How far in advance can we predict changes in large-scale flow leading to severe cold conditions over Europe?

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The potential of early warning for severe cold conditions is explored using the Subseasonal to Seasonal (S2S) Prediction research project data archive. We explore the use of a two-dimensional phase space based on the leading empirical orthogonal functions (EOFs) of mid-tropospheric flow computed over the Euro-Atlantic region in order to study the time evolution of flow patterns associated with high-impact temperature anomalies. We find that the phase space is an effective tool for monitoring predictions of regime transitions at medium and extended ranges. We show that a number of S2S systems have some skill in the prediction of cold spells over Europe, even beyond the medium range. In particular, the ECMWF (European Centre for Medium-Range Weather Forecasts) model represents well the observed preferential transition paths. We reveal that the impact of the Madden–Julian Oscillation (MJO) on the predictive skill of large-scale flow over Europe is asymmetric. The impact of the MJO on the Brier skill scores and reliability is significantly positive for predictions of the negative phase of the North Atlantic Oscillation (NAO): beyond week one, forecasts with the MJO in their initial state are significantly more reliable than forecasts with no MJO in their initial conditions. In contrast, the predictive skill for positive NAO shows little sensitivity to the MJO.

KEYWORDS
blocking, Euro-Atlantic regime transitions, large-scale flow, North Atlantic Oscillation, severe cold conditions, subseasonal predictions

1 | INTRODUCTION

Severe weather conditions, such as periods of extreme cold temperatures, pose serious threats to health and welfare. As a consequence, there is increased interest in the development of early warning systems that could allow more time for mitigation actions. The ability to predict weeks ahead the onset of a period with severe temperature anomalies is closely linked with the ability to accurately forecast the time evolution of a large-scale circulation. Here we explore the skill of subseasonal forecast systems to predict changes in large-scale circulation patterns associated with persistent cold conditions in winter. We do not expect subseasonal forecasts to accurately represent the day-to-day weather variability. Rather, these forecasts are more likely to capture large-scale circulation patterns that typically last longer than a week. Therefore, at the extended range, the main goal is to identify and predict severe events that are characterized by persistent weather conditions. Anomalous surface weather is modulated by strong and persistent large-scale anti-cyclonic systems, such as blocking (Rex, 1950). Severe cold episodes in winter as well as dry spells and heat waves in summer are often associated with the occurrence of such high-pressure systems. For example, during the heat wave of August 2003, the hot dry tropical continental air mass that characterized this event was pushed over western Europe by a persistent anti-cyclonic system (Black et al., 2004). Also, the sequence of severe cold spells over northern and western Europe that occurred in...
winter 2009/2010 was associated with record persistence of the negative phase of the North Atlantic Oscillation (NAO) (Jung et al., 2011). The structure of the negative phase of the NAO (NAO−), with anomalously high pressure over Greenland and low pressure over the Azores, causes a substantial reduction of the westerly flow across the Atlantic and a strengthening of northerly winds from the Arctic. NAO− is often referred to as Greenland blocking (Michel and Riviere, 2011).

The large spatial scale and the low-frequency nature of such circulation patterns are the crucial attributes for successful predictions on the subseasonal timescale (Grams et al., 2017). In fact, flow patterns such as the NAO have been associated with tropical forcing through propagation of Rossby wave trains (Cassou, 2008). Several studies have shown that the Madden–Julian Oscillation (MJO) modulates the lagged correlations between the tropics and the NAO (Cassou, 2008; Lin et al., 2009). Vitart and Molteni (2010) assessed the impact of the MJO on the probabilistic skill of subseasonal forecasts over the extratropics, finding that the forecast reliability is enhanced when an MJO event is detected in the initial conditions. More recently, Vitart (2017) documented the ability of several subseasonal forecasting systems to predict the MJO and the associated extratropical teleconnections. He concluded that, despite significant skill in predicting MJO propagation beyond 2 weeks, the predictability associated with the MJO over Europe could be better exploited by improving the model representation of MJO teleconnections.

In this article, we explore the ability of the ECMWF (European Centre for Medium-Range Weather Forecasts) ensemble forecast (ENS) to provide early warnings for severe cold spells over Europe using the extended-range predictions of large-scale circulation patterns. The main focus is to assess how far in advance and in which conditions do we have reliable forecasts of transitions between large-scale circulation patterns. The article is organized as follows. Section 2 describes the data. Section 3 introduces the diagnostic framework. Section 4 discusses the model ability in predicting transitions between large-scale patterns. In section 5, we examine the forecast skill in relation to the tropical variability. Section 6 contains the conclusion and further remarks.

2 DATA

We analyse coupled ensemble reforecast data from ECMWF (using IFS cycle 41r1, used operationally from October 29, 2015 to March 17, 2016). The ECMWF reforecasts cover a period of 20 years (1995–2014) with an ensemble size of 11 members (see Table 1). For part of the study we use reforecasts from five additional ensemble systems available from the Subseasonal to Seasonal (S2S) Prediction research project archive (Vitart et al., 2017). The S2S Prediction project, established by the World Weather Research Programme/World Climate Research Programme, has constructed an extensive database containing subseasonal forecasts (up to 60 days), 3 weeks behind real time, and reforecasts from 11 operational centres. The S2S database has been available to the research community since May 2015. In this study, the S2S database is used to set the scene by identifying the current skill level in predicting large-scale flow winter patterns over the Euro-Atlantic sector.

Since we processed reforecast data for boreal winter months that were available in the S2S database by January 2016, only a subset of the S2S systems has been considered. Salient details about the S2S reforecast data used are presented in Table 1. To make the NCEP (National Centers for Environmental Prediction) ensemble (Saha et al., 2014) comparable in size with that of ECMWF, we combined three NCEP ensemble forecasts (initiated on consecutive days) into a single 12-member ensemble. (We define the initial date to be that of the central sub-ensemble; this has little effect on the results at extended lead times.) A 12-member ensemble for CMA (China Meteorological Administration) has been constructed with the same method as used for the NCEP ensemble. Given the wide range of ensemble sizes and methods used to generate ensembles, the S2S data could be used to assess the sensitivity of different ensemble configurations in predicting large-scale flow for the weeks ahead. Although this is a very interesting topic, it is beyond the scope of this study and will be addressed in future work. For verification data we use the ERA-Interim analyses (Dee et al., 2011). Beyond the medium range, when the forecast uncertainties can be larger than the verification uncertainties, the choice of verification analysis becomes less relevant. The variables used are daily fields of geopotential height at 500 hPa and 2-m temperature.

3 DIAGNOSTIC FRAMEWORK

In order to study changes between circulation patterns associated with high-impact temperature anomalies over Europe, we explore the use of a two-dimensional phase space based on
the leading empirical orthogonal functions (EOFs) of daily geopotential height at 500 hPa computed for the Euro-Atlantic region (30°N to 88.5°N, 80°W to 40°E). For the EOF computation a 5-day running mean was used and the mean seasonal cycle was removed. Figure 1 shows the two leading EOFs computed from 29 years of extended winter periods (October to March) of ECMWF ERA-Interim data. EOF1 (Figure 1a) shows a close resemblance to the positive phase of the NAO pattern (Cassou, 2008) and we will refer to EOF1 as NAO in the following. EOF2 (Figure 1b), with its high centred over Scandinavia and a low to the east over the Atlantic Ocean, is clearly reminiscent of the anomalous flow during northern European blocking events, so we refer to EOF2 as the blocking (BLO) pattern (Ferranti et al., 2015). These two EOFs are used here to define a phase space in which the low-frequency variability over the Euro-Atlantic region is characterized by the projection onto these two orthogonal patterns of NAO± and blocking/anti-blocking (trough over Scandinavia). This very simple view uses the same concept as the well-known MJO index of tropical variability from Weeler and Hendon (2004), where a two-dimensional phase space defined by the first two principal components (RMM1 and RMM2) of combined fields (OLR zonal wind at 850 and 200 hPa) averaged between 15°S and 15°N is used to represent the time evolution of the tropical organized convection associated with the MJO events. The NAO–BLO space explains 30.8% of the daily winter variability over Europe. This is a substantial portion if we consider that the spatial structures of the leading two EOFs of the combined fields of OLR zonal wind at 850 and 200 hPa, used for the MJO index (see Figure 4), together account for 25% of the variance of the original atmospheric fields (Weeler and Hendon, 2004). However, while in the tropics two main modes of tropical convection are sufficient to describe the eastward propagation of an MJO event around the globe, due to the complex structure of the extratropical variability the two-dimensional NAO–BLO phase space might provide a somewhat limited view. In fact, most Euro-Atlantic low-frequency winter variability can be explained by the variations of four climatological regimes (Vautard, 1990; Michel and Riviere, 2011), which represent the positive and negative phases of the NAO, the Scandinavian blocking and the Atlantic Ridge patterns. We have computed the projections of the four climatological regimes onto the NAO–BLO space (not shown). As expected, we find that the NAO+ (NAO−) regimes project large positive (negative) values onto the EOF1 patterns and smaller values onto the EOF2 patterns, while the Scandinavian blockings have large positive projections onto EOF2 and small projections onto EOF1. The representation of the Atlantic Ridge, with large negative projections onto both the EOF1 and EOF2 patterns, is the least optimal and could be better resolved by considering a three-dimensional phase space. However, because
NAO− and blocking are the patterns typically associated with severe and persistent temperature anomalies, the NAO–BLO phase space offers the advantage of a more appropriate and simplified framework to assess the performance in predicting temperature extremes. The idea of representing the temporal evolution of weather in a low-dimensional space defined by large-scale circulation patterns has been explored by a number of authors. For example, Straus et al. (2017) discussed a method for identifying recurrent and persistent flow patterns on intraseasonal time-scales and the use of such patterns to verify forecast scenarios. Moron et al. (2013) used the leading modes of interannual variability to describe the subseasonal evolution of long rainy seasons over Eastern Africa. To provide an example of the use of the NAO–BLO space, Figure 1c,d shows the daily evolution of the analysed 500 hPa geopotential anomalies during the winters of 2009/2010 and 2013/2014, respectively. Figure 1c shows that during most of
December 2009 and February 2010, the flow circulation projected strongly onto the negative phase of the NAO pattern, while in January 2010 the circulation was characterized by a Scandinavian blocking. Such persistent southward advection of cold Arctic air resulted in record-breaking cold temperatures over Europe as shown in Figure 2a. In contrast, the winter of 2013/2014 (Figure 1d) was dominated by NAO+ and westerly flow anomalies across the Atlantic (Huntingford et al., 2014). Consistent with the anomalous flow conditions, winter 2013/2014 was a season of exceptional storminess and severe rainfall but with rather mild temperatures over Europe (Figure 2b). The systematic relationship between the NAO–BLO space and the severe cold European spells is highlighted in Figure 3, where the distribution of the severe cold events, detected using the 2-m temperature reanalysis, is represented in the NAO–BLO space. The reanalysis temperature data cover the November–February winter periods from 1980 to 2015. We identify severe cold events over nine predefined regions covering the European domain (Figure 3a). A severe event is detected if daily mean temperatures are cooler than the 10th percentile of the daily climate for at least 60% of the grid points located over each individual region and if this criterion is satisfied for 4 consecutive days. The corresponding projection into the NAO–BLO phase space is determined from the reanalysis 500 hPa geopotential field from the first day of the event. For each of the nine regions an NAO–BLO diagram depicts all the events detected in that region. For the northern regions 2 and 3 the majority of the severe cold episodes correspond to NAO− events with rather large amplitudes. For region 1 an equal number of cold episodes are characterized by NAO− and anti-blocking types of circulation. For the central and southern regions severe cold events are associated with NAO− and with blocking. The projections onto NAO− and blocking are generally very large, indicating that this space is optimal for describing most severe cold episodes. For the eastern European domain (regions 3, 6 and 9) there are some cases with relatively smaller projections. This indicates that for these regions the NAO–BLO phase space is less optimal in representing the link with severe temperatures. Overall, however, Figure 3 shows that there is a
strong link between large projections onto the NAO– and BLO sectors and the occurrence of severe cold spells over Europe.

3.1 Monitoring forecasts: illustration of one case

The NAO–BLO phase space can be used to monitor ensemble forecast performance in predicting large-scale flow at different forecast ranges. We have been using it for some time and it has proved to be an effective monitoring tool for the performance of regime transitions from the medium to the extended range. Figure 4 shows examples of plots used to monitor the ability of the ECMWF ENS to predict transitions between the different regimes. The top two panels represent the evolution of forecast trajectories from day 0 to day 8 of two independent forecast ensembles. The forecast trajectories of the ENS initiated on April 29, 2017 (Figure 4a) indicate a clear transition from westerly flow (NAO+) into a Scandinavian block by day 3 and a transition into NAO– by day 7. The ENS of May 5, 2017 (Figure 4b) shows a transition from blocking into NAO– by day 3 and then a persistence of NAO– conditions up to day 8. For both forecasts the verification analyses (black lines) and the ensemble mean trajectories (red lines) match quite closely. The evolution of forecast uncertainties is well depicted by the NAO–BLO phase space. The forecast with transitions away from blocking conditions exhibits a more confident outlook than the forecast predicting transitions into blocking.

A similar approach is used for the extended range (Figure 4c). However, due to the substantially larger uncertainty, the day-to-day forecast trajectories are not plotted. Instead, the evolution of the forecast anomalies is represented by instantaneous values from each ensemble member every 5 days through the forecast. Figure 4c shows the extended-range forecast evolution of the ENS forecast from 0000 UTC on April 27, 2017. The forecast starts in the anti-blocking sector and, following an anti-clockwise direction, makes almost a full circle in the phase space. Looking at the time evolution of the verification analysis (black line), this specific forecast provided an accurate signal despite the rather large uncertainties beyond day 15. This specific case is an example of rapid and large changes in the large-scale flow for which the medium-range forecast was remarkably accurate and the extended-range forecast was able to provide good guidance (possible reasons for this are discussed below and in section 5).

On April 27, 2017, at forecast initial time, enhanced convective activity over the western Pacific associated with an MJO event was observed. The time evolution of the predicted MJO index (Figure 5) shows an anomalous tropical convection moving from the western to the eastern Pacific. The large diabatic heating and upper-level divergence anomalies associated with the MJO event are the sources of wave trains that condition the extratropical circulation anomalies about 10–20 days later. Several authors have discussed the preconditioning role of the MJO in setting the phase of the NAO, indicating that the enhanced convection over the western Pacific favours the occurrence of NAO– (Cassou, 2008; Lin et al., 2009). Considering the phase and the amplitude of this MJO event, it is likely that optimal conditions for higher levels of Euro-Atlantic predictability were in place (Vitart and Molteni, 2010).

Figure 6 shows the forecast performance for temperature for this case. The temperature predictions (Figure 6b), expressed in terms of weekly mean anomalies for the 12–18 day range, show cold conditions over Scandinavia and northeastern Europe with anomaly values ranging between −3 and −6°C. Figure 6a shows the corresponding verifying weekly temperature anomalies for the period May 8–14, 2017. The forecast gave a good indication of the location and geographical extent of the anomalies, although in terms of the ensemble mean the values are underestimated. During May 8–14 the circulation was predominantly negative NAO-like (Figure 4c). Consistent with this, the anomalies in Figure 6, with cold conditions over northern Europe, exhibit the typical temperature signature of the NAO– circulation (cf. Figure 2a). It is worth noting that a linear regression between temperature anomalies and PC1 (not shown) gives a very similar temperature pattern.

3.2 Skill assessment

The forecast skill in the NAO–BLO space is evaluated with the same approach as used for the MJO index verification. First we assess the skill in predicting NAO and BLO separately, then we consider the skill in predicting the evolution in the NAO–BLO space to better understand the ability to capture transitions between the different flow patterns. Figure 7a,b shows the skill of six S2S forecasting systems, as a function of forecast range, in predicting the principal components associated with westerly/easterly flow across the Atlantic (NAO+ and NAO−) and blocked/anti-blocked flow over Scandinavia (BLO+ and BLO−). The skill metric is the anomaly correlation between the observed and ensemble mean forecast projections onto each EOF pattern, computed for the common period of reforecast available in the S2S archive covering 12 years (1999–2010). Since beyond 2 weeks ahead the forecast is not expected to have day-to-day accuracy, a 5-day running mean (centred on the day) has been applied to the projections of both the verification analysis and the ensemble mean prior to the anomaly correlation computation. We use the S2S models to estimate the current skill range of subseasonal predictions. Looking at the forecast range at which the anomaly correlation drops below 0.5, the skill ranges from 11 to 17 days for the NAO predictions and from 9 to 13 days for the blocking predictions. The ECMWF skill in predicting BLO, consistent with previous results (Ferranti et al., 2015), drops below 0.5 at about 13 days – a few days earlier than for the NAO. This result may be associated with higher predictability of the persistence of the NAO–
regime. Probabilistic skill scores for S2S predictions of NAO and BLO (not shown) provide consistent results.

In order to assess the accuracy of the forecast trajectories in the NAO–BLO phase space, we compute temporal correlation between the forecast and verification projections onto EOF1 and EOF2 (Figure 7c). This metric, known as bivariate correlation, is commonly adopted as a score for evaluating forecast trajectories in the MJO phase space (Lin et al., 2008; Rashid et al., 2010). The metric formulation used is documented by Gottschalck et al. (2010). The bivariate correlation is generally applied to measure the temporal correlation between two vectors defined in a two- or higher-dimensional space and is thus also appropriate for assessing trajectories in the NAO–BLO space. Although this score is a pathwise measure and therefore does not necessarily highlight the prediction skill in terms of strong versus weak events, it does provide an objective skill measure for forecasting transitions between the flow circulation patterns associated with high-impact weather over Europe. The S2S skill in terms of bivariate correlation (Figure 7c) ranges between 10 and 15 days, indicating some potential to predict the onset of cold spells over Europe beyond the medium range.

4 | TRANSITIONS

Early warning of high-impact weather relies on the model’s ability to forecast weeks ahead changes into flow patterns typically associated with the persistence of severe atmospheric conditions (e.g. harsh cold temperatures in winter, or relentless warm and dry conditions in summer). However, transitions from one flow type to another can lead to very large forecast errors. Recently, Magnusson (2017) showed that
medium-range forecasts with very large errors over Europe
are typically associated with flow-regime transitions over the
Euro-Atlantic region, especially with blocking. In this section
we analyse transitions in the two-dimensional phase space.
We first assess the transition statistics in both the model
and the analysis data and then we evaluate their predictability.

4.1 Preferred transitions in the analysis and the model

In this section we test the existence of a preferred progression
in the NAO–BLO phase space and, by comparing the analysis
and the model, we assess the presence of model biases.

The NAO–BLO phase space can be divided in four sectors
delimited by two diagonals and an internal circle as in
Figure 4. The top (bottom) sector is populated by cases with
blocking (anti-blocking) type flow. These cases have large
positive projections onto EOF2 (P2) and relatively small pro-
jections onto EOF1 (P1). Projections are considered “major”
if they exceed one standard deviation ($\sigma$) of the correspond-
ing principal component. Projections are considered “minor”
if they range between $-\sigma$ and $+\sigma$. Similarly, the left (right)
sector is populated by cases with negative (positive) NAO
types of flow. Cases where both projections are located inside
the circle are not well described in the NAO–BLO phase space
and are therefore excluded. We identified all cases in one of
the four sectors and we tracked back their positions through
the previous 6 days recording a transition (or a persistence) if
a change of sector had (had not) occurred. For some cases, the
projections for the previous 6 days were small (located inside
the circle) and therefore it is not possible to identify the sector
of provenance; such cases are also recorded.

The data used in this section does not cover the same
period for analysis and forecasts. In order to increase the sam-
ple size for the analysis, we used 36 years of ERA-Interim
data (1979–2014) from the November to March periods
(151 days). The 11 ensemble members in the ECMWF
reforecasts with twice-weekly start dates (for a total of 40 start
dates per season) compensate for the smaller 20-year period.
For the purpose of estimating climatology of transitions, the
benefit of having a larger sample outweighs the benefit of hav-
ing matched analysis and forecast samples. In fact, by using
the analysis data limited to the “verifying period” we obtain
consistent results (not shown).

In assessing the model statistics, we consider each individ-
ual forecast member as an independent realization. For each
member, we track the trajectories back in time ending respec-
tively at forecast days 11, 16, 21 and 31. For a given forecast
range we identify all the cases where each forecast member
predicts strong projections onto one of the two leading EOFs
and for each of these cases we track their trajectories back
over the previous 6 days and register the sector of provenance.
Table 2 provides the relative frequency of transitions into one
of the four sectors in the analysis and in the model at differ-
ent forecast ranges. The transitions to blocking and negative
NAO are slightly more frequent than transitions to NAO $+$,
consistent with previous studies (Vautard, 1990; Michel and
Riviere, 2011). Transitions into negative blocking are about
one order of magnitude smaller than the others. The model
relative frequencies, at all forecast ranges, compare well with
those from the analysis.

Figure 8 shows the percentage of transitions into the four
sectors (indicated by the x-axis) stratified according to their
provenance. For example, the first five bars represent transi-
tions into blocking. The first bar indicates the analysis values
and the subsequent four bars indicate model values at forecast
days 11, 16, 21 and 31.

About 16.1% of the transitions into blocking originated
from NAO+. Less than 10% originated from either NAO$-$
or BLO$-$, while the blocking persistence accounts for about
24.6% of the total cases. The origin sector could not be
assigned to 44.6% of transitions into blocking. Persistence and NAO+ are the most probable precursors for blocking. The model beyond day 11 shows a reduction in persistence and a more equiprobable distribution among the precursors. However, with the exception of the 16-day forecast range, the model still represents blocking and NAO+ as the most likely precursors.

About 38% of the transitions to NAO− originated from blocking, while persistence accounts for 30.1% of the cases. The percentage of NAO− transitions originating from NAO+ and BLO− are much smaller. So, blocking is the most likely precursor of NAO− and it is more probable than the persistence. The signal of a preferred progression from blocking into NAO− is very clear in both the analysis and the model data even at the longest forecast ranges. This is consistent with results from Croci-Maspoli et al. (2007), who show that in the Euro-Atlantic sector blockings significantly contribute to the establishment of the negative NAO phase. Michel and Riviere (2011) investigated the dynamical processes involved in the transition from blocking to NAO−. They found that strong cyclonic wave breaking south of Greenland kicks off the regime transition by favouring the destruction of the Scandinavian high, while the nonlinear interactions among the transient eddies play the major role in the establishment of NAO−.

While the persistence in NAO+ (zonal flow type) accounts for 23.6% of the cases, the most likely precursors for transitions into NAO+ are BLO− (18.7%) and BLO+ (12.6%). Transitions into zonal flow type do not seem to have a strong preferential path. The model statistics compare well with those of the analysis. Persistence and NAO+ are the most likely precursors for transitions into BLO−. The model statistic is consistent with the analysis, indicating a good ability of the model to simulate transitions. It is worth noting that the number of transitions into BLO− is about one order of magnitude smaller than the other transitions and therefore the results associated with these events might be less robust.

The above results are not sensitive to the choice of 6-day trajectories. We found similar results (not shown) when we repeated the computation considering trajectories from 5 to 8 days. As discussed above, the most likely atmospheric circulation before a blocking event is the blocking, consistent with the fact that the life cycle of the blocking typically exceeds the 6-day period. NAO+ is favourable for transitions into blocking. The model at day 11 reproduces well the observed statistics, but by day 16 the blocking persistence is under-represented. The Scandinavian blocking circulation (BLO+) is the most favourable condition for a transition into the Greenland blocking (NAO−). The large percentage of persistence cases is consistent with the fact that the probability of NAO− persisting beyond 12 days is about twice that of the probability for the other regimes (Dawson et al., 2012). The forecast shows a remarkably consistent signal with the analysis at all forecast ranges.

The preferred transitions into BLO+ and NAO− follow an anti-clockwise direction in the NAO–BLO space, corresponding to a cyclonic wave breaking progression. There is no clear preferred direction for transitions into NAO+ (westerly flow pattern), so both cyclonic and anti-cyclonic wave breaking are likely to occur. Overall, the model statistics are
TABLE 2  Total number of transitions and percentages of transitions into each of the four regimes, for the reanalysis and for the forecast at different ranges. The total number of cases in the reanalysis is 5,436 (36 years \( \times \) 151 days), while the number of cases in the forecast is 8,800 (20 years \( \times \) 40 start dates \( \times \) 11 members).

|                  | Analysis | Day 11 | Day 16 | Day 21 |
|------------------|----------|--------|--------|--------|
| All transitions  | 668      | 1,003  | 1,070  | 1,038  |
| NAO+             | 27.2%    | 27.3%  | 27.2%  | 26.2%  |
| BLO+             | 33.5%    | 36%    | 33.4%  | 34.7%  |
| NAO−             | 34.3%    | 30.4%  | 33.6%  | 33%    |
| BLO−             | 5%       | 6%     | 5.8%   | 6%     |

FIGURE 8  Frequency (in percentages) of days leading to a given regime. For each category (e.g. transition to BLO+ for reanalysis), the total number of transitions is indicated above each bar. The BLO+ and BLO− days are shown in pink or pale red and purple while the NAO+ and NAO− days are in blue and green, respectively. Days with no clear provenance are shown in grey. The bars with black solid outlines indicate the reanalysis values, while the other bars indicate the forecast values at day 11, day 16, day 21 and day 31, respectively. Where the frequency is larger than 5% its value is indicated on the bar.

broadly consistent with the analysis, even at the extended range, indicating that the model biases cannot be the main hindrance for accurate forecasts of transitions.

4.2  Predictability of transitions

In this section we assess whether predictability varies systematically within the NAO–BLO space. We use the spread of ensemble forecasts to estimate the predictability. For a well-constructed ensemble prediction system, the ensemble spread is an indicator of forecast uncertainty and the rate at which the spread grows can be used as a predictability estimate. When the ensemble spread grows rapidly, the estimated forecast uncertainty increases rapidly with lead time, and the predictability is lower. Conversely, when the ensemble spread grows slowly, the estimated forecast uncertainty increases slowly with lead time, and the predictability is higher. Although predictability is not a forecast skill measure, it does provide an a priori estimator of the rate at which forecast skill is lost. Evidence that the ECMWF ensemble spread is a good indicator of the expected forecast error is given in fig. 8 of Ferranti et al. (2015).

The rate of change of ensemble variance is used as a measure of predictability and the ensemble mean is used to determine the position within the NAO–BLO space. Both the ensemble mean and the ensemble variance are calculated within the NAO–BLO space. Figure 9a shows the mean rate of change of the ensemble variance at about forecast day 6 for different regions of the NAO–BLO space; the change of variance is estimated using the difference between the ensemble variances at day 7 and day 5. In order to get higher definition on the predictability distribution we have divided the NAO–BLO space into nine regions (Figure 9a). For each ensemble, with the ensemble mean at day 6 lying within one of the predefined regions, the mean rate of change of the ensemble variance is calculated by averaging the change in ensemble variance between day 5 and day 7. At about forecast day 6 the variance is still sufficiently small for the ensemble to be contained within a local region. The trajectories of ensemble members diverge at different rates in different regions. The region of the NAO–BLO space associated with the largest rate of change of the ensemble variance corresponds to blocking. In contrast, NAO− is associated with
relatively small changes in the ensemble variance indicating higher predictability. We have checked that these results hold for lead times up to 10 days.

The ensemble spread variations associated with forecast trajectories crossing high/low predictability regions is illustrated by Figure 9b. Since the ensemble spread evolution, at a given forecast range, is affected by the whole preceding forecast trajectory, we use forecast day 3, rather than looking at longer lead times, to better identify the impact on the ensemble spread of entering a low/high predictability region. Figure 9b shows the mean ensemble variance as a function of lead time for four mutually exclusive subsamples of the forecast data. The green (blue) line shows the mean ensemble variance of all forecasts with the ensemble mean entering the NAO− (NAO+) region at day 3. The red (purple) line indicates the mean ensemble variance of all forecasts with the ensemble mean entering the BLO+ (BLO−) sector at day 3. After day 3, forecasts with the ensemble mean first entering the NAO− sector have a lower mean ensemble variance than those with the ensemble mean entering any other sectors. The differences between the mean ensemble variances could be associated with the fact that, by entering into a high predictability region, the forecast uncertainties increase at a much lower rate. An analogy for this would be the region close to the top of the wings (Palmer, 1993) of the Lorenz attractor (Lorenz, 1963), where the trajectories remain close to each other so that the spread is low and the predictability is high. The differences between the ensemble variances (Figure 9b) are particularly evident beyond 10 days. This is possibly related to the extended life cycle of NAO− events.

5 | CONDITIONAL SKILL

So far we have examined the forecast skill using the NAO–BLO phase space considering the entire reforecast sample. However, it has been shown that during the occurrence of low-frequency phenomena such as El Niño–Southern Oscillation (ENSO), Sudden Stratospheric Warming (SSW) and MJO, the Northern Hemisphere skill is enhanced, creating a so-called “window of opportunity” for the extended-range predictions (Moron et al., 2015; Robertson et al., 2015; Muñoz et al., 2016; Hannachi et al., 2017; Tripathi et al., 2015). The MJO is the most prominent mode of intraseasonal variability in the tropics (Madden and Julian, 1971). The MJO, through Rossby wave trains, conditions the occurrence of long-lasting circulation patterns over the Atlantic sector. In particular, a significant increase in the NAO amplitude happens about 10–15 days after the MJO-related convection anomaly reaches the tropical Indian Ocean (MJO phases 2–3) and the western Pacific region (MJO phases 6–7) (Cassou, 2008; Lin et al., 2009).

It is not surprising that the high level of predictability in the April 27, 2017 forecast (Figures 4c and 6) occurred during an MJO event (Figure 5). Although ENSO and the stratospheric polar vortex can also affect the occurrence of weather patterns such as the NAO (Baldwin and Dunkerton, 2001; Li and Lau, 2011; Scaife et al., 2014), we limit our analysis to the role of the MJO in modulating the forecast skill.

In this section, we examine the impact of the MJO on forecast skill in the context of the NAO–BLO phase space. Figure 10 shows the bivariate correlation for forecasts initiated with and without an MJO event. Forecasts initiated with an MJO event (red line) show higher skill between day 8 and day 15. Correlations are significantly different for day 11 and day 12 at a 90% confidence level and for day 10 and 13 at an 80% confidence level. The impact of the MJO on this deterministic skill measure appears at a relatively shorter range compared with the impact on the probabilistic skill discovered by Vitart and Molteni (2010).

Yadav and Straus (2017) and Lin and Brunet (2018) have discussed the non-symmetric nature of the MJO extratropical teleconnections. Lin and Brunet (2018) have shown that the NAO− response to phase 6 of the MJO (enhanced convection over the western Pacific) is much stronger than the NAO+ response to phase 2 of the MJO (enhanced convection over...
the Indian Ocean). Yadav and Straus (2017), by assessing the MJO extratropical response on the basis of its speed of propagation, found a dramatic increase in the frequency of occurrence of NAO− following phase 6 for the slow MJO episodes. In contrast, the authors found that modest changes in the NAO+ frequency were associated with the fast MJO episodes.

In light of these recent studies, we assess the impact of the MJO on the skill of NAO+ predictions separately from the skill of NAO− predictions. For this evaluation, we use probabilistic skill measures to evaluate the accuracy of the predicted probabilities and the forecast reliability. In particular, we use de-biased Brier skill scores (BSS) (Müller and Appenzeller, 2005) to take into account the relatively small ensemble size (11 members) of the ECMWF reforecast. In order to separate the NAO+ predictions from those of NAO− and disregard the cases with relatively small projections on EOF1, we consider two events as follows: the NAO+ event when P1 exceeds the 60th percentile of the climatological distributions (model and verification respectively) and the NAO− event when all P1 values are lower than the 40th percentile of the respective climatological distributions. The reference forecast is the climate. A positive value of BSS indicates a forecast that is better than climatology.

The impact of the MJO on the BSS for NAO+ (Figure 11a) is relatively small. In contrast, the forecasts with MJO in the initial conditions show a significantly higher skill in predicting NAO− up to day 18 (Figure 11b). The BSS can be decomposed (Murphy, 1973) into reliability and resolution components. The reliability, measuring how close the forecast probabilities are to the observed frequencies, is indeed
a necessary precondition for issuing useful probabilistic predictions. Figure 11b shows that the forecasts initiated with an MJO are significantly more reliable. This is consistent with the results of Vitart and Molteni (2010). The asymmetry in the impact of the MJO on the forecast skill is consistent with the asymmetry in the strength of the MJO teleconnections discussed by Lin and Brunet (2018) and Yadav and Straus (2017).

Despite the fact that the extratropical response to tropical forcing associated with a specific MJO phase typically manifests with a delay of between 10 and 15 days (Lin et al., 2009), the skill of the NAO predictions initiated with an MJO is higher already by day 3 (Figure 11b). When the MJO effect on the skill is stratified according to the MJO phases (Figure 12), it appears that, from day 8 to day 13, the greater impact is mainly associated with MJO phases 6–7. For longer lead times, up to day 20, the MJO phases 4–5 play a role. The improved skill at early lead times is mainly associated with forecasts initiated during the advanced phases of the MJO events, notably phases 4–5 and 6–7. This is not surprising, since for these forecasts the atmospheric initial conditions have already been conditioned by the tropical–extratropical links associated with the MJO initial phases.

Using the same approach, we have computed the impact of the MJO on the skill for predictions of blocking and anti-blocking (not shown). Although overall predictions initiated with an MJO event show slightly higher skill, the increase is relatively small and not significant.

6 | CONCLUSIONS

Reliable extended-range forecasts of flow patterns such as the NAO and blocking are instrumental for early warnings of severe cold events over Europe. At medium range, predictions for severe temperature conditions can be directly based on temperature forecast probabilities. At the extended range, we argue that the predictable signal for severe and persistent cold spells is better exploited by the use of large-scale circulation patterns. At the subseasonal time-scale, forecasts would not be expected to be able to predict day-to-day variability of the weather at individual grid points. By inferring the surface weather through large-scale flow patterns, we identify the spatial extension of temperature anomalies that are predictable. We have explored the use of a novel framework based on the NAO–BLO phase space to monitor and evaluate forecast performance in predicting transitions. The illustration of forecast trajectories in the NAO–BLO space has proven to be effective. ECMWF is planning to introduce such graphical displays as an additional tool for forecasters to better assess the likelihood of regime transitions and the occurrence of severe cold episodes.

We show that several S2S systems exhibit useful skill well beyond 10 days for predictions of NAO and blocking, indicating a strong potential for early warning of cold spells over Europe. Further assessment of the S2S systems focused on investigating the advantages and disadvantages of different ensemble configurations in predicting the onset of severe conditions is underway.
Looking at 35 years of daily reanalysis, we detect clear preferred paths in the time evolution of the NAO and BLO patterns. NAO+ favours transitions into blocking, while blocking (BLO+) is the most favourable condition for a transition into NAO−. This is consistent with the results of Croci-Maspoli et al. (2007), who showed that in the Euro-Atlantic sector blockings contribute significantly to the establishment of the NAO−. The ECMWF model accurately reproduces the observed preferential paths of blocking to NAO− transitions even at the extended range. On the other hand, beyond day 11, it is no longer able to distinguish NAO+ as the most favourable circulation for transitions into BLO+. The preferred transitions into BLO+ and into NAO− follow an anti-clockwise direction in the NAO–BLO space, corresponding to a cyclonic wave breaking progression. There is no clear preferred direction for transitions into NAO+ (westerly flow pattern), so both cyclonic and anti-cyclonic wave breaking are likely to occur. The ECMWF model representation for transition into NAO+ is accurate. The preferred transitions, detected in the NAO–BLO space, are in general agreement with those found by C. Grams (personal communication) while using a range of seven weather patterns for his recent work discussing how weather regimes can provide a meteorological explanation for multi-day fluctuations in Europe’s wind power (Grams et al., 2017). We conclude that the model biases cannot be a significant hindrance to successful forecasts of transitions.

Using the rate of change of ensemble variance as a measure of predictability, we show that the NAO− sector is a region with relatively high levels of inherent predictability, while the BLO+ is a region with low predictability. This is consistent with the results of Ferranti et al. (2015), who show that NAO− leads to the most skilful forecasts and the spread of the ensemble is generally small in forecasts initiated in the NAO− regime.

By assessing the MJO impact on forecast skill and looking separately at the NAO+ and NAO− cases, we find an asymmetry in performance. Forecasts initiated with an MJO event show higher skill and higher reliability in predicting NAO−. In contrast, the skill of NAO+ predictions is not significantly affected by the existence of an MJO event in the initial state. This asymmetry in the impact of the MJO on forecast skill is consistent with the asymmetry in the strength of the MJO teleconnections discussed by Lin and Brunet (2018) and Yadav and Straus (2017). The increase in NAO+ frequency is smaller than the increase in NAO− frequency following MJO events with large amplitudes.

Yadav and Straus (2017), by stratifying the extratropical MJO responses according to the MJO propagating speed, show a strong increase in NAO (positive and negative) occurrence following “slow” MJO episodes. While the NAO− response is dominated by “slow” MJO events, NAO+ stems from both “slow” and “fast” MJO events. As a consequence, the average increase in the NAO+ frequency is weaker than the average increase in that for NAO−. Lin and Brunet (2018), performing idealized simulations, showed that the extratropical response to MJO dipole heating is not linear (meaning that the extratropical response to MJO phases 6–7 is not the mirror image of the response to MJO phases 2–3) and it is dependent on the position of the westerly jet. The dynamics associated with the MJO response and its nonlinearity are complex and not completely understood. For example, as discussed by Garfinkel et al. (2012), the vertical and poleward propagation of Rossby waves excited by the MJO can modulate the stratospheric polar vortex which in turn can affect the tropospheric NAO. The skill of the blocking predictions is not highly sensitive to the existence of an MJO in the initial conditions; consistent with this, the blocking exhibits lower predictability than NAO−.

By assessing the skill of the S2S models, we conclude that subseasonal predictions present enormous potential to provide early warnings of severe cold events over Europe. Current models can already provide skilful predictions for some large-scale patterns 2 weeks ahead, and longer in certain cases. However, the success of forecasting weeks ahead changes in large-scale flow that lead to cold conditions depends on the type of transitions. The ECMWF ENS, beyond the medium range, is able to provide reliable probabilities of cold conditions associated with the establishment of Greenland blocking. In addition, the predictive skill of such events can be significantly enhanced by MJO activity via tropical–extratropical teleconnections. An example of such an event is the April 27, 2017 forecast discussed in section 3. On the other hand, forecasting probabilities at the extended range for the occurrence of cold events associated with blocking transitions might present a bigger challenge. Understanding these flow-dependent variations in forecast skill and using the new NAO–BLO phase space trajectories will enable users to exploit periods of enhanced extended-range predictability.

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