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Seasonal winter forecasts and the stratosphere

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Abstract

We investigate seasonal forecasts of the winter North Atlantic Oscillation (NAO) and their relationship with the stratosphere. Climatological frequencies of sudden stratospheric warming (SSW) and strong polar vortex (SPV) events are well represented and the predicted risk of events varies between 25 and 90% from winter to winter, indicating predictability beyond the deterministic range. The risk of SSW and SPV events relates to predicted NAO as expected, with NAO shifts of −6.5 and +4.8 hPa in forecast members containing SSW and SPV events. Most striking of all is that forecast skill of the surface winter NAO vanishes from these hindcasts if members containing SSW events are excluded.

Keywords: **seasonal forecast; NAO; stratosphere**

1. Introduction

Previous studies have quantified the deterministic limit on the predictability of the *timing* of sudden stratospheric warming (SSW) events. These studies typically indicate significant forecast skill out to around 2 weeks (Mukougawa *et al.*, 2005; Stan and Straus, 2009; Marshall and Scaife, 2010; Sigmond *et al.*, 2013) and very occasionally 1 month (Kuroda, 2008) ahead. However, there could be additional forecast skill beyond this timescale if we consider the probabilistic *risk* of an event occurring. In addition, there could also be forecast skill for strong polar vortex (SPV) events which have received relatively little attention compared with SSW events despite the apparent symmetry between the tropospheric impacts of both types of event (Baldwin and Dunkerton, 1999). Given the stratospheric influence on winter surface climate (e.g. Boville, 1984; Scaife and Knight, 2008; Kolstad *et al.*, 2010; Mitchell *et al.*, 2013; Sigmond *et al.*, 2013), we also investigate the relationship with winter seasonal forecasts of the surface North Atlantic Oscillation (NAO).

Here, we investigate retrospective forecasts of the risk of winter SSW and SPV events and the resulting impact on seasonal forecasts of surface winter climate from the Met Office Global Seasonal forecast system GloSea (Arribas *et al.*, 2011). We use ensembles of 24 forecasts starting in early November for each of the 20 winters from 1992/1993 to 2011/2012 from the fifth generation of GloSea (MacLachlan *et al.*, 2014). These winter forecasts have statistically significant forecast skill for the surface NAO (Scaife *et al.*, 2014). We define stratospheric events using the daily zonal Arctic winds at 10 hPa and averaged around 60 N in each forecast ensemble member. SSW events are defined to occur if this wind decreases below zero at some time in the winter, while SPV events are defined to occur if this wind increases above 48 m s^{-1} on some day in the winter. This SPV (upper) threshold is chosen as it is broken with the same frequency as the lower SSW threshold in our forecasts.

2. Predictability of stratospheric events beyond the deterministic range

To eliminate predictability on the timescale of weeks described above, we discard forecast data from the first month (November) and include only data for the December to February period. The 20 winters from 1992/1993 to 2011/2012 are included, with 24 member ensemble forecasts for each winter, making a total of 480 winter forecasts. This total number of realizations is an order of magnitude greater than the number of stratospheric winters we have in the observational record since the advent of comprehensive satellite data for the stratosphere (e.g. Pawson and Fiorino, 1999; Scaife *et al.*, 2000). This allows more stable statistics to be calculated than are possible from the observational record alone.

Figure 1 shows the ensemble of 24 member forecasts for the winters 1997/1998 and 1999/2000.

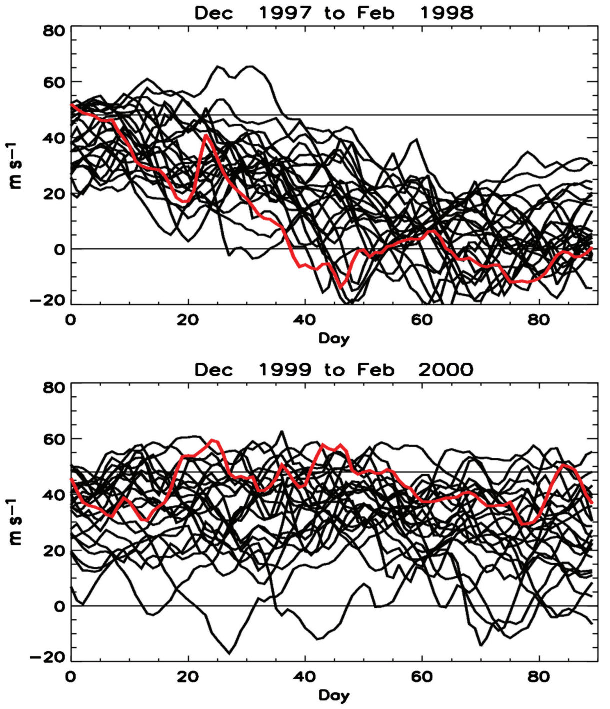

Figure 1. Ensemble forecast evolution of zonal wind in the stratosphere. Zonal mean U winds are shown (10 hPa, 60 N) in two different winters, with 24 ensemble members per winter and an example member colored red. The horizontal lines show the threshold for SSW (0 ms^{-1}) events and SPV (48 ms^{-1}) events. The two winters shown exhibit quite different predicted probability of a SSW or SPV event, indicating the potential for forecasting the risk of these events well beyond the deterministic range of a few weeks.

Forecast members highlighted in red illustrate example evolutions of the stratospheric wind. In the case of 1997/1998, the sample member undergoes a SSW event around day 37 (6 January) when it crosses the zero wind line. Similarly, while the sample member for 1999/2000 does not show any sudden warmings, it does go through an SPV event around day 18 (18 December) when it crosses the upper threshold. Counting whether at least one event occurs in each forecast member yields a forecast probability of either a SSW or SPV event for each winter. The climatological frequency of SSW and SPV events averaged over all 20 winters and all forecast members is 0.53 and 0.55, respectively. This matches the observed frequency of 0.45 and 0.60 for the same period to within statistical sampling uncertainty, using the same criteria. GloSea5 evidently produces a good simulation of stratospheric climate variability in this sense.

The winter ensembles in Figure 1 illustrate the very different probability of SSW and SPV events between winter 1997/1998 and winter 1999/2000 in these long-lead forecasts. This variation in the predicted risk of such events changes from 1 year to the next for both SSW and SPV events and varies between 25 and 90% across the 20 winters considered. Given that we discard the first month of the forecasts, these events therefore show potential predictability, at least in a probabilistic sense, well beyond the previously identified deterministic limit of a few weeks. To quantify the predictability further, we would ideally take many observed events from a very long sequence of winters and quantify the frequency of an observed event as a function of forecast probability. However with the limited number of observed events over the period used here, this is not possible due to the small sample size. Instead, we create a more statistically stable estimate of predictability using the forecast ensemble data alone (sometimes called perfect predictability) and resampling individual members for each year to create 1000 series of proxy observations. We then calculate how much the risk of a SSW event or SPV event changes on average (with replacement of the observed proxy member) in the years when an event occurred in the proxy observations. The result of this calculation is almost identical for both SSW and SPV events and the forecast probability of an event rises by 12% on average from 47% in winters in which there is no event to 59% in winters in which an event occurs. Although this is a modest shift in probability, the large number of samples involved means that this potential probabilistic forecast skill is significant beyond the 95% level.

3. Relationship with the surface NAO

The latest generation of seasonal forecast systems has begun to show consistent and statistically significant skill for seasonal predictions of the winter NAO (Scaife *et al.*, 2014) and its hemispheric equivalent of the Arctic Oscillation (AO; Riddle *et al.*, 2013; Athanasiadis *et al.*, 2014; Kang *et al.*, 2014; Stockdale *et al.*, 2015). The stratosphere is expected to contribute to this skill (Orsolini *et al.*, 2011; Folland *et al.*, 2012; Smith *et al.*, 2012) due to its influence on the tropospheric NAO and AO, which is present in our model (e.g. Fereday *et al.*, 2012). The seasonal forecasts examined here are consistent with this idea because the predicted surface NAO shows a significant interannual correlation of −0.43 with the predicted frequency of SSW events (Figure 2). As expected, the correlation with the predicted frequency of SPV events shows the opposite sign, with an increase in predicted SPV events coinciding with an increase in predicted NAO. However, the correlation in this case is only 0.23 and is not statistically significant for the 20 years available here.

The impact of the predicted occurrence of a SSW event or SPV event on predicted winter NAO values is shown in Figure 3. Distributions of predicted NAO, conditioned on the occurrence or absence of a SSW, are shown in the upper panels of Figure 3 and indicate a mean shift of −6.5 hPa when a SSW occurs. This is a large value given that the interannual standard deviation of the NAO is around 8 hPa. A similar result holds for the SPV events, with a mean shift of +4.8 hPa when a SPV event occurs in forecast members. Both shifts are statistically significant beyond the 99% level due to the large sample size. While very low or very high NAO values can still occur irrespective of

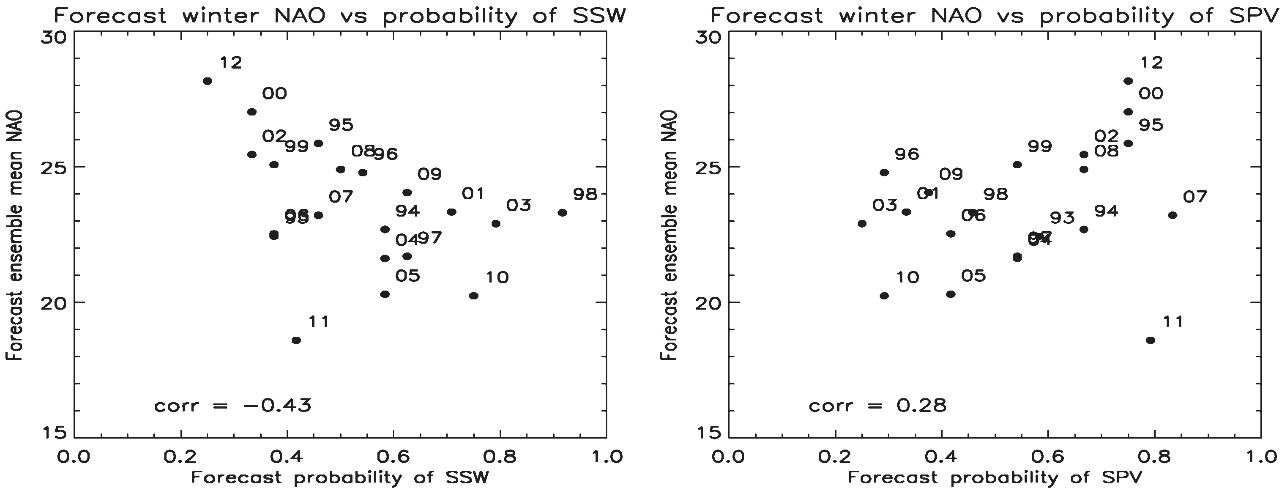

Figure 2. Correlation between ensemble mean NAO forecast and risk of SSW (left), and between ensemble mean NAO forecast and risk of SPV (right) events. Results are over the 20 winters from 1992/1993 to 2011/2012 and are significant at the 95% level in the SSW case. The correlation with SPV risk is not statistically significant but does show the expected sign. Winters are labeled by the year of the corresponding January.

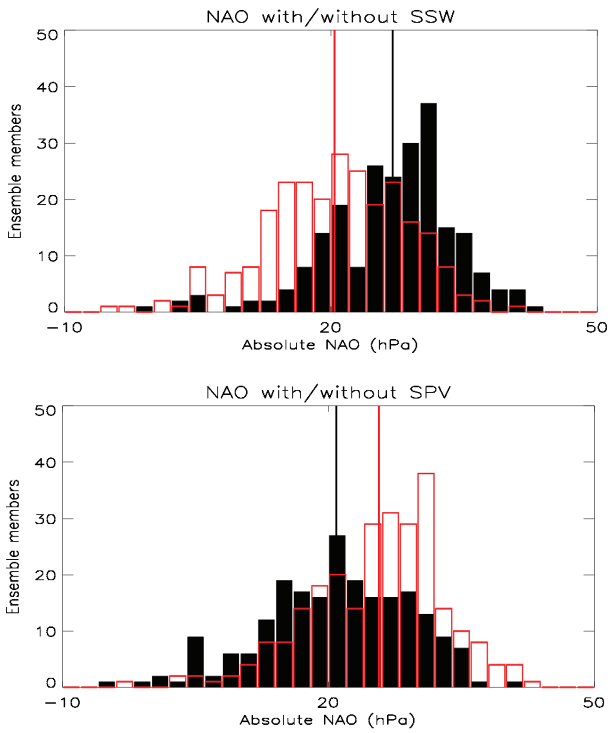

Figure 3. Distribution of ensemble forecasts of the surface NAO. Upper panels show NAO forecasts with (red) and without (black) SSW events. Lower panels show NAO forecasts with (red) and without (black) SPV events. There are 480 individual forecasts in the distributions (20 winters × 24 members). Vertical lines show the distribution means. Differences between the means with and without events are significant beyond the 99% level according to a one-sided *t*-test.

the occurrence of a stratospheric event, and this does not mean that forecast NAO signals originate in or are driven by the stratosphere, these large shifts in surface climate confirm that the ensemble forecast surface winter NAO is strongly conditional on events in the stratosphere.

4. Impact on surface forecast skill

We have seen that on average, the occurrence of a strong (SPV) or weak (SSW) stratospheric event gives large conditional changes in the predicted surface NAO toward positive or negative values. Here, we quantify how this affects forecast skill. To do this, we calculate the forecast skill with and without members that include a SSW (Figure 4). In the case of SSW events, this produces a striking result: the full ensemble mean correlation skill of the NAO (0.62, Scaife *et al.*, 2014) vanishes if SSW events are excluded. The remaining ensemble mean shows a correlation skill of just 0.09 which is statistically insignificant. A smaller (but statistically insignificant) reduction occurs if SPV events are instead omitted from the ensemble. Skill in these NAO forecasts is therefore conditional on the inclusion of SSWs.

While this result is striking, we must interpret it carefully. Given the downward propagating and lagged influence of the stratosphere on the troposphere, the lack of NAO skill without SSW events is consistent with the stratosphere playing a key role in NAO predictability. However, it does not necessarily mean that the source of NAO forecast skill originates in the stratosphere (see Sun *et al.*, 2012). Second, after members containing SSW events are removed, the ensemble size is reduced by about half (the frequency of SSW events in the hindcasts) and so the skill will inevitably drop due to the smaller ensemble size (Scaife *et al.*, 2014, Figure 3). We therefore tested whether the correlation of 0.09 represents a significant reduction in skill given the smaller ensemble size. To do this, we resampled ensembles of the same average reduced size and calculated their ensemble mean correlation with the observed NAO. Using 1000 resampled ensembles of the same average reduced size, 99% resulted in a correlation that exceeds the case with no SSW events, confirming that

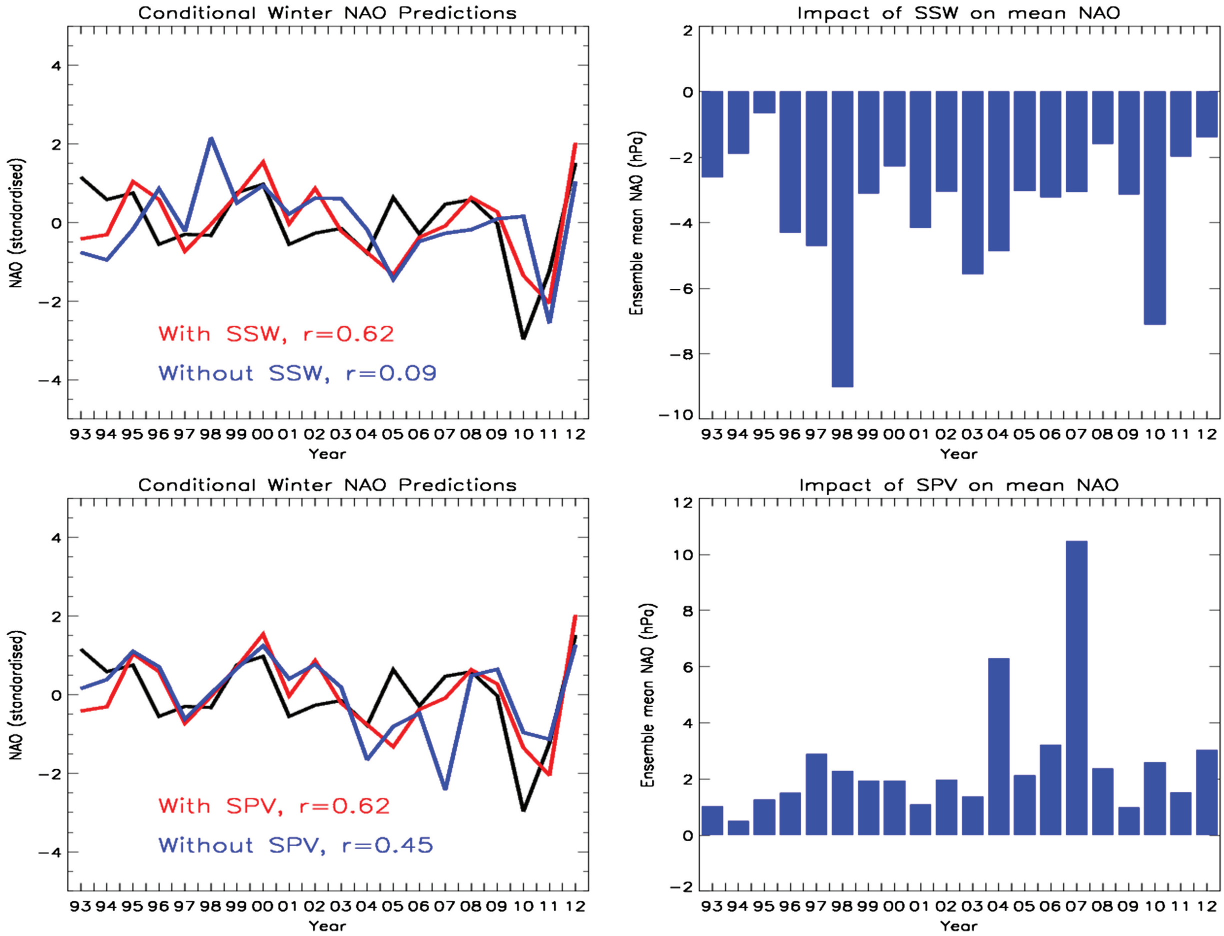

Figure 4. Relationship between SSW (upper) and SPV (lower) events and seasonal winter forecasts of the NAO. Panels on the left show standardized ensemble mean forecasts for each winter including members with stratospheric events (red) and excluding members with stratospheric events (blue). Observed NAO values are in black. Panels on the right show the difference in ensemble mean NAO predictions when SSW events are included (upper right) and when SPV events are included (lower right). Large forecast impacts are seen in 1997/1998 and 2009/2010 for SSW events and 2003/2004 and 2006/2007 for SPV events.

removing SSW events very likely leads to a genuine reduction in forecast skill.

Some winter forecasts are much more strongly influenced than others by the occurrence of stratospheric events. The influence of stratospheric SSW or SPV events on each winter NAO forecast is shown in the histograms in Figure 4. Members containing SSW events decrease the ensemble mean NAO forecast in all winters, as expected. However, forecasts for the winters of 1997/1998 and 2009/2010 are particularly strongly affected. There was a very high forecast probability of SSW events in these two winters (92 and 75% respectively) and both are El Niño winters. We can therefore explain this result by the well-known increase in stratospheric sudden warmings during El Niño (Brönnimann *et al.*, 2004; Taguchi and Hartmann, 2006; Bell *et al.*, 2009; Butler and Polvani, 2011; Domeisen *et al.*, 2015) and the need for this stratospheric response in order to generate a strong surface NAO signal in the Atlantic (Toniazzo and Scaife, 2006; Cagnazzo and Manzini, 2009; Ineson and Scaife, 2009; Butler *et al.*, 2014). It is interesting to note that the very negative NAO forecast for winter 2010/2011 was unaffected and this winter is also an outlier in the correlation plot in Figure 2. This is consistent with evidence for an Atlantic Ocean rather than stratospheric origin of the negative NAO in this particular winter (Maidens *et al.*, 2013). The occurrence of SPV events is associated with higher forecast NAO values in all winters but the effect was largest in 2003/2004 and 2006/2007 (Figure 4). We have no simple explanation for why these winters are particularly influenced but it will be interesting to see if the same winters are highlighted in future seasonal forecast systems.

5. Conclusions

Deterministic forecast skill for stratospheric sudden warmings has been demonstrated out to around 2 weeks lead time in several previous studies. Here, we use a seasonal forecast system with a good simulation of climate variability in the stratosphere to provide evidence of potential predictability of SSW and SPV occurrence well beyond this deterministic limit, with the risk of an event varying between 25 and 90% between different winters in forecasts out to 4 months ahead. Perfect predictability is however still modest and demonstration of actual skill by comparing against observed occurrence of events requires further work and more cases.

The impact of stratospheric variability on surface winter forecasts is as expected, with SSW/SPV events being associated with lower/higher ensemble mean surface NAO forecasts for winter. The occurrence or absence of a stratospheric event is associated with a shift of several hPa in the surface NAO, a substantial fraction of the interannual variability of the NAO itself. A striking result is that the previously reported skill for seasonal NAO predictions (Scaife *et al.*, 2014) is conditional on the inclusion of forecast members containing SSW events. This is consistent with the idea (though does not conclusively demonstrate) that a well-resolved stratosphere is important for winter forecast skill in the Atlantic basin. This result may also be robust across forecast systems and timescales (e.g. Sigmond *et al.*, 2013; Stockdale *et al.*, 2015).

The El Niño winters of 1997/1998 and 2009/2010 were periods of high risk of a SSW event, whereas the winters of 2003/2004 and 2006/2007 were winters with a high risk of a SPV event. Winter 2009/2010 is already known to have been highly disturbed in the stratosphere and this was important for seasonal winter forecasts of this event (Fereday *et al.*, 2012). However, the observed 1997/1998 winter did not quite reach the threshold for SSW categorization. Assuming a good simulation of the teleconnection and the background wave field (Fletcher and Kushner, 2011) so that the modeled ENSO teleconnection is realistic (e.g. Fereday *et al.*, 2012), the multiple seasonal realizations used here suggest that we were unlucky not to see a SSW in that winter. More generally, the results shown here suggest that the year to year risk of SSW and SPV events in future winters is likely to be predictable on seasonal timescales, months ahead of the actual event.

Acknowledgements

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References

Arribas A, Glover M, Maidens A, Peterson KA, Gordon M, MacLachlan C, Graham R, Fereday D, Camp J, Scaife AA, Xavier P, McLean P, Colman A, Cusack S. 2011. The GloSea4 ensemble prediction system for seasonal forecasting. *Monthly Weather Review* **139**: 1891–1910.

Athanasiadis PJ, Bellucci A, Hermanson L, Scaife AA, MacLachlan C, Arribas A, Materia S, Borrelli A, Gualdi S. 2014. The representation of atmospheric blocking and the associated low-frequency variability in two seasonal prediction systems (CMCC, Met-Office). *Journal of Climate* **27**: 9082–9100, doi: 10.1175/JCLI-D-14-00291.1.

Baldwin MP, Dunkerton TJ. 1999. Propagation of the Arctic Oscillation from the stratosphere to the troposphere. *Journal of Geophysical Research* **104**(D24): 30937–30946, doi: 10.1029/1999JD900445.

Bell CJ, Gray LJ, Charlton-Perez AJ, Joshi M, Scaife AA. 2009. Stratospheric communication of El Niño teleconnections to European Winter. *Journal of Climate* **22**: 4083–4096.

Boville BA. 1984. The influence of the polar night jet on the tropospheric circulation in a GCM. *Journal of the Atmospheric Sciences* **41**: 1132–1142.

Brönnimann S, Luterbacher J, Staehelin J, Svendby TM, Hansen G, Svenøe T. 2004. Extreme climate of the global troposphere and stratosphere in 1940–42 related to El Niño. *Nature* **431**: 971–974, doi: 10.1038/nature02982.

Butler AH, Polvani LM. 2011. El Niño, La Niña, and stratospheric sudden warmings: a re-evaluation in light of the observational record. *Geophysical Research Letters* **38**: L13807, doi: 10.1029/2011 GL048084.

Butler AH, Polvani LM, Deser C. 2014. Separating the stratospheric and tropospheric pathways of El Nino-Southern Oscillation teleconnections. *Environmental Research Letters* **9**: 024014, doi: 10.1088/1748-9326/9/2/024014.

Cagnazzo C, Manzini E. 2009. Impact of the stratosphere on the winter tropospheric teleconnections between ENSO and the North Atlantic and European region. *Journal of Climate* **22**: 1223–1238.

Domeisen DIV, Butler AH, Fröhlich K, Bittner M, Müller WA, Baehr J. 2015. Seasonal predictability over Europe arising from El Niño and stratospheric variability in the MPI-ESM seasonal prediction system. *Journal of Climate* **28**: 256–271, doi: 10.1175/JCLI-D-14-00207.1.

Fereday D, Maidens A, Arribas A, Scaife AA, Knight JR. 2012. Seasonal forecasts of Northern Hemisphere Winter 2009/10. *Environmental Research Letters* **7**: 034031, doi: 10.1088/1748-9326/7/3/034031.

Fletcher CG, Kushner PJ. 2011. The role of linear interference in the annular mode response to tropical SST forcing. *Journal of Climate* **24**: 778–794.

Folland CK, Scaife AA, Lindesay J, Stephenson DB. 2012. How potentially predictable is northern European winter climate a season ahead? *International Journal of Climatology* **32**: 801–808, doi: 10.1002/joc.2314.

Ineson S, Scaife AA. 2009. The role of the stratosphere in the European climate response to El Niño. *Nature Geoscience* **2**: 32–36.

Kang D, Lee MI, Im J, Kim D, Kim H-M, Kang H-S, Schubert SD, Arribas AA, MacLachlan C. 2014. Prediction of the Arctic Oscillation in boreal winter by dynamical seasonal forecasting systems. *Geophysical Research Letters* **10**: 3577–3585, doi: 10.1002/2014GL060011.

Kolstad EW, Breiteig T, Scaife AA. 2010. The association between stratospheric weak polar vortex events and cold air outbreaks. *The Quarterly Journal of the Royal Meteorological Society* **136**: 886–893.

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**: L19701, doi: 10.1029/2008 GL034902.

MacLachlan C, Arribas A, Peterson KA, Maidens A, Fereday D, Scaife AA, Gordon M, Vellinga M, Williams A, Comer RE, Camp J, Xavier P. 2014. Description of GloSea5: the Met Office high resolution seasonal forecast system. *The Quarterly Journal of the Royal Meteorological Society* **141**: 1072–1084, doi: 10.1002/qj.2396.

Maidens A, Arribas A, Scaife AA, MacLachlan C, Peterson KA, Knight JR. 2013. The influence of surface forcings on the North Atlantic Oscillation regime of winter 2010/11. *Monthly Weather Review* **141**: 3801–3813.

Marshall A, Scaife AA. 2010. Improved predictability of stratospheric sudden warming events in an AGCM with enhanced stratospheric resolution. *Journal of Geophysical Research* **115**: D16114, doi: 10.1029/2009JD012643.

Mitchell DM, Gray LJ, Anstey J, Baldwin MP, Charlton-Perez AJ. 2013. The influence of stratospheric vortex displacements and splits on surface climate. *Journal of Climate* **26**: 2668–2682, doi: 10.1175/JCLI-D-12-00030.1.

Mukougawa H, Sakai H, Hirooka T. 2005. High sensitivity to the initial condition for the prediction of stratospheric sudden warming. *Geophysical Research Letters* **32**: L17806, doi: 10.1029/2005GL022909.

Orsolini YJ, Kindem IT, Kvamstø NG. 2011. On the potential impact of the stratosphere upon seasonal dynamical hindcasts of the North Atlantic Oscillation: a pilot study. *Climate Dynamics* **36**: 579–588, doi: 10.1007/s00382-009-0705-6.

Pawson S, Fiorino M. 1999. A comparison of reanalyses in the tropical stratosphere. Part 3: inclusion of the pre-satellite data era. *Climate Dynamics* **15**: 241–250.

Riddle EE, Butler AH, Furtado JC, Cohen JL, Kumar A. 2013. CFSv2 ensemble prediction of the wintertime Arctic Oscillation. *Climate Dynamics* **41**: 1099–1116.

Scaife AA, Knight JR. 2008. Ensemble simulations of the cold European winter of 2005/6. *The Quarterly Journal of the Royal Meteorological Society* **134**: 1647–1659, doi: 10.1002/qj.312.

Scaife AA, Austin J, Butchart N, Pawson S, Keil M, Nash J, James IN. 2000. Seasonal and interannual variability of the stratosphere diagnosed from UKMO TOVS analyses. *The Quarterly Journal of the Royal Meteorological Society* **126**: 2585–2604.

Scaife AA, Arribas A, Blockley E, Brookshaw A, Clark RT, Dunstone N, Eade R, Fereday D, Folland CK, Gordon M, Hermanson L, Knight JR, Lea DJ, MacLachlan C, Maidens A, Martin M, Peterson AK, Smith D, Vellinga M, Wallace E, Waters J, Williams A. 2014. Skilful long range prediction of European and North American Winters. *Geophysical Research Letters* **41**: 2514–2519, doi: 10.1002/2014 GL059637.

Sigmond M, Scinocca JF, Kharin VV, Shepherd TG. 2013. Enhanced seasonal forecast skill following stratospheric sudden warmings. *Nature Geoscience* **6**: 98–102, doi: 10.1038/ngeo1698.

Smith D, Scaife AA, Kirtman B. 2012. What is the current state of scientific knowledge with regard to seasonal and decadal forecasting? *Environmental Research Letters* **7**: 015602, doi: 10.1088/1748-9326/7/1/015602.

Stan C, Straus DM. 2009. Stratospheric predictability and sudden stratospheric warming events. *Journal of Geophysical Research* **114**: D12103, doi: 10.1029/2008JD011277.

Stockdale TN, Molteni F, Ferranti L. 2015. Atmospheric initial conditions and the predictability of the Arctic Oscillation. *Geophysical Research Letters* **42**: 1173–1179, doi: 10.1002/2014GL062681.

Sun L, Robinson WA, Chen G. 2012. The predictability of stratospheric warming events: more from the troposphere or the stratosphere? *Journal of the Atmospheric Sciences* **69**: 768–783, doi: 10.1175/JAS-D-11-0144.1.

Taguchi M, Hartmann DL. 2006. Increased occurrence of stratospheric sudden warmings during El Niño simulated by WACCM. *Journal of Climate* **19**: 324–332, doi: 10.1175/JCLI3655.1.

Toniazzo T, Scaife AA. 2006. The influence of ENSO on winter North Atlantic climate. *Geophysical Research Letters* **33**: L24704, doi: 10.1029/2006GL027881.