Seasonal to decadal prediction of the winter NAO and AO.

Doug M. Smith[1] and Adam A. Scaife[1]

[1] Met Office Hadley Centre, FitzRoy Road, Exeter, EX1 3PB, UK
doug.smith@metoffice.gov.uk

Introduction

Systematic climate change from anthropogenic forcing is generally too small to account for much of the variability in regional climate on timescales out to a decade ahead. Instead, variability on these timescales is mainly due to changes in atmospheric circulation. Whereas ENSO explains the largest proportion of tropical variability, the Arctic Oscillation (Thompson and Wallace 1999) or its regional equivalent, the North Atlantic Oscillation (Walker and Bliss 1932), is the single pattern that is responsible for the largest proportion of extratropical variability in surface climate. Examples of positive and negative NAO winters are shown in Figure 1. The winter of 2009/10 is chosen as a recent negative case. This winter had the lowest recorded value of the winter NAO in over a century of sea level pressure records (Fereday et al 2011). The anomaly in the NAO in winter 2009/10 exceeded 20hPa (Fig.1a) and was so large that the winter mean meridional gradient of sea level pressure was of opposite sign to the usual climatological gradient, increasing with latitude corresponding to winter mean easterly flow across the Atlantic. This flow in turn resulted in anomalous heat transport around the Atlantic basin. Cold advection into northern Europe and southeastern parts of North America resulted in lower than average temperatures, while corresponding warm advection into eastern Canada and southern Europe raised temperatures well above the climatological winter mean (Fig. 1b). Winter of 1999/2000 is prominent example of the positive phase of the NAO. In this case, a stronger meridional gradient of sea level pressure and northward shifted, stronger westerly jet across the Atlantic delivers warm moist air to northern Europe and the eastern United States and a roughly opposite quadrupole pattern of surface temperature anomalies.

Fluctuations in the NAO and AO also govern changes in the frequency of extreme daily events over large and heavily populated regions of the northern hemisphere (Thompson et al 2002, Scaife et al 2008, Hegerl et al 2009?). Many different types of extremes are related by the NAO and associated changes in the extratropical jet stream. For example, in Northern Europe positive AO/NAO conditions greatly reduce the incidence of extreme low temperatures but increase the risk of heavy rainfall and severe storms. Indeed, the positive NAO winter shown in Figure 1 contained the devastating European storm Lothar, closely followed by a second named storm Martin (ref), and causing intense damage due to high winds across France, Germany, Switzerland and Italy in December 1999.

A good null hypothesis for NAO variability is that it is the residual of internal atmospheric weather noise due to the chaotic nature of the atmosphere.

However, given that the NAO is key for understanding many near term climate fluctuations and identifying periods of increased risk of imminent extreme weather events, understanding other possible causes of NAO variability, beyond this null hypothesis is of high priority. As we show below, some drivers of variability in the NAO have already been identified and are related to slowly varying elements of the climate system, offering the prospect of predictability of at least some of the variability in the NAO.

Potential sources of skill

Many previous studies have identified surface climate signatures associated with internal phenomena or external boundary conditions that appear to project onto the NAO or AO. To avoid observation bias, we first discuss only those drivers of the NAO/AO in this summary that have stood the test of time in terms of updated historical observational analyses and also show at least some reproduction in numerical models based on first principles.

Numerous studies have investigated the possible role of Atlantic SST changes in driving changes in the jet stream and associated NAO like patterns. Early studies (Namias, Ratcliffe and Murray) pointed to the region off Newfoundland and some subsequent experiments produced systematic effects (Peng et al 2005). The study by Rodwell and colleagues (Fig.1a,b) was particularly successful in this respect and identified a response in the NAO associated with N Atlantic SST gradients. Although there are issues around specified SST experiments (Bretherton and Battisti 2000) given the large influence of atmospheric circulation on the ocean (Hasselmann 1977) and it is difficult to interpret what such experiments imply for actual predictability. Nevertheless, experiments using coupled models with large SST differences in the N Atlantic (Scaife et al 2011) show a similar influence of the ocean on the atmosphere to that inferred by Rodwell et al.

While ENSO is a cornerstone of tropical seasonal forecasting and its connection to the Pacific North American pattern is well established, links between ENSO and the NAO/AO have only recently been confirmed. Observational studies suggest a systematic tendency for negative NAO/AO during El Niño conditions in boreal winter and the opposite during La Niña (e.g. Moron and Gouirand 2003, Toniazzo and Scaife 2006, Bronniman 2007). Figure 1c shows a similar composite result from sea level pressure reanalyses with a negative AO signal during El Niño. Recent modelling studies confirm this link (Manzini et al 2006, Bell et al 2009, Ineson and Scaife 2009, Cagnazzo and Manzini 2009, Fletcher and Kushnir 2011) and suggest that interference of the extratropical PNA pattern with climatological stationary waves is key to providing enhanced wave driving of the stratosphere and subsequent negative NAO/AO like patterns at the surface in late winter.

A slightly more controversial area is the role of Solar variability in surface NAO/AO variations. Many statistical studies link cold Northern European winters to low solar activity and mild winters to high solar activity (e.g. Lockwood et al 2010, c.f. Fig.1d) but the signals vary over the historical record. Lagged responses are more consistent (Gray et al 2013) and appear to be due to ocean-atmosphere interaction (Scaife et al 2013) which feeds back onto the initial atmospheric response. The fact that these responses are now being reproduced in climate model experiments adds weight to the observational evidence for negative NAO during low solar activity periods (Matthes et al 2006, Ineson et al 2011).

A second externally forced influence on the NAO and AO on seasonal to decadal timescales comes from explosive volcanic eruptions. There is evidence in the observational record that for 2 or so winters following eruptions which inject significant sulphate aerosol into the lower stratosphere, then there is a positive AO signature in extratropical surface climate (Fig.1e). Unfortunately only weak but similar signatures are reproduced in climate models (Stenchikov et al 2004, Marshall et al 2009), although recent experiments may indicate more success (Driscoll, personal communication).

So far, our sources of AO and NAO variability have included factors connected to the oceans and external climate forcing. It is generally the case that processes purely internal to the atmosphere have too short a timescale to contribute significantly to seasonal to decadal prediction. However, there is one notable example in the Quasi-Biennial Oscillation (QBO) which has a long standing teleconnection to the winter surface climate which again resembles the NAO (Ebdon 1975, Anstey and Shepherd 2011) and has been reproduced in some climate model experiments (Marshall and Scaife 2009, Niwano and Takahashi 1998).

Other decadal timescale drivers show possible evidence of influencing the NAO and AO but there is not yet strong evidence that these are reproducible in climate models. Atlantic multidecadal variability shows a promising potential link to the NAO (Fig.1g) and there is some evidence of similar signals in models (e.g. Knight et al 2006), although again care is needed in the interpretation of these signals given the large atmospheric forcing influence on the ocean. The Pacific Decadal Oscillation, itself a broad, low frequency pattern of variability similar to the ENSO shows a possible link to the NAO (Fig.1e) but this is less well established than than other signals and it does not agree with the shorter timescale variability from ENSO, perhaps casting doubt on this as a strong driver of the AO/NAO.

Model forecasts

Despite occasional signs of long-range predictability of the Arctic Oscillation in the free atmosphere (Müller et al 2005), skilful predictions of year to year fluctuations in the winter surface NAO and associated surface climate at lead times of months have been elusive (Johansson 2007, Kim et al 2012, Arribas et al 2011).

The latest Met Office seasonal forecasting system, GloSea5 (MacLachlan et al 2013), has been specifically designed to capture the potential sources of predictability of the NAO described above. Key features include:

- A well resolved stratosphere, with a total of 85 vertical levels in the atmosphere and a lid at 80km. This is important for capturing the downwards propagation of stratospheric wind perturbations into the troposphere (Baldwin and Dunkerton, 2001), as occurs for example in teleconnections between El Niño and the NAO (Ineson and Scaife 2008) and the NAO response to changes in solar radiation (Ineson et al 2011).
- A high horizontal resolution of 0.833^o x 0.556^o in the atmosphere and 0.25^o in the ocean. The high ocean resolution in particular reduces the cold bias in North Atlantic sea surface temperatures (SST) which is typically found in coarser models which are unable to simulate the northwards deflection of the Gulf Stream. Reducing this SST bias improves the simulation of Atlantic blocking frequency (Scaife et al 2011).
- Initialisation of sea ice (Peterson et al 2013). This is necessary to capture potential influences on the NAO from anomalous Arctic sea ice conditions, as suggested in several recent studies (e.g. Petoukhov and Semenov 2010, Overland and Wang 2010, Liu et al 2012, Francis and Vavrus 2012, Tang et al 2013).

GloSea5 retrospective forecasts (hindcasts) covering the period 1993 to 2012 (20 years) show correlations greater than 0.6 between the observed surface NAO index and model predictions starting around the beginning of November each year (Scaife et al 2013b). Many of the sources of predictability discussed above also appear to be operating in GloSea5, including ENSO, Arctic sea ice (especially in the Kara Sea), Atlantic SSTs and the QBO. However, the magnitude of the response in GloSea5 associated with some of these factors appears to be too weak, and the correlation skill for the ensemble mean is higher than would be expected given the signal to noise ratio present in individual ensemble members (Kumar 2009). This issue will be discussed further below. Nevertheless, GloSea5 does simulate on average the pressure pattern associated with high and low NAO indices (Figure 3), and this leads to significant skill for important surface climate impacts including extremes of temperature, wind speed and storminess over land regions in Europe and North America (Scaife et al 2013b).

Some of the drivers of the NAO, especially Atlantic SSTs and changes in Arctic sea ice, are potentially predictable on decadal timescales. Indeed, CMIP5 decadal predictions do show skill in predicting North Atlantic SSTs, with improvement through initialisation with observations (Doblas-Reyes et al 2013). This is consistent with idealised model studies showing potential predictability of the Atlantic Meridional Overturning Circulation (AMOC, e.g. Griffies and Bryan 1997, Pohlmann et al 2004, Collins et al 2006, Dunstone and Smith 2010) which is expected to influence North Atlantic SST (Delworth et al. 2007, Knight et al. 2005). Assessing the skill for real world predictions of the AMOC is hampered by a lack of observations for verification. However, Pohlmann et al (2013) found predictability of the AMOC a few years ahead when assessed against a multi-model synthesis of ocean observations, potentially providing a physical basis for improved North Atlantic SST predictions. Furthermore, case studies show that the rapid warming of the

North Atlantic sub-polar gyre in the mid-1990s (Robson et al 2012, Yeager et al 2012) and the cooling in the 1960s (Robson et al 2013) could have been predicted in advance, with initialisation of anomalous AMOC playing an important role in both cases.

Despite this encouraging evidence for decadal predictability of North Atlantic SST, skilful predictions of the NAO beyond the seasonal range have not yet been achieved.

Future issues

The NAO correlation skill achieved by GloSea5 is sensitive to ensemble size (Scaife et al 2013b). For small ensemble size the correlation is around 0.2 to 0.3, but increases to above 0.6 for 24 members, and asymptotes to greater than 0.8. This is inconsistent with the signal to noise ratio (measured by the variance of the ensemble mean divided by the variance of individual ensemble members, Kumar 2009) as shown in Figure 4. This means that the predictable signal is greater in reality than in individual model members, showing that the model NAO is too weakly constrained by the relevant driving factors. In particular, there is mounting evidence that models respond too weakly to North Atlantic SSTs. This is shown by direct analysis of model simulations (Rodwell and Folland 2002, Gastineau et al 2013) and inferred from a simple theoretical explanation of the lagged response to changes in solar radiation (Scaife et al 2013a). Evidence suggests that atmospheric response to North Atlantic SSTs is stronger in higher resolution models that resolve SST fronts in the Gulf Stream region (Minobe et al 2008). Future high resolution models may therefore yield improved levels of skill, or similar skill with fewer ensemble members.

Given the potential influence of North Atlantic SST on the NAO, predicting changes in the NAO over the coming decade likely requires predicting North Atlantic SSTs. Decadal variations in North Atlantic SST may occur through natural cycles of the Atlantic Multidecadal Oscillation (AMO) associated with changes in the strength of the AMOC (Ting et al 2009). However, there is evidence that recent variations in the AMO may have been forced by changes in anthropogenic aerosol emissions driven by socio-economic factors (Booth et al 2012, Dunstone et al 2013), although the magnitude of aerosol influences is debated (Zhang et al 2013). Understanding the interplay between natural variability and external factors is therefore needed to gain confidence in predictions of future changes in North Atlantic SST and associated influences on the NAO.

Conclusions

Current seasonal predictions have low skill for predicting the winter surface NAO (Johansson 2007, Kim et al 2012, Arribas et al 2011) and previous studies have concluded that there is little predictability (e.g. Jung et al 2011). However, observations and modelling studies suggest potential sources of skill, including ENSO, North Atlantic SST, Arctic sea ice, the QBO and solar variability. The latest Met Office seasonal forecasting system, GloSea5 (MacLachlan et al 2013), has been designed to capitalise on these potential sources of predictability, and yields high skill in retrospective forecasts of the surface NAO and associated weather including damaging winter storms, near surface wind-speeds which are important renewable energy, and extreme temperatures which impact energy prices and transport networks (Scaife et al 2013b). Some of the drivers of the NAO would also be expected to operate on multi-year timescales. Skilful decadal predictions of the NAO have not yet been achieved but might be possible with improved models that better capture these potential sources of skill.

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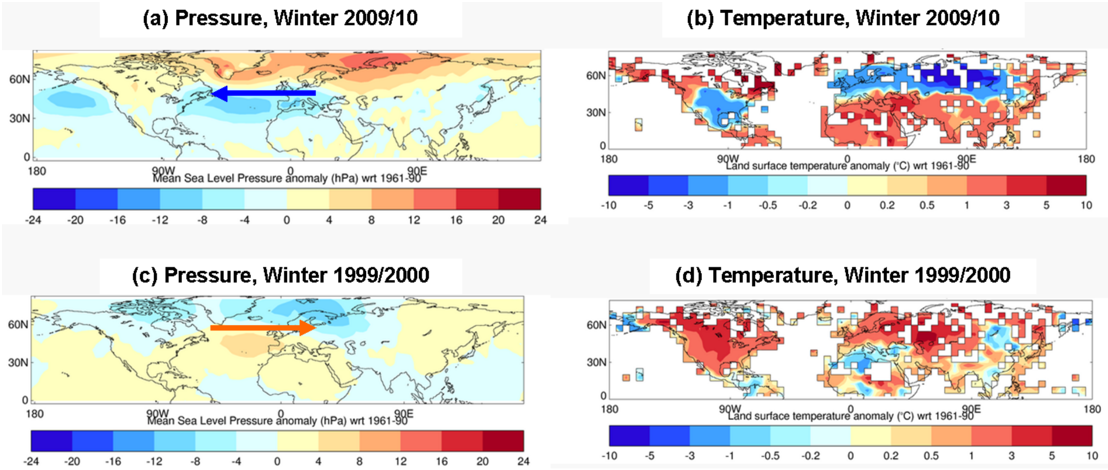

Figure 1: Influence of the NAO on European and North American winters. Shown are maps of sea level pressure (left panels, a,c) and temperature (right panels, b,d) anomalies for the winters 2009/10 (negative NAO, upper panels, a,b) and 1999/2000 (positive NAO, lower panels, c,d). Arrows on (a) and (c) show the anomalous wind direction.

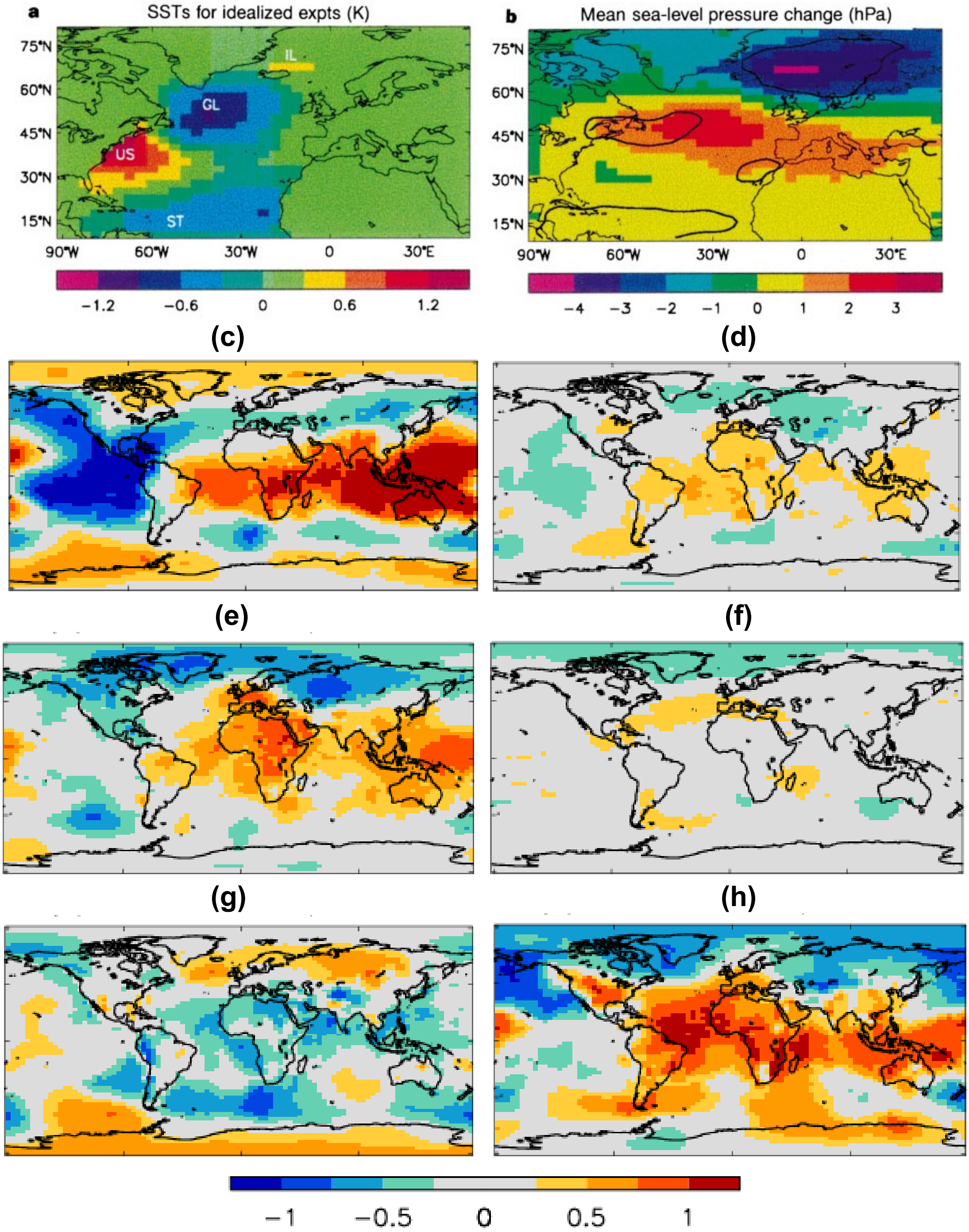

Figure 2: potential drivers of the NAO. (a) Atlantic tri-pole SST pattern and (b) mean sea level pressure response. Source: Rodwell et al 1999. (c)-(h) Observed composites of DJF mean sea level pressure associated with (c) ENSO (d) the 11 year solar cycle (e) major volcanic eruptions (f) the Quasi-Biennial Oscillation (QBO) (g) Atlantic multi-decadal variability (AMV) and (h) Pacific decadal variability (PDV). Units are standard deviations of annual (c-f) and decadal (g-h) timescales. Source: Smith et al 2012.

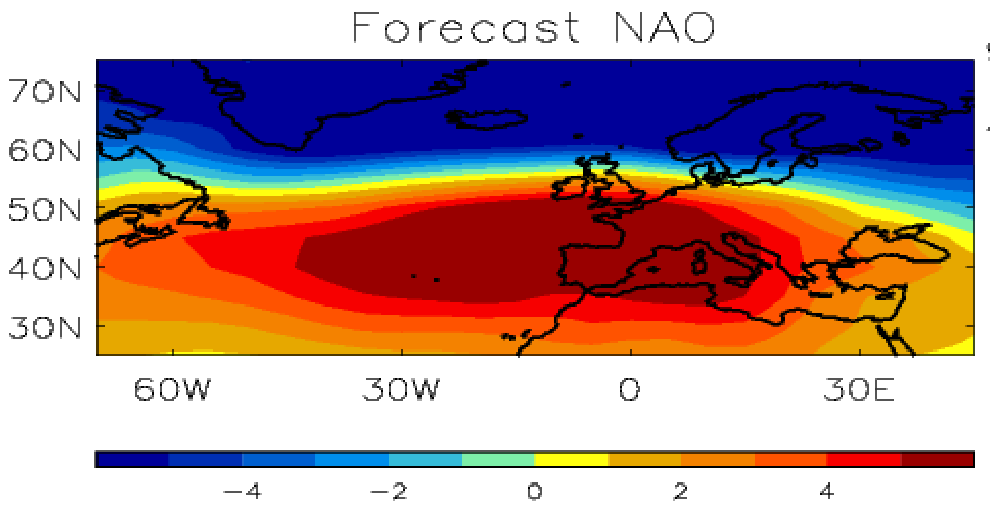

Figure 3: Pattern of forecast NAO variability. Modelled composite pattern of sea level pressure differences between positive and negative NAO winters.

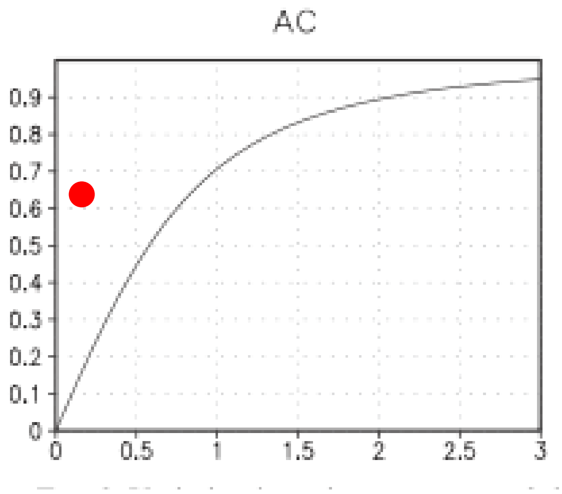

Figure 4: Skill versus signal to noise. Theoretical relationship between correlation and signal to noise ratio (solid curve, Kumar 2009) and value from 24 GloSea5 ensemble members (Scaife et al 2013b).