ENVIRONMENTAL RESEARCH
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Environmental Research Letters

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RECEIVED
22 October 2018

REVISED
15 January 2019

ACCEPTED FOR PUBLICATION
31 January 2019

PUBLISHED
6 March 2019



LETTER

# Stratospheric initial conditions provide seasonal predictability of the North Atlantic and Arctic Oscillations

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**Keywords:** seasonal prediction, stratosphere, NAO/AO, GloSea5

## Abstract
The North Atlantic Oscillation (NAO), the regional manifestation of the Arctic Oscillation (AO), dominates winter climate variability in Europe and North America. Skilful seasonal forecasting of the winter NAO/AO has been demonstrated recently by dynamical prediction systems. However, the role of initial conditions in this predictability remains unknown. Using a latest generation seasonal forecasting system and reanalysis data, we show that the initial upper stratospheric zonal wind anomaly contributes to winter NAO/AO predictability through downward propagation of initial conditions. An initial polar westerly/easterly anomaly in the upper stratosphere propagates down to the troposphere in early winter, favoring a poleward/equatorward shift of the tropospheric mid-latitude jet. This tropospheric anomaly persists well into the late winter and induces the positive/negative phase of NAO/AO in the troposphere. Our results imply that good representation of stratospheric initial condition and stratosphere-troposphere coupling in models is important for winter climate prediction.

## 1. Introduction

The North Atlantic Oscillation (NAO), the regional manifestation of the Arctic Oscillation (AO), dominates atmospheric variability in the North Atlantic winter circulation, and is typically described by the Sea Level Pressure (SLP) difference between the Arctic and Atlantic subtropics (Hurrell 1995, Vallis *et al* 2004). This annular pattern exhibits an equivalent barotropic dipolar structure, extending from the surface to the stratosphere in late winter. Variations of the NAO/AO are linked to the temperature and precipitation anomalies across Europe and North America (Hurrell *et al* 2013). Given these widespread impacts on surface climate, skillful seasonal prediction of the winter NAO/AO is of great importance.

As an internal mode of the atmospheric variability, the NAO/AO variability is often considered to be primarily maintained by eddy-mean flow interactions (Robinson 2000, Lorenz and Hartmann 2003, Barnes and Hartmann 2010, Zhang *et al* 2012). However, on monthly to seasonal time scales, a portion of the wintertime NAO/AO variability can be driven by external forcing besides the internal processes (Deser *et al* 2007), thus permitting more predictability of the NAO/AO on longer time scales (Smith *et al* 2012). Several possible sources of seasonal NAO/AO predictability have been proposed, including remote influence of tropical rainfall (Scaife *et al* 2017), autumnal Sea Surface Temperature (SST) anomaly over North Atlantic (Czaja and Frankignoul 2002, Deser *et al* 2004, Magnusdottir *et al* 2004), cryospheric forcings over Arctic and Eurasia (Cohen *et al* 2014), stratospheric forcings (Kidston *et al* 2015, Scaife *et al* 2016) and solar variability (Ineson *et al* 2011).

High-level NAO/AO prediction skill of dynamical prediction systems has been noted recently by several studies (Riddle *et al* 2013, Kang *et al* 2014,

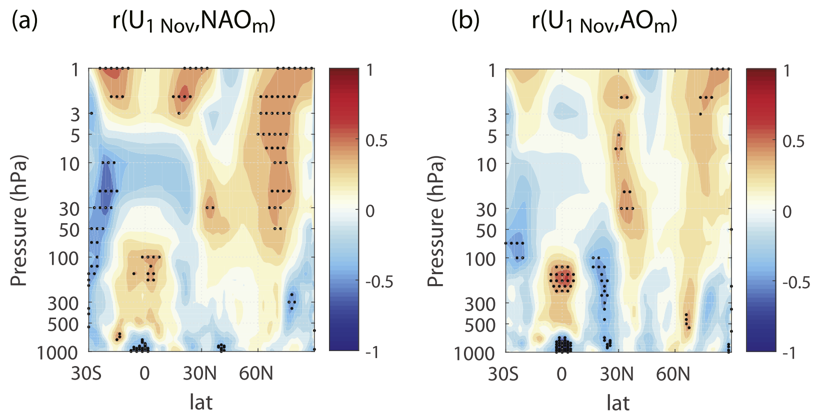


**Figure 1.** (a) Correlation between the initial zonal wind anomaly on 1 November and the predicted surface NAO index during DJF. (b) As in (a) but for the correlation between initial wind anomaly and the predicted AO index. Values significant at $\alpha = 0.05$ confidence level using one-tailed test are highlighted with black dots.

Scaife *et al* 2014, Dunstone *et al* 2016). For example, the forecast skill (as measured by the anomaly correlation coefficient, ACC) of DJF-mean NAO is 0.62 for 1993–2012 in Metoffice seasonal hindcasts (Scaife *et al* 2014) and even exceeding 0.8 for 1997–2011 in multi-model hindcasts (Athanasiadis *et al* 2016). However, not all winters are equally well predicted and although a large proportion of the extratropical forecast signals can be explained by their connections with tropical rainfall (e.g. Scaife *et al* 2017) there is other predictable variance that remains unexplained. Here, we show that the stratospheric initial conditions play a role in winter NAO/AO predictions. Moreover, we will show that the stratospheric initial conditions are an important source of skill.

## 2. Data and method

We analyze hindcasts of monthly-mean SLP, and zonal velocity from 1000 to 1 hPa from the Global Seasonal forecast System 5 (GloSea5) (MacLachlan *et al* 2014). The climate model at the core of this forecast system is the Hadley Centre Global Environmental Model version 3 (HadGEM3). It has atmospheric resolution of 0.83° longitude by 0.55° latitude (about 60 km at mid-latitudes), and 85 atmospheric levels with an upper boundary near the mesopause. The ocean resolution is 0.25° with 75 levels. The research ensemble described by MacLachlan *et al* (2014) is supplemented with recent operational hindcast to give a combined ensemble of 45 members per year for each winter during 1994–2012. The ensemble forecasts are initialized with observational estimate of the state of the climate system on three start dates centered on 1 November (25 October, 1 November, and 9 November). SLP and zonal velocity from ERA-Interim (Dee *et al* 2011) are used for validation. The robustness of the results is also checked using JRA-55 reanalysis (Kobayashi *et al* 2015).

In this study, the winter NAO index is computed as the SLP difference between Azores (38°*N*, 27°*W*) and Iceland (65°*N*, 20°*W*) averaged during DJF (December–February). The principal component-based definition is also used to guarantee the robustness of the results (Hurrell *et al* 2013). The AO index is defined by projection onto the leading empirical orthogonal function pattern of the SLP anomalies over 20°*N*–90°*N* of the observational reanalysis. To investigate the role of stratospheric initial conditions in the NAO/AO predictability, an initial wind index $U_i$ is also obtained by averaging the initial zonal wind anomaly in the upper stratosphere where the positive correlation with the predicted winter NAO/AO index is strongest. Here, the initial zonal wind anomaly is calculated as the difference between the zonal wind on the initial date from the observational reanalysis and its daily climatology. The explaining variance of predicted NAO/AO by initial wind anomaly is given by squaring the correlation coefficient between $U_i$ and NAO/AO index (a coefficient of determination). The evolution of the signals in winds is represented by the monthly-mean zonal wind anomaly which is computed as the difference between the 45-member ensemble mean zonal wind at each month and its 19-year climatological value.

## 3. Results

### 3.1. Upper stratospheric circulation: a source of winter NAO/AO predictability

To understand the role of initial atmospheric conditions in predicting the winter NAO, figure 1(a) shows the correlation between the initial zonally-averaged zonal wind anomaly on 1 November from the observational reanalysis and the 45-member ensemble mean predicted NAO index for the winter mean (DJF). A significant positive correlation is found in the polar upper stratosphere with further positive correlation at lower latitudes, implying that the initial stratospheric

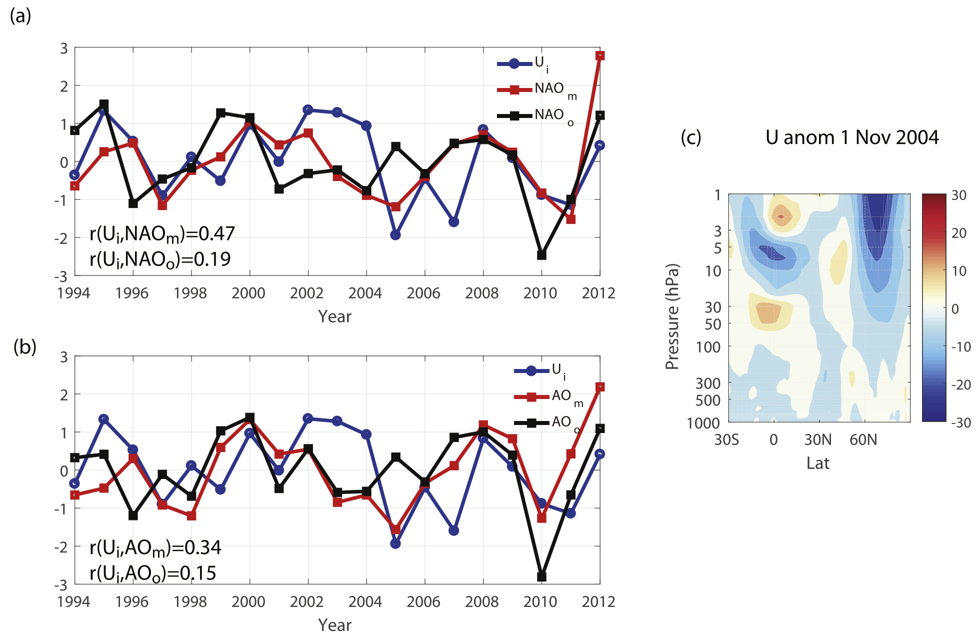


**Figure 2.** (a) Predicted ensemble mean winter standardized NAO index (red line) and $U_i$ index (blue line). The NAO index in observational reanalysis (black line) is shown for comparison. (b) As in (a) but for AO index and $U_i$ index. The labeled year corresponds to the January of each DJF season (e.g. 2005 forecast verifies in DJF 2004/2005). (c) The zonal wind anomaly on 1 November 2004 in the observational reanalysis, with positive/negative value denoting westerly/easterly anomaly.

conditions may play a role in subsequent winter NAO predictions. For comparison, the correlation between the initial wind anomaly and the ensemble mean predicted DJF AO index is displayed in figure 1(b). The correlation shows a similar spatial structure to figure 1(a), suggesting that the stratospheric initial conditions also play a role in AO predictions. Note, there is a similar but weaker pattern in observational reanalysis (not shown). This is to be expected given that the NAO/AO in observational reanalysis is in but one realization and contains unpredictable NAO/AO variability which is removed from our ensemble mean. Figure 1 suggests that the initial upper stratospheric zonal wind anomalies may exert a significant influence on the model predicted winter NAO/AO.

To represent the variation of initial stratospheric zonal wind anomalies, a stratospheric zonal wind index $U_i$ is defined by averaging the zonal-mean zonal wind anomaly on 1 November over (60°N–90°N, 1–5 hPa) where the positive correlation with the predicted winter NAO/AO index is strongest in figure 1. Figure 2(a) shows the time series of standardized $U_i$ as well as the standardized DJF NAO indices in ensemble mean forecasts and observational reanalysis. The correlation between the initial zonal wind index and the predicted NAO index is 0.47, which is significant at the $\alpha = 0.05$ level by Student's t-test. This implies that around 22% of the predicted NAO variability could come from the initial stratospheric zonal wind anomaly, and suggests that initial atmospheric conditions are important for seasonal prediction as in Stockdale *et al* (2015). The correlation between $U_i$ and the single DJF NAO in observational reanalysis is 0.19, which is well within the range of ensemble member correlations. Similar correlation analysis is also applied to the AO. As shown in figure 2(b), the correlation coefficient between $U_i$ and the predicted ensemble-mean AO index is around 0.34, implying that approximately 12% of the variance in the seasonal forecast of the AO can be explained by the stratospheric initial conditions.

It is interesting to note the 2004/2005 winter, for which the forecast NAO anomaly was previously noted for its difference from the observed NAO anomaly and that implied by predicted tropical rainfall (Scaife *et al* 2017). For this unusual winter, the initial zonal wind index $U_i$ reached its lowest value during 1994–2012. Given the relationship seen in the other years, this negative value of $U_i$ is linked to the unusually negative phase of the NAO predicted by the model ensemble mean, implying that the initial strong easterly wind anomaly gave rise to the negative phase of the NAO predicted for this winter. Figure 2(c) further shows the spatial pattern of the zonal wind anomaly on 1 November 2004. The strong easterly anomaly in the upper-stratospheric polar region suggests a weakening of the polar night jet at the start of the forecast. This anomalous signal persists in the November-mean (not shown), explaining the predicted negative phase of the NAO in 2004/2005 winter by the exceptional easterly anomaly of the upper stratospheric wind on the initial date. Although the observed 2004/2005 winter NAO is opposite to the ensemble mean predicted NAO, it is still within the range of the ensemble spread. There may not be an error in the model forecast for this winter, it is just that the ensemble mean was shifted down by the stratospheric initial

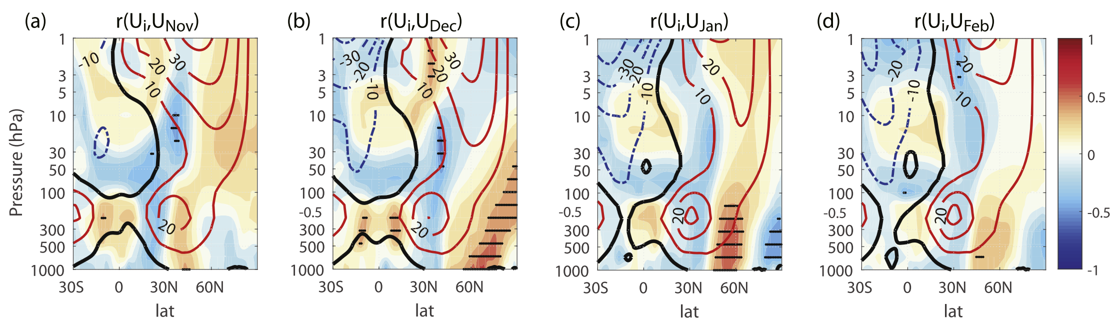

**Figure 3.** Correlation between initial wind index $U_i$ and the monthly-mean zonal wind anomaly for (a) November, (b) December, (c) January and (d) February, compared with climatological mean states (solid contours with an interval of 10 ms$^{-1}$; zero values in black thick lines). Values significant at $\alpha = 0.05$ confidence level using one-tailed test are highlighted with black dots.

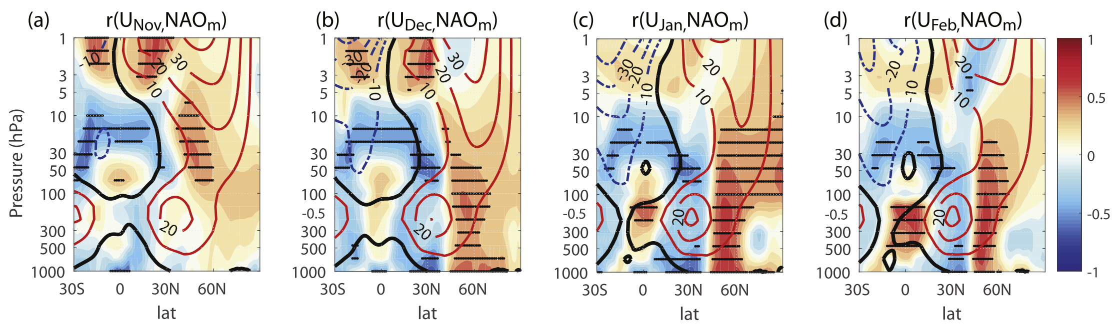

**Figure 4.** As in figure 3 but for the correlation between the predicted DJF NAO index and the monthly-mean zonal wind anomaly at (a) November, (b) December, (c) January and (d) February.

conditions whereas the observations happened to be higher, presumably due to internal unpredictable variability. It is also noteworthy to point out that the 2006/2007 winter, which is the year exhibiting second lowest value of $U_i$ during 1994–2012, shows a positive phase of NAO prediction. The predicted NAO index is opposite to the NAO suggested by the stratospheric initial condition but is consistent with the observed value. As suggested by Scaife *et al* (2017), the positive phase of NAO this year can be well explained by the tropical rainfall (their figure 12). The above case studies further suggest that the initial stratospheric zonal wind anomaly may provide an additional seasonal predictability source to the NAO besides tropical rainfall.

### 3.2. Space-time evolution of the stratospheric signal

To explore the connection between the initial zonal wind anomaly in the stratosphere and the predicted winter NAO/AO, figure 3 shows the correlation between the initial wind index $U_i$ and the model predicted zonal-mean zonal wind anomaly from November to February relative to the climatological mean states. The zonal wind climatology in all months shows a strong polar night jet in the stratosphere and two tropospheric jets: subtropical jet and extra-tropical jet. As shown in figure 3(a), the largest positive correlation between $U_i$ and November zonal wind anomaly is found in the polar lower stratosphere, suggesting a strengthening of the polar night jet in November. This stratospheric anomaly then extends down to the troposphere in December. As shown in figure 3(b), the strongest positive correlation is located around 60°$N$, suggesting a poleward shift of the tropospheric extra-tropical jet. This anomaly in the extra-tropical jet persists well into late winter as illustrated in figures 3(c)–(d), consistent with the positive phase of the predicted NAO/AO. This downward propagation of upper stratospheric zonal wind perturbation to the troposphere is consistent with similar signals in many other observation and modeling studies (Kodera *et al* 1990, Kodera 1995, Baldwin and Dunkerton 1999).

To further quantify the relative contribution of the initial stratospheric zonal wind anomaly to winter ensemble mean NAO prediction, figure 4 shows the correlation between the predicted DJF-mean NAO index and the predicted zonal-mean zonal wind anomaly from November to February compared to the climatological mean states. By doing so, the evolution of the signals in winds accompanying the DJF-mean NAO can be clearly shown and compared with the wind evolution induced by the stratospheric initial conditions. In November, as shown in figure 4(a), a strong positive correlation is found in the stratosphere, suggesting a strengthening of the polar night jet before positive NAO. In December (figure 4(b)), the correlation exhibits a dipolar structure in the

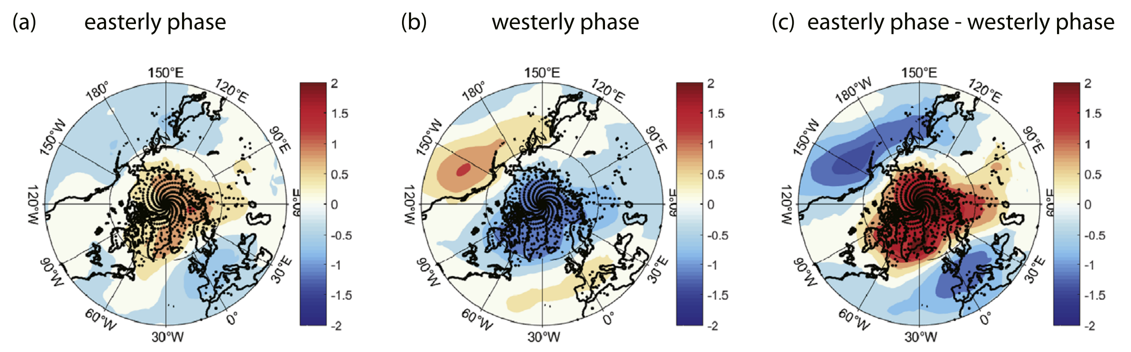


**Figure 5.** Composites of the DJF-mean SLP anomalies (hPa) with initial (a) easterly anomalies and (b) westerly anomalies. (c) Composites of the DJF-mean SLP difference (hPa) between initial easterly and westerly wind anomaly cases. Values significant at $\alpha = 0.05$ confidence level are highlighted with black dots.

troposphere, with positive correlation at high latitude and negative correlation at low latitude, thus indicating a poleward displacement of the midlatitude jet with positive phase of the NAO. This dipolar pattern of correlation persists into January and February and becomes stronger, as shown in figures 4(c)–(d). Comparison between figures 3 and 4 illustrates that the spatial and time evolution of the zonal wind anomaly induced by the initial upper stratospheric conditions is similar to the zonal wind evolution accompanying the predicted NAO. This further demonstrates that the downward propagation of initial stratospheric wind perturbations plays a role in the prediction of the winter NAO and demonstrates that the influence on the NAO is likely mediated by the zonal wind anomalies (figure 4). The conclusions for the NAO also hold for the AO (results not shown).

### 3.3. Impact on surface climate

The impact of the initial upper stratospheric zonal wind anomaly on the surface climate is examined through composite analysis. Figures 5(a) and (b) present the composite DJF-mean SLP anomalies with initial easterly and westerly anomalies in the stratosphere. By definition, the easterly (westerly) phase of $U_i$ refers to years when $U_i$ is below (above) $-0.5$ ($+0.5$) standard deviations. As shown in figure 5(a), for the initial easterly case, the winter SLP increases in the Arctic region and decreases at mid-latitudes in both the Atlantic and Pacific basins corresponding to a negative NAO and AO. For the initial westerly case, as shown in figure 5(b), the composite DJF SLP anomalies display opposite spatial pattern which represents positive phase of NAO/AO. The composite of SLP difference between initial easterly phase and westerly phase displays a stronger negative phase of NAO/AO as shown in figure 5(c). The above results illustrate that the initial upper-stratospheric easterly/westerly anomaly induces a negative/positive phase of the NAO and AO. Very similar patterns are seen in observed surface climate response to stratospheric variability (Gerber *et al* 2012, Kidston *et al* 2015).

## 4. Conclusions and discussion

Using a dynamical seasonal forecast system and reanalysis data, the role of the initial stratospheric conditions on the predictability of winter NAO/AO is investigated. We find that:

- The upper stratospheric zonal wind anomaly on the initial date plays a role in the winter prediction of the NAO/AO. Around 22% of the 19-year period winter NAO variability can be explained by the initial upper stratospheric zonal wind anomaly in November.
- An initial westerly anomaly in the stratospheric pole in November propagates downward to the troposphere in December, inducing a poleward shift of the tropospheric mid-latitude jet. Then the anomalous poleward jet shift persists well into January and February, which finally results in the positive phase of NAO/AO. The reverse happens for easterly initial anomalies.
- The resulting surface response resembles the NAO and AO in SLP and has an amplitude of 1–2 hPa.

As a source of predictability, tropical rainfall may make the leading contribution to the winter NAO/AO predictability (Scaife *et al* 2017). However, stratospheric initial condition can explain a significant additional part of the predicted variability. This study further proposes that the initial stratospheric zonal wind anomaly plays a role that can even dominate in some years (e.g. winter 2004/2005). An upper stratospheric easterly anomaly in November leads to a negative anomaly in the predicted winter NAO/AO in the model and vice versa. A role for initial atmospheric conditions in NAO/AO predictions was also found by Stockdale *et al* (2015) using an 8-year period but the source was not identified and we suggest it may be located in the stratosphere. The important role played by the stratospheric initial conditions in our model in the winter NAO/AO predictability is also consistent with a very recent modeling study by

O'Reilly *et al* (2018), in which the influence of the initial conditions in the tropical stratosphere is emphasized. The influence of stratospheric conditions in November on the subsequent winter NAO/AO is evident in observations as well during some particular years (e.g. extreme 2009/2010 winter) as suggested by Wang and Chen (2010) and Fereday *et al* (2012). The mechanism for initial stratospheric conditions affecting the tropospheric NAO/AO appears to be very similar to downward propagating signals in other contexts such as sudden stratospheric warming (Baldwin and Dunkerton 2001, Kuroda 2008, Marshall and Scaife 2010) and quasi-biennial oscillation (Marshall and Scaife 2009, Taguchi 2018). As these events appear to be important for seasonal prediction of the NAO/AO (Mukougawa *et al* 2009, Sigmond *et al* 2013, Scaife *et al* 2016), it may also be fruitful to further examine these events in hindcasts. Finally, since the stratospheric initial conditions are important for the winter NAO/AO prediction, improving initial conditions and the representation of stratosphere–troposphere coupling in climate models may further enhance winter prediction skill.

## Acknowledgments

We thank the two anonymous reviewers for their constructive suggestions, which help improve the quality of the manuscript. This work is supported by the National Key Research and Development Program on monitoring, Early Warning and Prevention of Major Natural Disaster (2017YFC1502302), NSF of China under grant 41705043, and the UK-China Research & Innovation Partnership Fund through the Met Office Climate Science for Service Partnership (CSSP) China as part of the Newton Fund. This work was done while the lead author was visiting Adam A Scaife at the Met Office Hadley Center.

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