The Influence of Surface Forcings on Prediction of the North Atlantic Oscillation Regime of Winter 2010/11

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ABSTRACT

December 2010 was unusual both in the strength of the negative North Atlantic Oscillation (NAO) intense atmospheric blocking and the associated record-breaking low temperatures over much of northern Europe. The negative North Atlantic Oscillation for November–January was predicted in October by 8 out of 11 World Meteorological Organization Global Producing Centres (WMO GPCs) of long-range forecasts. This paper examines whether the unusual strength of the NAO and temperature anomaly signals in early winter 2010 are attributable to slowly varying boundary conditions [El Niño–Southern Oscillation state, North Atlantic sea surface temperature (SST) tripole, Arctic sea ice extent, autumn Eurasian snow cover], and whether these were modeled in the Met Office Global Seasonal Forecasting System version 4 (GloSea4). Results from the real-time forecasts showed that a very robust signal was evident in both the surface pressure fields and temperature fields by the beginning of November. The historical reforecast set (hindcasts), used to calibrate and bias correct the real-time forecast, showed that the seasonal forecast model reproduces at least some of the observed physical mechanisms that drive the NAO. A series of ensembles of atmosphere-only experiments was constructed, using forecast SSTs and ice concentrations from November 2010. Each potential mechanism in turn was systematically isolated and removed, leading to the conclusion that the main mechanism responsible for the successful forecast of December 2010 was anomalous ocean heat content and associated SST anomalies in the North Atlantic.

1. Introduction

Winter 2010/11 saw extremely cold temperatures in late November and December over northern and central Europe (see box in Fig. 1b). Cold conditions in Europe started on 22 November 2010. The United Kingdom recorded the coldest December mean temperature since the start of its average temperature record in 1910 (Prior and Kendon 2011a), while the central England temperature record (Manley 1974) showed the second coldest value in the series since 1659 (Prior and Kendon 2011b). December 2010 was the coldest December for over 40 yr in Germany and France, with monthly mean temperatures between 3° and 5°C below normal, while Norway had its fourth coldest December on record. Societal impacts were large: for instance, airports were closed due to snow in France, Belgium, Switzerland, Germany, and the Netherlands (Blunden et al. 2011). Surrounding the North Atlantic basin, the quadrupole pattern typical of a negative phase of the North Atlantic Oscillation (NAO) was observed (Figs. 1a and 1b). Colder-than-average conditions were seen over northern Europe and the East Coast of the United States, together with warmer-than-average conditions over Canada and the Mediterranean. The NAO index in December 2010 was the second lowest value since 1825 (Osborn 2011; Taws et al. 2011), for an NAO index based on the difference in pressure at mean sea level (PMSL) between Gibraltar and southwest Iceland (Jones et al. 1997).

In addition to the strong negative NAO, December 2010 also had a positive value for the east Atlantic index (EAI), defined as the pressure anomaly west of Iceland on the climatological nodal line between the centers of action for the NAO (Moore and Renfrew 2011). The EAI represents the second most important mode of variability in North Atlantic surface pressure patterns, and tracks northward–southward shifts in the centers of action of the NAO dipole (Azores high and Icelandic
FIG. 1. December surface pressure and temperature anomalies. Observed (a) pressure anomalies (HadSLP2r) and (b) temperature anomalies (HadCRUT3). The region outlined in (b) corresponds to northern Europe as referred to in the text. Contour intervals for HadSLP2r are 2 hPa, with a maximum positive anomaly south of Greenland of 18 hPa and a minimum negative anomaly west of Gibraltar of −12 hPa. Forecast anomalies for forecasts initialized on (c),(d) 23 Aug, 30 Aug, and 6 Sep 2010; (e),(f) 20 Sep, 27 Sep, and 4 Oct 2010; and (g),(h) 18 Oct, 25 Oct, and 1 Nov 2010. See section 2 for the details of the lagged ensemble approach. Blank regions in (b) are due to missing data: HadCRUT3 does not interpolate. Observed anomalies are relative to the period 1981–2010. Forecast anomalies are relative to the operational hindcast periods used [1989–2002 prior to the operational upgrade in (c)–(f) and during 1996–2009 in (g),(h)].
The combination of positive values of the EAI (southward shifts) and a negative NAO state are associated with a southward extension of the cold anomalies typical of a negative phase of the NAO. This situation was seen in December 2010.

The Met Office Global Seasonal Forecasting System version 4 (GloSea4) showed a negative NAO signal in December in forecasts from September. The strength of the signal for December increased over the following 2 months (Figs. 1c, 1e, and 1g). The small strength of the circulation anomaly in September forecasts was not big enough to drive a significant cold anomaly in the ensemble mean. However, a cold anomaly was forecast in October and by early November GloSea4 was forecasting cold anomalies over most of northern Europe (Figs. 1d, 1f, and 1h). In addition to the Met Office’s forecast, a majority of forecasts produced in October by the World Meteorological Organization’s (WMO) Global Producing Centres (GPCs: http://wmolc.org) showed a negative NAO for November–January (NDJ).

The observed signal (Figs. 1a and 1b) is approximately 4 times larger than the forecast ensemble mean signal (Figs. 1c–h). However, the overall patterns are in good agreement. Individual ensemble members (41) initialized in late October and early November show a range of forecast values for PMSL and temperature anomalies in December. A number of members show a negative NAO pattern [in some cases, shifted southward, in keeping with the negative NAO–positive EAI pattern identified by Moore and Renfrew (2011)], some with magnitudes comparable to those of the observed signal (20-hPa anomalies over Greenland and −15-hPa anomalies over the subtropical Atlantic). Using the Jones et al. (1997) index, the hindcast set shows a standard deviation of 10 hPa for the difference between Gibraltar and southwest Iceland, comparable to the observed standard deviation of 8hPa. Figure 2 shows histograms of the forecast and hindcast values of the NAO index, with the forecast histogram clearly shifted toward more negative values relative to the hindcast distribution. For the 41 forecast members, 11 have negative values of this index in excess of one standard deviation from the mean, and 3 of those have values more than two standard deviations from the mean. Only one member has a positive value greater than one standard deviation from the mean.

There are several possible explanations for the difference in magnitude between the forecast ensemble mean and the observed signal: for example, either the forced response is a small component of the observed anomaly, with much of the observed signal being chaotically driven, or the model may underestimate the predictable response of the atmosphere. Our aim here is to investigate the source of the ensemble mean forecast signal.

It is clear that 2010 was a highly unusual situation in two respects: the strength and consistency of a negative NAO signal in forecasts from different lead times and the unusual strength of the observed negative NAO and associated cold anomalies. Although average skill for 1.5-m temperature over Europe assessed over a multiyear period of hindcasts is low (only marginally better than climatology), extreme events, where stronger driving factors are present, may present higher levels of predictability [for instance, the forecast of the exceptionally strong negative NAO of 2009/10 and the associated cold winter, as discussed in Fereday et al. (2012)]. We therefore assess the candidate forcing mechanisms identified in statistical analyses of the observational record and ask whether any of these mechanisms are in evidence in the 2010/11 winter and in our seasonal forecast system.

Various physical drivers of seasonal predictability have been identified. In this study, we examine the following: the tripole pattern of sea surface temperature (SST)/ocean heat content anomalies in the North Atlantic in autumn (Rodwell and Folland 2002; Taws et al. 2011); the tropical Pacific and El Niño–Southern Oscillation (ENSO) state (Bell et al. 2009); Arctic ice extent (Strey et al. 2010); and Eurasian snow extent in autumn (Cohen and Entekhabi 1999). Generally speaking, these slowly varying physical drivers act by introducing heat sources that drive wave activity; Rossby wave breaking higher in the atmosphere then drives the NAO state and surface temperature response (Woollings et al. 2008;
Frankze et al. 2004). Atmospheric preconditioning
(Perlitz and Graf 1995; Baldwin and Dunkerton 2001)
has also been suggested as a mechanism, but is not con-
sidered here because the long lead time for the forecast of
negative NAO (Fig. 1) suggests that boundary conditions
that influence the system over longer time scales are more
likely to be the primary driver.

The impact of ocean heat content on atmospheric
circulation is well documented. For instance, the role of
the position of the ocean frontal zone on the midlatitude
jet has been examined by Nakamura et al. (2004). More
specifically, anomalous patterns of ocean heat content in
the North Atlantic have been identified as one of the
causes of the observed negative NAO during late 2010.
The previous winter of 2009/10 had the most negative
NAO value since 1825 (Taws et al. 2011; Osborn 2011)
and record-breaking low temperature anomalies (Wang
et al. 2010). The cold near-surface temperatures and
easterly Atlantic wind anomalies associated with the
negative NAO drove the formation of negative mixed
layer thermal anomalies in the ocean off the East Coast
of the United States, and warm anomalies over eastern
Canada led to the formation of positive thermal anom-
aliies farther north in the Atlantic. This negative North
Atlantic tripole in SST is a typical response to negative
NAO conditions and was well established by spring. In
summer, the subsurface ocean heat content anomalies
are masked by the formation of a shallow mixed layer,
but the anomalies persist below the surface and re-
emerge in the autumn, driving a tendency toward a sec-
ond year of negative NAO conditions (Alexander and
Deser 1995; Rodwell and Folland 2002). Taws et al.
(2011) suggested that this mechanism was one of the
drivers for the repeated negative NAO in 2010, and the
reemergence of the tripole pattern in ocean heat content
was seen in GloSea4.

Although remote, ENSO also has an effect on the
European winter climate, and late 2009 was a strong La
Niña event (−1.5°C for the Niño-3.4 region). While the
late winter (January–March, JFM) response to El Niño
tends to be a negative phase of the NAO with enhanced
probability of sudden stratospheric warmings (Toniaszzo
and Scaife 2006; Brönnimann 2007) and is well docu-
mented, there is also a slight tendency for El Niño events
to be associated with positive NAO in early winter
[November–December; Huang et al. (1998)]. Similarly,
there is also a tendency for La Niña events to be asso-
ciated with blocking events in early winter (Moron and
Plaut 2003; Moron and Gouirand 2003).

Arctic ice extent may also have an impact on circula-
tion patterns in the extratropical Northern Hemisphere.
Deser et al. (2004) showed that winter ice loss leads to
pressure patterns similar to a negative NAO. Francis
et al. (2009) examined the link between lower-than-
normal summer ice extent and weather patterns in the
following autumn and winter. They were able to provide
supporting evidence for the mechanism proposed by
Deser et al. (2007), whereby increased heat and mois-
ture fluxes lead to a deeper boundary layer depth. This
increases the vertical thicknesses in the lower atmos-
phere, reducing the poleward temperature gradient be-
tween mid- and high latitudes, thus weakening the storm
track. Changes in temperature gradient can be seen out
to 6 months from the September ice minimum. Strey et al.
(2010) showed that low ice extent leads to a ridge–trough
ridge pattern starting in North America and extending
eastward. GloSea4 is one of two seasonal forecast systems
among the GPC models to use initialized rather than cli-
matological ice (together with the Canadian Seasonal to
Interannual Prediction System), so we are able to use it to
investigate the role of ice in the Met Office forecast.
However, since other models (without initialized ice) also
forecast a negative NAO, ice is unlikely to be the only, or
even the major, driver behind the forecasts of extreme
December conditions. For instance, Balmaseda et al.
(2010) argue that the primary driver is SST anomalies,
with ice extent contributing a second order effect.

Another mechanism identified in observation-based
studies is the role of Eurasian snow cover. Anomalously
high Eurasian snow cover in autumn is correlated with
a negative NAO in winter (Cohen and Entekhabi 1999;
(2007) propose a mechanism for this link: anomalously
high snow in September–November (SON) affects the
surface albedo and appears to shift the Siberian high
westward, resulting in Rossby wave trains that then
break below the polar jet, resulting in a negative NAO in
winter. This mechanism seems to be supported by model
studies (Allen and Zender 2010). However, it has been
suggested that the observational evidence for this link
is dependent on the precise time period chosen for the
analysis and that the proposed link is not statistically
robust prior to the 1980s (Peings et al. 2013).

The primary physical process whereby remote events
such as ENSO or Eurasian snow cover affect the NAO
is Rossby wave breaking. Woollings et al. (2008) suggest
that the NAO can be seen as being representative of
periods of low and high blocking frequency episodes
resulting from Rossby wave breaking. Precursors to
wave breaking can include quasi-stationary Rossby
wave trains originating in the Pacific, and may provide
a mechanism for linking tropical Pacific variability to the
NAO (Hoerling et al. 2001) and the variability of the
stratospheric polar vortex to the NAO (Scaife et al.
2005). Frankze et al. (2004) examine the links between
Rossby wave breaking, jet position, and NAO phase in a
general circulation model (GCM), and show that GCMs are capable of simulating the typical 10-day to 2-week period of variability in the NAO, with cyclonic Rossby wave-breaking events associated with negative phases of the NAO, and anticyclonic Rossby wave breaking associated with positive phases of the NAO.

This paper considers whether one or more of these physical mechanisms are captured in the Met Office GloSea4 system, whether they can be shown to provide skill in the hindcasts, and whether any of the mechanisms can be shown to be a driving factor behind the December 2010 forecast. We begin in section 2 by discussing the operational forecasting system used at the Met Office. In section 3 we examine whether the mechanisms outlined above are represented in the hindcast set. In section 4 we examine the Met Office’s real-time forecast for winter 2010/11, using the forecast SST and sea ice fields to drive an ensemble of atmosphere-only runs. The SST and ice fields from the forecast are then relaxed back to climatology over a number of regions (equatorial Pacific, North Atlantic, Arctic) to see if the source of the cold signal seen in the forecast can be identified.

2. Data and methods

GloSea4 is the Met Office’s operational seasonal prediction system, producing forecasts on a weekly basis out to 6-month lead time (Arribas et al. 2011). GloSea4 is based on version 3 of the Hadley Centre Global Environment Model (HadGEM3), comprising the Met Office Unified Model (UM) for the atmosphere (Hewitt et al. 2010), the Nucleus for European Modeling of the Ocean (NEMO) ocean model (Madec 2008; Vancoppenolle et al. 2012), and the Joint U.K. Land Environment Simulator (JULES) land surface model (Walters et al. 2011). The atmospheric model has 192 \times 145 grid points (longitude and latitude) giving a grid spacing of approximately 120 km in the midlatitudes, with 85 levels in the vertical, 30 of which are in the stratosphere, and a model top at 85 km (near the mesopause). Ocean resolution is 1° (with refinement to ½° near the equator) and 75 levels in the vertical. Fourteen forecast members are run each week, initialized from Met Office atmospheric analyses and its own operational ORCA1 (Madec et al. 1998) version of the Forecasting Ocean Assimilation Model (FOAM) NEMO–optimal interpolation system. Forty-two hindcast members (three for each year during the period 1996–2009) are run on four forecast dates (1st, 9th, 17th, and 25th) during each month. The atmosphere and land surface are initialized using the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERAI) dataset. The ocean is initialized with the Met Office optimal interpolation analysis using Enhanced Ocean Data Assimilation and Climate Prediction (ENACT/ENSEMBLES) version 3 (EN3) data (Ingleby and Huddleston 2007), and the sea ice initialization uses observed Special Sensor Microwave Imager (SSM/I) ice concentration (Andersen et al. 2007). Model uncertainties are represented through stochastic physics and a lagged approach is used to represent initial condition uncertainties (rather than perturbed initial conditions), with the previous 3 weeks’ forecasts being combined to produce an operational forecast each Monday. For each forecast week, the four nearest hindcast dates are used to construct a model climatology for bias correction, giving 12 hindcast members per year.

Note that due to a system upgrade in October 2010 (giving higher vertical resolution and introducing the initialization of sea ice) the 2010 forecasts at long lead times (September initialization) will not have ice extent as a candidate mechanism, but short lead-time forecasts (late October and November) have initialized sea ice (A. Arribas et al. 2013, unpublished manuscript).

There is evidence that improving the horizontal grid spacing to approximately 40 km improves the Atlantic blocking statistics. Jung et al. (2012) found improvements in blocking statistics in spectral models (atmosphere only) used in the Athena Project, with the largest improvement occurring for a change from T159 (126 km; approximately equivalent to GloSea4) to T511 (39 km). T159 showed an approximately 10% shortfall in the frequency of blocked days in winter (December–March, western Europe, 0°–10°E) relative to the reanalysis (ERA1); the frequency of blocked days in T511 was approximately equal to that in ERAI. However, ocean coupling is also important. Scaife et al. (2011) show that in coupled models large improvements in blocking frequency can be achieved by removing ocean biases. At a grid spacing of 192 \times 145 (120 km in midlatitudes), there is a 50% shortfall in the frequency of blocked days relative to ERAI in a model with significant ocean biases; this can be improved to close to the observed frequency by bias correcting the ocean fields. Thus, ocean coupling is likely to be a dominant factor in explaining forecasts of December 2010 with its negative NAO and prolonged blocking over Europe, although further significant improvements in forecast performance are likely to result from improved resolution in the future.

3. Mechanisms driving winter pressure and temperature signals in the seasonal hindcast

The hindcast set provides a collection of historical reforecasts. It has a sufficient number of ensemble members and a large enough sample of different initial states to provide a statistically significant assessment of
whether the dynamical model underlying GloSea4 is capable of representing the mechanisms proposed above as putative drivers of the observed precursors of the negative NAO described in the introduction. Our first mechanism is the ENSO teleconnection. As noted above, El Niño conditions in November are associated with negative NAO in January–March (JFM) and modeling this mechanism requires a well-resolved stratosphere (Bell et al. 2009; Cagnazzo and Manzini 2009; Ineson and Scaife 2009). La Niña events in November are associated with increased blocking frequency in December. The results for the El Niño teleconnection appear to be more statistically robust than those for La Niña.

It is far from clear that there is any statistically robust link between pressure patterns in December and La Niña events. Depending on whether we composite the top 5 events, the top 5% of events, or anomalies greater than one standard deviation from the mean [events since 1870, with mean sea level pressure anomalies taken from the HadSLP2 dataset; Allan and Ansell (2006)], we get different results. The five strongest events, with temperature anomalies greater than 2°C, show a positive pressure anomaly over Scandinavia. The eight strongest events (approximately the most extreme 5% of events; Fig. 3a) show a negative NAO pattern. All La Niña events, using one standard deviation temperature anomaly as the cutoff, show a positive NAO pattern. None of the composites (top 5 events, top 5% of events, anomalies greater than one standard deviation from the mean) is statistically significant over the North Atlantic. If we restrict the observational composites to the hindcast years, we see a positive NAO pattern (Fig. 3b). When we composite La Niña years in the hindcast, we do not see a negative NAO pattern in the surface pressure field (Fig. 3c). In summary, there is a lack of statistical significance for a link between La Niña conditions in November and negative NAO in December in the observational record, and no evidence of a strong signal in the hindcasts. Nonetheless, because 2010 was an unusually strong La Niña event, we include this as a possible mechanism to be investigated further in section 4.

Rodwell et al. (1999) and Graham et al. (2006) showed evidence for a feedback from SSTs into the atmosphere in a GCM. Rodwell and Folland (2002) showed that there was a link between SSTs in spring, ocean heat content in early autumn, and PMSL patterns later in the winter. We use the SST index introduced by Czaja and Marshall (2001), and composite the hindcast members according to the value of this index for the SST fields in the initial analysis [Czaja and Marshall’s index uses a dipole, but the resulting patterns are qualitatively similar to those identified by Rodwell et al. (1999)]. Figure 4a shows the uppermost quintile (top 20% of the 84 members) of SST for the ERAI analysis used to initialize the hindcasts (25 October and 1 November), together with the boundaries of the boxes used to construct the index. We then form composites of ensemble members corresponding to this uppermost quintile for the December surface pressure (Fig. 4b) and December 1.5-m temperature (Fig. 4c). The negative tripole in November is associated with a negative phase of the NAO and cold anomalies over
Europe in December. Note that although the initial SST states are associated with positive and negative phases of the NAO, the decorrelation time scale for pressure anomalies is approximately 10 days to 2 weeks (Vallis et al. 2004), so the cause of the negative NAO and cold anomalies in December is the SST tripole rather than atmospheric preconditioning. This can be confirmed by compositing outer quintiles of NAO states (not shown) in the initial analysis and looking at corresponding December pressure anomalies in the hindcasts: the initial NAO signals have vanished a month later (in contrast to the composites categorized by SST).

The role of Arctic sea ice in the hindcast set is more complex and the signal is less robust. For the period up to and including 2010, September 2007 had the lowest ice extent on record, and the low ice extent was successfully hindcast by the GloSea4 system. However, 2007 also saw a strong positive NAO, providing an illustration of the extent to which competing mechanisms and chaos can lead to a complicated response. The hindcast system initialized with climatological ice correctly forecast this positive NAO (albeit with a smaller-amplitude response than was seen in the observations), consistent with the hypothesis that mechanisms other than the ice extent drove the pressure response in this instance. When initialized with observed ice extent, GloSea4 still produced a positive NAO signal, but it was even weaker than that seen with climatological ice, suggesting that the system responds to low ice in the statistically expected way. However in this case, the modeled response took the forecast further from the observed situation.

Eurasian snow cover was also tested as a potential source of predictability in the hindcast set. Observational analysis (Cohen and Entekhabi 1999) suggests that the surface pressure in December–February (DJF) responds to anomalously high snow cover in SON. In the hindcast set, a higher than average autumn snow cover leads to high pressure anomalies over the pole and Greenland, a negative NAO pattern, and a deepening of the Aleutian low in winter. In order for snow cover to be a potential driver of predictability within the model, two conditions must be met: first, the snow cover needs to be initialized in a realistic manner and, second, the model needs to show the correct response to anomalous snow cover. Even if the model shows the correct response to anomalous snow cover, if it is initialized with lower than average snow cover in a year in which there was higher than average snow cover, the predicted forecast response will be unlikely to match the observed response.

As regards the mechanism, there is evidence that the hindcast set shows a link between lower than average snow in SON and negative NAO in DJF. Compositing outer quintiles (anomalously high minus anomalously low snow in SON) results in a positive pressure anomaly over the pole during DJF. However, when we turn to the initialization, we find two problems. For the hindcast set, year-to-year snow amounts from ERAI used to initialize the model are problematic (Dee et al. 2011) and poorly correlated with observations for some start dates based on the Rutgers dataset (Robinson et al. 1993; Robinson and Frei 2000) the Canadian Meteorological Centre (CMC) dataset (Brown and Brasnett 2012), and the Interactive Multisensor Snow and Ice Mapping System (IMS) dataset (NOAA/NESDIS/OSD/P/SSD 2012). For example, for 1 November for the hindcast period from 1996 to 2009, the anomaly correlation between ERAI and CMC snow cover is only 0.42. Furthermore, the Met Office NWP analysis for 1 November 2010 used to initialize the forecast runs shows anomalously low snow cover relative to the average snow cover in the ERAI reanalyses for the hindcast period and, thus, would not be expected to drive a negative NAO. For this reason this...
mechanism was not pursued further in the atmosphere-only runs.

Rossby wave activity can affect the NAO state via Rossby wave breaking, but a detailed analysis is outside the scope of this paper. However, a preliminary examination of daily 200-hPa geopotential height fields showed that anticyclonic Rossby wave–breaking events with ridging over western Europe tended to precede anomalously warm conditions over western Europe, while cyclonic Rossby wave–breaking events tended to precede anomalously cold conditions over western Europe, with a lag of approximately 1 day, in keeping with the findings of Woollings et al. (2008) and Frankze et al. (2004). Previous work (Scaife et al. 2011) suggests that the HadGEM3 model used in the GloSea4 system successfully models blocking events and their link with the NAO. A detailed examination using the Pelly and Hoskins (2003) blocking index will be the subject of future work.

4. Testing the mechanisms in atmosphere-only runs

We now describe perturbation experiments to determine the importance of the mechanisms identified above as possible drivers for the negative NAO/cold winter signal seen in the forecast for December 2010: Atlantic SSTs, sea ice extent, and equatorial Pacific SSTs.

We ran sets of ensembles of atmosphere-only runs with prescribed SST and sea ice extent fields, constructed as described here. For the “forecast” set, we used the ensemble mean of the forecast daily mean SSTs from the real-time forecast centered on 1 November 2010 (42 members). For the model climatology set, we used SSTs constructed from an average over all members of the corresponding hindcast (nine per year over the period 1996–2009) for initialization dates centered on 1 November. The same procedure was used for the sea ice extent, but using monthly means instead of daily means. Figure 5 shows the mean difference between the resulting model climatology and forecast SSTs for December and the difference in sea ice extents at the start of December. The SST field shows La Niña conditions in the Pacific and signs of a negative North Atlantic tripole with bands of warm anomalies in the tropics and in the northernmost Atlantic, as well as cooler midlatitude anomalies. The SST pattern is ambiguous compared to the clear tripole patterns in the reanalysis (Fig. 4a), but it should be noted that the model’s 1° ocean is low resolution and fails to represent the Gulf Stream correctly (the Gulf Stream moves eastward at roughly 40°N rather than heading northeastward).

Figure 5a could be interpreted as showing an overall warming of the North Atlantic, which has been related to periods of increased Atlantic blocking, albeit on decadal rather than intraseasonal time scales (Häkkinen et al. 2011; Deser and Blackmon 1993). However, given the shortcomings of the representation of the Gulf Stream, this also seems consistent with a rudimentary representation of the North Atlantic tripole; either interpretation is consistent with increased blocking and a negative NAO. Additionally, the overall warming discussed by Häkkinen et al. appears to operate at different time scales. They offer the hypothesis that changes in wind stress curl affect the ocean gyres, which in turn feed back to reinforce the wind stress curl anomalies, thus modulating what would otherwise have been high-frequency variations down to much lower frequencies. Thus, the effects of blocking on the ocean gyres give whole decades or more of warmer, more saline seas coupled with
A continued period of higher blocking frequency. The main issue that suggests to us that the driving mechanism is the SST tripole rather than an overall warming is the time scale: the fluctuations between warm, saline periods and cold, relatively fresh periods that Häkkinen et al. discuss are decadal/multidecadal fluctuations, not fluctuations from one season to the next.

Having constructed the forcing SST and ice extent fields, the atmosphere-only experiments for both the forecast situation and model climatology were initialized using the Met Office global NWP analysis for 1 November 2010. Forty members each were run for forecast and climatological ocean and sea ice conditions, with differences between ensemble members arising from the stochastic physics. The difference between the ensemble means gives the control anomalies (CTL). Note that the same NWP analysis was used to initialize climatological and forecast runs, so the initial atmospheric and snow-cover states were identical.

Two additional SST forcing fields were constructed by perturbing the forecast ensemble mean SST. In the first (NOP), the Pacific La Niña signal was removed by relaxing the equatorial Pacific back to climatology between 17°N and 17°S, and in the second (NOA), the North Atlantic anomalies were removed by setting SST back to climatology between the equator and 70°N (with the Hudson Strait as its western edge); see Fig. 5a. Both regions had a four-gridbox margin with linear interpolation between the forecast and climatological fields, sufficient to ensure a smooth relaxation. A third experiment (NOI) was run without the observed sea ice anomaly, instead using climatological sea ice extent. Forty members were run for each of these three experiments and anomalies were calculated relative to the model climatology runs.

Figure 6 shows the 1.5-m temperature response in the North Atlantic region in each case. The CTL experiment (Fig. 6a) reproduces the cold signal seen in the original coupled forecast, and the results over central Europe are significant at the 95% level (using a Student’s t test). Figure 6b shows the results from the NOP experiment. The quadrupole surface temperature response is still present and the cold signal over northern Europe is still statistically significant at the 95% level. In contrast, the NOI experiment (Fig. 6d) shows smaller cold anomalies than the control case, suggesting that the Arctic sea ice anomalies played some role in creating cold anomalies in the CTL case. A similar, though more pronounced, influence is evident in the NOA experiment. In this case, with Atlantic SST relaxed to climatology (Fig. 6c)
anomalies are close to zero over much of northern Europe. In both the NOI and NOA cases, the cold anomaly is no longer significant at the 95% level.

Figure 7 shows the PMSL anomalies for the four experiments. The CTL, NOP, and NOI experiments (Figs. 7a, 7b, and 7d) all show a strong and statistically significant negative NAO. The removal of La Niña conditions in NOP deepens the Aleutian low (not shown), as expected. In the NOA experiment (Fig. 7c), the negative NAO is much weaker and no longer statistically significant over much of the North Atlantic. This change is small in the ensemble mean, but signals in individual members can show pressure differences between low and high anomaly regions of 20 hPa or more. The ensemble mean plots show that the negative NAO state is still present to some degree in all experiments.

Figure 8 shows histograms for the NAO index (based on the pressure difference between Reykjavik, Iceland, and Gibraltar) in the model climatology and the four experiments, with dashed vertical lines indicating ensemble mean values. The CTL experiment is shifted relative to the model climatology with a difference in ensemble mean value for the NAO index of 7 hPa (Fig. 8a). The NOI case (Fig. 8d) also shows a difference in the ensemble mean of 7 hPa, and a similar distribution to CTL, while NOP (Fig. 8b) shows a difference of 8 hPa in the ensemble mean. However, NOA shows a difference in ensemble mean of only 2 hPa and a histogram noticeably shifted relative to the CTL case (consistent with Fig. 7c, where neither of the pressure anomalies over Iceland or Gibraltar is statistically significant at the 95% level).

Thus, the removal of the Atlantic tripole from the SST field removes any statistically significant signal in the near-surface temperature field and considerably weakens the negative NAO signal in the pressure field. We conclude that the North Atlantic tripole was the major driver behind the unusually cold temperatures in northern Europe during December 2010. However, the fact that all four experiments show pressure anomalies consistent with a negative NAO signal suggests that the North Atlantic tripole was not the only driving mechanism for the unusually strong atmospheric response in December 2010. Because the model climatology was initialized with the same atmospheric state as the four forecast experiments, atmospheric preconditioning can be ruled out as a possible cause. It seems plausible that a combination of mechanisms could be responsible for this residual anomaly, with the North Atlantic tripole

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**Figure 7.** Surface pressure anomaly response (December average) in atmosphere-only runs. (a) Control forecast minus hindcast. (b) Relaxed equatorial Pacific minus control hindcast. (c) Relaxed North Atlantic forecast minus control climatology. (d) Simulation with forecast SST and ice extent relaxed to model climatology minus control hindcast. Stippling indicates confidence at the 95% level.
playing a dominant role. It is also possible that other mechanisms not investigated here, such as the Indian Ocean dipole (Hoerling et al. 2001; Bader and Latif 2005), may also have contributed to the negative NAO.

5. Summary and conclusions

The NAO state is driven by a mixture of chaotic atmospheric processes and some slowly varying boundary conditions. Some of these slowly varying boundary conditions seem to be represented in the correct way within GloSea4. Examination of the hindcast set for GloSea4 shows that HadGEM3 appears to represent the mechanisms underlying the observed link between North Atlantic SST–ocean heat content and the NAO. The possible teleconnection between La Niña conditions and negative NAO in early winter is not present in the hindcast. The effect of changes in Eurasian snow cover extent on Arctic surface pressure mirrors that seen in the observations, but the hindcast snow cover itself is poorly initialized. Arctic surface pressure also responds to Arctic sea ice. While the forecasts capture some of the

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**FIG. 8.** December NAO index (Reykjavik – Gibraltar) in atmosphere-only runs. The control forecast is shown in red in all panels, with (a) model climatology in black and (b),(c),(d) perturbed forecasts in blue. Control forecast relative to the (b) NOP, (c) NOA, and (d) NOI cases. The vertical black line is the ensemble mean for model climatology (zero by construction) and the dashed lines show the ensemble mean for CTL (red) and each of the perturbed experiments (blue).
slowly varying boundary conditions and mechanisms that can supply predictability at seasonal time scales, this study has identified areas where model development could lead to improvements in seasonal predictions, such as better representations of Atlantic SST patterns.

Statistical analysis of the sets of atmosphere-only simulations carried out using forecast fields from the Met Office 2010 winter forecast indicates that the successful forecast signal was reproducible. This supports the hypothesis that although skill in general over the European region is low, there are grounds for having higher confidence in forecasts for individual years where strong forcings exist. In this case, the unusually cold conditions in Europe during December 2010, and the associated strongly negative NAO, were driven primarily by ocean heat content anomalies in the North Atlantic, with a negative North Atlantic tripole consisting of warm anomalies to the south of Greenland and in the sub-tropical Atlantic, and cold anomalies off the East Coast of the United States. The initialization of sea ice extent also seems to have played a role in the negative NAO. However, the surface pressure response seen in all four experiments using atmosphere-only simulations suggests that each mechanism individually is not sufficient to explain the response and that some combination of them is required.

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