.

Acknowledgments

EC acknowledges support by the Natural Environment Research Council via the INSPIRE Doctoral Training Partnership (NE/S007210/1). AAS 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. HL, BS, and GM are supported by CANARI, a National Capability Multi-Centre Science programme of the Natural Environment Research Council (NEB2026, NE/W004984/1). We would like to thank Tony Phillips for providing access to the reanalysis data.

References

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*(4), 1461–1475. https://doi.org/10.1175/JCLI-D-16-0153.1

Baker, L., Shaffrey, L., Sutton, R., Weisheimer, A., & Scaife, A. (2018). An intercomparison of skill and overconfidence/underconfidence of the wintertime North Atlantic Oscillation in multimodel seasonal forecasts. *Geophysical Research Letters*, *45*(15), 7808–7817. https://doi.org/10.1029/2018GL078838

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), e2020RG000708. https://doi.org/10.1029/2020RG000708

Baldwin, M. P., & Dunkerton, T. J. (1999). Propagation of the Arctic oscillation from the stratosphere to the troposphere. *Journal of Geophysical Research*, *104*(D24), 30937–30946. https://doi.org/10.1029/1999JD900445

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., & Dunkerton, T. J. (2005). The solar cycle and stratosphere–troposphere dynamical coupling. *Journal of Atmospheric and Solar-Terrestrial Physics*, *67*(1–2), 71–82. https://doi.org/10.1016/j.jastp.2004.07.018

Barnes, E. A., & Hartmann, D. L. (2010). Dynamical feedbacks and the persistence of the NAO. *Journal of the Atmospheric Sciences*, *67*(3), 851–865. https://doi.org/10.1175/2009JAS3193.1

Bell, C. J., Gray, L. J., Charlton-Perez, A. J., Joshi, M. M., & Scaife, A. A. (2009). Stratospheric communication of El Niño teleconnections to European winter. *Journal of Climate*, *22*(15), 4083–4096. https://doi.org/10.1175/2009JCLI2717.1

Benedict, J. J., Lee, S., & Feldstein, S. B. (2004). Synoptic view of the North Atlantic oscillation. *Journal of the Atmospheric Sciences*, *61*(2), 121–144. https://doi.org/10.1175/1520-0469(2004)061%3C0121:SVOTNA%3E2.0.CO;2

Bett, P. E., Scaife, A. A., Hardiman, S. C., Thornton, H. E., Shen, X., Wang, L., & Pang, B. (2023). Using large ensembles to quantify the impact of sudden stratospheric warmings and their precursors on the North Atlantic Oscillation. *Weather and Climate Dynamics*, *4*(1), 213–228. https://doi.org/10.5194/wcd-4-213-2023

Bordi, I., Fraedrich, K., Lunkeit, F., & Sutera, A. (2007). Tropospheric double jets, meridional cells, and eddies: A case study and idealized simulations. *Monthly Weather Review*, *135*(9), 3118–3133. https://doi.org/10.1175/MWR3464.1

Butler, A. H., Sjoberg, J. P., Seidel, D. J., & Rosenlof, K. H. (2017). A sudden stratospheric warming compendium. *Earth System Science Data*, *9*(1), 63–76. https://doi.org/10.5194/essd-9-63-2017

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

Charney, J. G., & Drazin, P. G. (1961). Propagation of planetary-scale disturbances from the lower into the upper atmosphere. *Journal of Geophysical Research (1896-1977)*, *66*(1), 83–109. https://doi.org/10.1029/JZ066i001p00083

Chen, P., & Robinson, W. A. (1992). Propagation of planetary waves between the troposphere and stratosphere. *Journal of the Atmospheric Sciences*, *49*(24), 2533–2545. https://doi.org/10.1175/1520-0469(1992)049⟨2533:POPWBT⟩2.0.CO;2

Cohen, J., Furtado, J. C., Jones, J., Barlow, M., Whittleston, D., & Entekhabi, D. (2014). Linking Siberian snow cover to precursors of stratospheric variability. *Journal of Climate*, *27*(14), 5422–5432. https://doi.org/10.1175/JCLI-D-13-00779.1

Czaja, A., & Frankignoul, C. (2002). Observed impact of Atlantic SST anomalies on the North Atlantic oscillation. *Journal of Climate*, *15*(6), 606–623. https://doi.org/10.1175/1520-0442(2002)015⟨0606:OIOASA⟩2.0.CO;2

Degenhardt, L., Leckebusch, G. C., & Scaife, A. A. (2024). Understanding winter windstorm predictability over Europe. *Weather and Climate Dynamics*, *5*(2), 587–607. https://doi.org/10.5194/wcd-5-587-2024

Deser, C., Tomas, R. A., & Peng, S. (2007). The transient atmospheric circulation response to North Atlantic SST and sea ice anomalies. *Journal of Climate*, *20*(18), 4751–4767. https://doi.org/10.1175/JCLI4278.1

Domeisen, D. I. (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., & 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., 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: 2. Predictability arising from stratosphere-troposphere coupling. *Journal of Geophysical Research: Atmospheres*, *125*(2), e2019JD030923. https://doi.org/10.1029/2019JD030923

Domeisen, D. I., Sun, L., & Chen, G. (2013). The role of synoptic eddies in the tropospheric response to stratospheric variability. *Geophysical Research Letters*, *40*(18), 4933–4937. https://doi.org/10.1002/grl.50943

Dunstone, N., Smith, D., Scaife, A., Hermanson, L., Eade, R., Robinson, N., et al. (2016). Skilful predictions of the winter North Atlantic Oscillation one year ahead. *Nature Geoscience*, *9*(11), 809–814. https://doi.org/10.1038/ngeo2824

Ebdon, R., & Veryard, R. (1961). Fluctuations in equatorial stratospheric winds. *Nature*, *189*(4767), 791–793. https://doi.org/10.1038/189791a0

Eliassen, A. (1951). Slow thermally or frictionally controlled meridional circulation in a circular vortex. *Astrophisica Norvegica*, *5*, 19.

Feldstein, S. B. (2003). The dynamics of NAO teleconnection pattern growth and decay. *Quarterly Journal of the Royal Meteorological Society*, *129*(589), 901–924. https://doi.org/10.1256/qj.02.76

Feng, P.-N., Lin, H., Derome, J., & Merlis, T. M. (2021). Forecast skill of the NAO in the subseasonal-to-seasonal prediction models. *Journal of Climate*, *34*(12), 4757–4769. https://doi.org/10.1175/JCLI-D-20-0430.1

Fereday, D., Chadwick, R., Knight, J., & Scaife, A. A. (2020). Tropical rainfall linked to stronger future ENSO-NAO teleconnection in CMIP5 models. *Geophysical Research Letters*, *47*(22), e2020GL088664. https://doi.org/10.1029/2020GL088664

Franzke, C., Lee, S., & Feldstein, S. B. (2004). Is the North Atlantic oscillation a breaking wave? *Journal of the Atmospheric Sciences*, *61*(2), 145–160. https://doi.org/10.1175/1520-0469(2004)061⟨0145:IT{NAO}A⟩2.0.CO;2

Garfinkel, C. I., Schwartz, C., White, I. P., & Rao, J. (2020). Predictability of the early winter Arctic oscillation from Autumn Eurasian snowcover in subseasonal forecast models. *Climate Dynamics*, *55*(3–4), 961–974. https://doi.org/10.1007/s00382-020-05305-3

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

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., et al. (2017). The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). *Journal of Climate*, *30*(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Global Modeling and Assimilation Office (GMAO). (2015). MERRA-2 inst6_3d_ana_nv: 3d, 6-hourly, instantaneous, model-level, analysis, analyzed meteorological fields v5.12.4 [dataset]. *Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC)*. https://doi.org/10.5067/IUUF4WB9FT4W

Gray, L. J., Brown, M. J., Knight, J., Andrews, M., Lu, H., O'Reilly, C., & Anstey, J. (2020). Forecasting extreme stratospheric polar vortex events. *Nature Communications*, *11*(1), 4630. https://doi.org/10.1038/s41467-020-18299-7

Gray, L. J., Lu, H., Brown, M. J., Knight, J. R., & Andrews, M. B. (2022). Mechanisms of influence of the Semi-Annual Oscillation on stratospheric sudden warmings. *Quarterly Journal of the Royal Meteorological Society*, *148*(744), 1223–1241. https://doi.org/10.1002/qj.4256

Gray, L. J., Sparrow, S., Juckes, M., O'Neill, A., & Andrews, D. G. (2003). Flow regimes in the winter stratosphere of the Northern Hemisphere. *Quarterly Journal of the Royal Meteorological Society*, *129*(589), 925–945. https://doi.org/10.1256/qj.02.82

Greer, K., Thayer, J. P., & Harvey, V. L. (2013). A climatology of polar winter stratopause warmings and associated planetary wave breaking. *Journal of Geophysical Research: Atmospheres*, *118*(10), 4168–4180. https://doi.org/10.1002/jgrd.50289

Hardiman, S., Scaife, A. A., Dunstone, N., & Wang, L. (2020). Subseasonal vacillations in the winter stratosphere. *Geophysical Research Letters*, *47*(9), e2020GL087766. https://doi.org/10.1029/2020gl087766

Haynes, P., McIntyre, M., Shepherd, T., Marks, C., & Shine, K. P. (1991). On the "downward control" of extratropical diabatic circulations by eddy-induced mean zonal forces. *Journal of the Atmospheric Sciences*, *48*(4), 651–678. https://doi.org/10.1175/1520-0469(1991)048<0651:otcoed>2.0.co;2

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., et al. (2023). ERA5 hourly data on pressure levels from 1940 to present [dataset]. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. https://doi.org/10.24381/cds.bd0915c6

Hitchcock, P., & Haynes, P. H. (2016). Stratospheric control of planetary waves. *Geophysical Research Letters*, *43*(22), 11884–11892. https://doi.org/10.1002/2016GL071372

Hitchcock, P., & Simpson, I. R. (2016). Quantifying eddy feedbacks and forcings in the tropospheric response to stratospheric sudden warmings. *Journal of the Atmospheric Sciences*, *73*(9), 3641–3657. https://doi.org/10.1175/JAS-D-16-0056.1

Holton, J. R., Haynes, P. H., McIntyre, M. E., Douglass, A. R., Rood, R. B., & Pfister, L. (1995). Stratosphere-troposphere exchange. *Reviews of Geophysics*, *33*(4), 403–439. https://doi.org/10.1029/95RG02097

Hurrell, J. W., & Deser, C. (2010). North Atlantic climate variability: The role of the North Atlantic oscillation. *Journal of Marine Systems*, *79*(3–4), 231–244. https://doi.org/10.1016/j.jmarsys.2009.11.002

Hurrell, J. W., Kushnir, Y., Ottersen, G., & Visbeck, M. (2003). An overview of the North Atlantic oscillation. *Geophysical Monograph-American Geophysical Union*, *134*, 1–36. https://doi.org/10.1029/134GM01

Hurrell, J. W., Kushnir, Y., & Visbeck, M. (2001). The North Atlantic oscillation. *Science*, *291*(5504), 603–605. https://doi.org/10.1126/science.1058761

Ineson, S., Scaife, A. A., Knight, J. R., Manners, J. C., Dunstone, N. J., Gray, L. J., & Haigh, J. D. (2011). Solar forcing of winter climate variability in the Northern Hemisphere. *Nature Geoscience*, *4*(11), 753–757. https://doi.org/10.1038/ngeo1282

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

Kidston, J., Scaife, A. A., Hardiman, S. C., Mitchell, D. M., Butchart, N., Baldwin, M. P., & Gray, L. J. (2015). Stratospheric influence on tropospheric jet streams, storm tracks and surface weather. *Nature Geoscience*, *8*(6), 433–440. https://doi.org/10.1038/ngeo2424

Kodera, K., Yamazaki, K., Chiba, M., & Shibata, K. (1990). Downward propagation of upper stratospheric mean zonal wind perturbation to the troposphere. *Geophysical Research Letters*, *17*(9), 1263–1266. https://doi.org/10.1029/GL017i009p01263

Koushik, N., Kumar, K. K., & Pramitha, M. (2022). A tropical stratopause precursor for sudden stratospheric warmings. *Scientific Reports*, *12*(1), 2937. https://doi.org/10.1038/s41598-022-06864-7

Kuroda, Y. (2008). Role of the stratosphere on the predictability of medium-range weather forecast: A case study of winter 2003–2004. *Geophysical Research Letters*, *35*(19). https://doi.org/10.1029/2008GL034902

Limpasuvan, V., Hartmann, D. L., Thompson, D. W., Jeev, K., & Yung, Y. L. (2005). Stratosphere-troposphere evolution during polar vortex intensification. *Journal of Geophysical Research*, *110*(D24). https://doi.org/10.1029/2005JD006302

Limpasuvan, V., Thompson, D. W., & Hartmann, D. L. (2004). The life cycle of the Northern Hemisphere sudden stratospheric warmings. *Journal of Climate*, *17*(13), 2584–2596. https://doi.org/10.1175/1520-0442(2004)017⟨2584:TLCOTN⟩2.0.CO;2

Lindgren, E. A., & Sheshadri, A. (2020). The role of wave–wave interactions in sudden stratospheric warming formation. *Weather and Climate Dynamics*, *1*(1), 93–109. https://doi.org/10.5194/wcd-1-93-2020

Lorenz, D. J., & Hartmann, D. L. (2003). Eddy–zonal flow feedback in the Northern Hemisphere winter. *Journal of Climate*, *16*(8), 1212–1227. https://doi.org/10.1175/1520-0442(2003)16⟨1212:EFFITN⟩2.0.CO;2

Lu, H., Gray, L. J., Martineau, P., King, J. C., & Bracegirdle, T. J. (2021). Regime behavior in the upper stratosphere as a precursor of stratosphere–troposphere coupling in the northern winter. *Journal of Climate*, *34*(18), 7677–7696. https://doi.org/10.1175/JCLI-D-20-0831.1

Lu, H., Scaife, A. A., Marshall, G. J., Turner, J., & Gray, L. J. (2017). Downward wave reflection as a mechanism for the stratosphere–troposphere response to the 11-Yr solar cycle. *Journal of Climate*, *30*(7), 2395–2414. https://doi.org/10.1175/JCLI-D-16-0400.1

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

McIntyre, M. E., & Palmer, T. N. (1983). Breaking planetary waves in the stratosphere. *Nature*, *305*(5935), 593–600. https://doi.org/10.1038/305593a0

Molteni, F., Stockdale, T. N., & Vitart, F. (2015). Understanding and modelling extra-tropical teleconnections with the Indo-Pacific region during the northern winter. *Climate Dynamics*, *45*(11–12), 3119–3140. https://doi.org/10.1007/s00382-015-2528-y

NCAR, U. J. H. (2003). NAO index data provided by the climate analysis section. updated regularly. Retrieved from https://climatedataguide.ucar.edu/climate-data (Accessed: 2024-10-30)

Nie, Y., Scaife, A. A., Ren, H.-L., Comer, R. E., Andrews, M. B., Davis, P., & Martin, N. (2019). Stratospheric initial conditions provide seasonal predictability of the North Atlantic and Arctic Oscillations. *Environmental Research Letters*, *14*(3), 034006. https://doi.org/10.1088/1748-9326/ab0385

O'Neill, A., & Pope, V. D. (1988). Simulations of linear and nonlinear disturbances in the stratosphere. *Quarterly Journal of the Royal Meteorological Society*, *114*(482), 1063–1110. https://doi.org/10.1002/qj.49711448210

O'Reilly, C. H., Weisheimer, A., Woollings, T., Gray, L. J., & MacLeod, D. (2019). The importance of stratospheric initial conditions for winter North Atlantic Oscillation predictability and implications for the signal-to-noise paradox. *Quarterly Journal of the Royal Meteorological Society*, *145*(718), 131–146. https://doi.org/10.1002/qj.3413

Perlwitz, J., & Harnik, N. (2003). Observational evidence of a stratospheric influence on the troposphere by planetary wave reflection. *Journal of Climate*, *16*(18), 3011–3026. https://doi.org/10.1175/1520-0442(2003)016⟨3011:OEOASI⟩2.0.CO;2

Perlwitz, J., & Harnik, N. (2004). Downward coupling between the stratosphere and troposphere: The relative roles of wave and zonal mean processes. *Journal of Climate*, *17*(24), 4902–4909. https://doi.org/10.1175/JCLI-3247.1

Plumb, R. A. (2010). Planetary waves and the extratropical winter stratosphere. *Geophysical Monograph Series*, *190*, 23–41. https://doi.org/10.1029/2009GM000888

Riddle, E. E., Butler, A. H., Furtado, J. C., Cohen, J. L., & Kumar, A. (2013). CFSv2 ensemble prediction of the wintertime Arctic Oscillation. *Climate Dynamics*, *41*(3–4), 1099–1116. https://doi.org/10.1007/s00382-013-1850-5

Rodwell, M. J., Rowell, D. P., & Folland, C. K. (1999). Oceanic forcing of the wintertime North Atlantic oscillation and European climate. *Nature*, *398*(6725), 320–323. https://doi.org/10.1038/18648

Rogers, J. C. (1997). North Atlantic storm track variability and its association to the North Atlantic oscillation and climate variability of Northern Europe. *Journal of Climate*, *10*(7), 1635–1647. https://doi.org/10.1175/1520-0442(1997)010⟨1635:NASTVA⟩2.0.CO;2

Scaife, A. A., Arribas, A., Blockley, E., Brookshaw, A., Clark, R., Dunstone, N., et al. (2014). Skillful long-range prediction of European and North American winters. *Geophysical Research Letters*, *41*(7), 2514–2519. https://doi.org/10.1002/2014GL059637

Scaife, A. A., Baldwin, M. P., Butler, A. H., Charlton-Perez, A. J., Domeisen, D. I., Garfinkel, C. I., et al. (2022). Long-range prediction and the stratosphere. *Atmospheric Chemistry and Physics*, *22*(4), 2601–2623. https://doi.org/10.5194/acp-22-2601-2022

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

Scaife, A. A., Karpechko, A. Y., Baldwin, M., Brookshaw, A., Butler, A., Eade, R., et al. (2016). Seasonal winter forecasts and the stratosphere. *Atmospheric Science Letters*, *17*(1), 51–56. https://doi.org/10.1002/asl.598

Shaw, T. A., & Perlwitz, J. (2013). The life cycle of Northern Hemisphere downward wave coupling between the stratosphere and troposphere. *Journal of Climate*, *26*(5), 1745–1763. https://doi.org/10.1175/JCLI-D-12-00251.1

Shaw, T. A., Perlwitz, J., & Harnik, N. (2010). Downward wave coupling between the stratosphere and troposphere: The importance of meridional wave guiding and comparison with zonal-mean coupling. *Journal of Climate*, *23*(23), 6365–6381. https://doi.org/10.1175/2010JCLI3804.1

Smith, D. M., Scaife, A. A., Eade, R., Athanasiadis, P., Bellucci, A., Bethke, I., et al. (2020). North Atlantic climate far more predictable than models imply. *Nature*, *583*(7818), 796–800. https://doi.org/10.1038/s41586-020-2525-0

Song, Y., & Robinson, W. A. (2004). Dynamical mechanisms for stratospheric influences on the troposphere. *Journal of the Atmospheric Sciences*, *61*(14), 1711–1725. https://doi.org/10.1175/1520-0469(2004)061⟨1711:DMFSIO⟩2.0.CO;2

Strommen, K. (2020). Jet latitude regimes and the predictability of the North Atlantic oscillation. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 2368–2391. https://doi.org/10.1002/qj.3796

Strong, C., & Magnusdottir, G. (2011). Dependence of NAO variability on coupling with sea ice. *Climate Dynamics*, *36*(9–10), 1681–1689. https://doi.org/10.1007/s00382-010-0752-z

Taguchi, M. (2018). Seasonal winter forecasts of the northern stratosphere and troposphere: Results from JMA seasonal hindcast experiments. *Journal of the Atmospheric Sciences*, *75*(3), 827–840. https://doi.org/10.1175/JAS-D-17-0276.1

Thayer, J. P., Greer, K., & Harvey, V. L. (2010). Front-like behavior in the Arctic wintertime upper stratosphere and lower mesosphere. *Journal of Geophysical Research*, *115*(D3). https://doi.org/10.1029/2010jd014278

Thompson, D. W., Baldwin, M. P., & Wallace, J. M. (2002). Stratospheric connection to Northern Hemisphere wintertime weather: Implications for prediction. *Journal of Climate*, *15*(12), 1421–1428. https://doi.org/10.1175/1520-0442(2002)015⟨1421:SCTNHW⟩2.0.CO;2

Vallis, G. K., & Gerber, E. P. (2008). Local and hemispheric dynamics of the North Atlantic Oscillation, annular patterns and the zonal index. *Dynamics of Atmospheres and Oceans*, *44*(3–4), 184–212. https://doi.org/10.1016/j.dynatmoce.2007.04.003

Woollings, T., Hannachi, A., & Hoskins, B. (2010). Variability of the North Atlantic eddy-driven jet stream. *Quarterly Journal of the Royal Meteorological Society*, *136*(649), 856–868. https://doi.org/10.1002/qj.625