Supplementary Method

The weather regime paradigm: description and properties

Weather regimes are traditionally obtained using cluster analysis or classification methods\(^\text{31}\). Those organize pressure maps into nested sequences of clusters forming a growing tree association (hierarchical method), or iteratively perform the classification from predefined initial centroids randomly selected from the total sample, according to a given number of cluster \(k\) (partition method). Daily extended winter maps of geopotential height at the 500 hPa altitude (Z500) from the National Centers for Environmental Prediction-National Center for Atmospheric Research reanalysis\(^\text{32}\) (NCEP-NCAR) are used in this study over 1974-2007 from November 1\(^{\text{st}}\) to March 31\(^{\text{st}}\) leading to a total of 4991 days. 1974 is chosen as “first year” to match the satellite-data period for Outgoing Longwave Radiation (OLR) further analysed in the course of the paper. The geographical domain is limited to 90\(^{\circ}\)W-30\(^{\circ}\)E/20\(^{\circ}\)N-80\(^{\circ}\)N (hereafter referred to as NAE for North Atlantic-Europe) and a cosine weight as a function of latitude is applied to the data. Here we use the \(k\)-means algorithm\(^\text{11}\) that iteratively finds the partition that minimizes the ratio of the variance within clusters to the variance between clusters centroids. The decomposition is done in the Empirical Orthogonal Functions (EOFs) phase space span by the first 14 EOFs and principal components retaining 90% of the total Z500 daily variance.

Weather regimes should be understood as “envelops” for daily variability and would correspond to the preferred circulation patterns produced by the interaction between planetary-scale and synoptic-scale waves. Their spatial (basin-wide) characteristics and their temporal (persistence) characteristics are such that, citing Molteni et al (2006)\(^\text{10}\), “weather regimes or flow regimes should be regarded as statistical-dynamical equilibria, which are defined by averaging the dynamical tendencies on a timescale longer than the typical period of baroclinic transients”. Decomposition in weather regimes could thus be interpreted as an efficient spatio-temporal filter of the turbulent North Atlantic circulation.

Standard reproducibility and classifiability tests have been performed to objectively define \(k\) and to assess the robustness and the consistency of the partition presented in this paper. We have verified that temporal sub-samplings or the use of the full 1948-2007 NCEP-NCAR reanalysis dataset do not change both the spatial structure of the regimes and the optimal partition that is equal to \(k = 4\) in our case (Fig.1, main paper). We have performed the same analysis using European Center for Medium range Weather Forecast ERA40 reanalysis over 1958-2001 and found no significant differences. Our decomposition is robust and perfectly matches the ones described in literature\(^\text{3}\).

In the present study, each winter day is classified into one of the four regimes based on its closest distance (Euclidian in our case) to the centroid. We have verified that our conclusions are insensitive to the type of distance used for aggregation. Note that since each day is identified with a regime, the entire variance of the daily Z500 field is retained through the
attribution procedure. The frequency of occurrence of the weather regimes (Fig.1, main paper) corresponds to the fraction of days spent in each regime during the cold season, and by construction, their sum is equal to 100%. A distinction should thus be made between the determination of the centroids based on EOFs used here to diminish the phase-space and speed up a long and consuming computation, and the second step of attribution done in the physical space where the full variance is conserved.

Considering the 5-month NDJFM period instead of the traditional DJF definition for winter has two main advantages. Statistically, clustering is known to be sensitive to sampling\textsuperscript{31}; adding two months into the pool of days to be classified reinforces the significance of the weather regime partition presented here. Physically, the 5-month definition fits the seasonal march of the MJO split into two seasons: “extended winter” from Nov. to March and “extended summer” from May to Sept\textsuperscript{15}. To test the relevance of this definition for the North Atlantic atmospheric daily dynamics, clustering was performed separately for DJF and for JJA to obtain winter and summer regimes\textsuperscript{33}, respectively. All calendar days are then projected onto this set of 8 regimes (4 for winter and 4 for summer) and are attributed to one of them based on the closest distance. We then count the number of days attributed to winter regimes versus summer regimes considering the 12 calendar months separately (Supplementary Fig. 1). As expected by construction, ~80% of D/J/F days fit in one of the 4 winter centroids. Results show that it is also definitively the case for March (about 75%) and for November (about 65%) to a lower extent though. The transition between summer and winter dynamics seems to occur in October and April for which about half of days are either closer to DJF or to JJA centroids. Supplementary Fig.1 confirms that all the five “extended winter” months behave rather similarly in terms of daily dynamics in the North Atlantic and could be treated together.

**Supplementary Figure 1**

![Supplementary Figure 1](image)

**Supplementary Figure 1**: Percentage of days attributed to one of the four winter regimes among the eight winter+summer centroids as a function of calendar months.

Despite some controversy about their existence\textsuperscript{34} and significance, as well as their number\textsuperscript{35}, it is now widely recognized that changes in the occurrence and intrinsic properties of the weather regimes may be an important issue for medium-range (weekly to monthly) to climate change forecasts (decadal to trend)\textsuperscript{9}. Their spatial-temporal characteristics are such that they appear to be promising candidates to optimally extract potential external forcings (e.g. tropical ocean\textsuperscript{36}, stratosphere, greenhouse gases\textsuperscript{37} etc.) on the extratropical atmosphere, thus allowing for higher potential predictability at midlatitudes.
Supplementary Discussion and Figures

1. Relationship between weather regimes and extremes

Links between regimes and mean conditions have been described from daily to decadal timescale. For instance, high pressure over Greenland (reinforced Icelandic Low) during NAO- (NAO+) leads to slackened and southward-shifted (reinforced and northward displaced) westerly winds affecting downstream temperature and precipitation over the entire Europe. The day-to-day weather fluctuations can be described in terms of temporal transition between regimes. The year-to-year (or longer timescales) climate fluctuations can be interpreted as changes in their frequency of occurrence. Here we investigate the relationships between extremes and regimes occurrence. There are various definitions for indices of extreme events (see for instance http://www.cru.uea.ac.uk/projects/stardex for the STARDEX FP5 EU project). In this paper, we adopt the method of exceeding threshold obtained from percentiles. The latter are computed for individual meteorological station and each winter calendar day over 1974-2007. Daily anomalies are first calculated. The 95\textsuperscript{th} percentiles (or 5\% chance of occurrence), referred hereafter to as "climatological thresholds" are then calculated from 5-day windows centred on each calendar day yielding a total sample size of 33yr x 5days = 155 for each day per station. To assess the changes in the probability of extreme cold and wet day occurrence as a function of the four regimes (Supplementary Fig.2), we build four new distributions by selecting the days where a given regime is excited. New percentages of days that exceed the climatological thresholds are computed for each individual station and for the four distributions and compare to the climatological 5\% probability of occurrence\textsuperscript{38}. Within such a framework, if the new percentage is 10\% for instance, it should be viewed as multiplying the likelihood for extreme warm days to happen by 2 (label bar of Supplementary Fig.2). Observed temperature and precipitation data are taken from the European Climate Assessment\textsuperscript{39} (ECA) dataset. In order to have temporal homogeneity over the 1974-2007 period, only stations which have less than 20\% of missing data are retained for plotting.

Supplementary Fig.2 shows that chances for extreme events to occur can be clearly related to the four weather regimes. In terms of temperature (left maps), NAO+ precludes any cold extremes over the entire Europe while NAO- regimes clearly favor cold outbreaks over a large northern domain. No significant changes in cold extremes can be tracked for AR, except over the Iberian Peninsula where their probability of occurrence is significantly increased. During SBL, cold events are favored in central Europe extending westward towards France. In terms of precipitation, NAO- increases chances of extreme rainfall events to occur over a large western Europe with values as strong as 3 to 4 over most of the Iberian Peninsula. By contrast, precipitation extreme events are favored for NAO+ regimes in northern Europe while they are less likely in the Mediterranean basin. BL also precludes extreme rainfall to occur over a large portion of Europe. In addition to large scale signals, regime decomposition also provides useful information about regional features especially for precipitation extremes. For instance, the influence of the Pyrenees is marked for NAO- (AR) in association with föehn conditions during southwesterly (northwesterly) flows responsible for dry weather downwind the mountain range. Note also the confined and pronounced increase for extreme rainfall along the Spanish Mediterranean coast during SBL associated with the dominant southeasterly circulation pumping moisture and heat from the Mediterranean Sea to coastal areas.
Based on the observed link between weather regimes and temperature/precipitation extremes, we suggest that the high predictive skill score based on the lagged MJO-NAO relationship presented subsequently in this paper could provide a reliable probabilistic view for chances of extreme events to occur over the entire European continent.

Supplementary Figure 2

**Supplementary Figure 2**: Relative changes for each individual regime in the frequency of extreme cold days (left maps) and wet days (right maps) defined by the 95th percentile for each station data from the ECA dataset. The value 1 means that the regime is not discriminative for extremes, while 0 shows that there is no chance of extreme to occur when the regime is excited, and 2 or 4 indicates that there is respectively double or quadruple chance of extreme to occur in association with the regime.
2. Relationship between MJO and North Atlantic weather regimes

2.1 Decomposition of the MJO in eight phases

The approach adopted here follows Wheeler and Hendon (2004)\(^\text{15}\) (hereafter WH04) results and recommendations. The Real-time Multivariate MJO Index (RMMI) is extracted from http://www.bom.gov.au/bmrc/clfor/cfstaff/matw/maprooom/RMM on a daily basis for the cold season (1\(^\text{st}\) Nov. 1974 to 31\(^\text{st}\) March 2007 i.e. 4991 days). As described previously, this seasonal definition for the MJO matches the one for North Atlantic atmospheric dynamics. Composites are built for daily OLR satellite raw data\(^\text{40}\) from NCEP and for the raw streamfunction at 300 hPa (PSI300) from NCEP-NCAR reanalysis\(^\text{32}\). Only strong cycles of the MJO (RMMI amplitude greater than 1) are retained for compositing in Fig.2 (main paper) and subsequently, corresponding to 67% of the total sampling. A clear advantage of WH04 method relies on the extraction of both the frequency and phase of the MJO pattern without the use of typical band pass filters while considering the entire globe from both a dynamical (large-scale circulation changes) and thermodynamical (convection etc.) perspective. This approach is thus very promising for operational forecasting issue at medium range.

Supplementary Fig.3 is similar to Fig.2 (main paper) but for the velocity potential at 300hPa (CHI300) traditionally used to describe large scale upper-level divergent/convergent flow associated with the MJO. During phases 2-4, anomalous upper-level convergence clearly occurs in the eastern part of the Pacific and western hemisphere in general when convection is reinforced in the Indian Ocean and over the Maritime Continent. Such a flow balance, but opposite in sign, is found for phases 6-8. CHI300 and PSI300 (Fig.2, main text) have the main advantage to capture the MJO dynamics along the course of its propagation, whereas OLR becomes nondescript when the convection moves outside the so-called Indo-Pacific warmpool (western hemisphere).
Supplementary Figure 3: Same as Fig.2 (main paper) but for Velocity Potential at 300hPa (CHI300, thick contours) instead of OLR. Contour interval is $3 \times 10^6$ starting at $\pm 6 \times 10^6$ s$^{-1}$. Positive (negative) CHI300 values or upper-level convergence (divergence) are in black (green). The streamfunction at 300 hPa (PSI300) is now in colour shade by contrast with Fig.2 (main paper). Bluer (redder) colours correspond to cyclonic (anticyclonic) circulation in the northern (southern) hemisphere. Unit is $1 \times 10^6$ s$^{-1}$. 

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2.2 Robustness of the MJO-NAE regimes relationship

In the present study, all extended winter days are put in one of four regimes by their nearest Euclidian distance in a multi-dimensional phase space. It is true though that some days will not actually project very well onto any of the four regimes. It is always a dilemma in clustering analyses to find a minimum threshold for similarity to aggregate or reject a given event. The difficulty comes from the fact that there is not a “good” one, those thresholds being multiple and often dependant on the specific target of the study (e.g. evaluation of extremes versus mean conditions etc.) and/or on the sensitivity of each scientist. Some consider the duration of the excited regime as crucial; the criterion in that case is “persistence”\(^3\). Others find the spatial correlation between the regime centroid and the anomalous daily Z500 circulation to be classified as a critical parameter.

Fig.3 is first reproduced with days whose spatial correlation between the regime centroid and the anomalous circulation is lower than 0.30, excluded (Supplementary Fig. 4a). Fig.3 (main paper) is then reproduced with transition days (persistence of the excited regime lower than 4 days excluded in the lagged MJO-NAE regimes analysis (Supplementary Fig. 4b). Those criteria lead to a reduction of sampling by 18% and 25% respectively. We show that the relationship between the MJO and NAE regimes described in the main text is largely preserved. The biggest difference can be found for the persistence criterion, especially for phase 1 of the MJO (Supplementary Fig. 4b). The NAO- enhanced occurrence passes the significance tests and is compensated by diminished AR excitation at longer lead-time. This difference is however marginal and justifies to “keep it simple” and to use the full sample in our subsequent analyses.

**Supplementary Figure 4**

*Supplementary Figure 4*: (a) Same as Fig.3 but with days whose spatial correlation with the regime centroid is lower than 0.30, removed.
Supplementary Figure 4: (b) Same as Fig.3 (main paper) but with transition days removed. Note that the Y-axis interval is 40% instead of 30% in Fig.3 and Supplementary Fig.3a. Higher changes, albeit less significant, are expected due to a larger diminution of the sample size.

2.3 Mechanisms for the MJO-NAO regimes connection.

Modern literature suggests that the NAO can be interpreted at intraseasonal timescale as the by-product of upper-level wave-breaking events over the North Atlantic. NAO+ (NAO-) is generally linked to anticyclonic (cyclonic) wave-breakings and the preconditioning for the sign of the breaking leading to one NAO phase or the other is shown to be asymmetrical. Precursors for NAO+ are found upstream in the eastern Pacific, while precursors for NAO- are more in-situ in the North Atlantic. Our findings are very much in line with these conclusions as shown by Fig.4 (main paper). In the present paper, we thus go one step further and provide evidence that the precursors for NAO phases described in the modern literature are linked to the phase of the MJO. In particular, we address two of the main prospective questions raised in Fedstein (2003): “what process excites the North Pacific wave train that precedes the onset of the positive phase of the NAO?”, and “What process organizes the North Atlantic transient eddies in such a manner so as to drive the NAO?”.

Figs. 3 and 4 show that NAO+ regimes are mostly favored about 10-12 days post to phase 3 of the MJO and are related with a quasi-stationary Rossby wave train stretching across the North American continent from the Pacific and propagating eastward. Supplementary Fig. 5a shows that phase 3 of the MJO is initially associated with a reinforced and southward shifted storm track in the eastern Pacific, considered as precursors for NAO+. This equatorward displacement of the North Pacific jet/storminess and its link with intraseasonal tropical dynamics has been extensively documented in literature following the traditional forced Rossby wave paradigm. Reinforced convection over Indonesia typically precedes above normal precipitation along the west coast of North America associated with the eastward penetration of the jet. In terms of geopotential, when the MJO is convectively active over the Indian Ocean and Indonesia, the central North Pacific is dominated by positive height (maximum core located around 35°N and 170°W) while northeastern latitudes (Gulf of Alaska...
and along the North American continent) are dominated by below normal values following a preferred arching path and a typical 10-15 day lag\textsuperscript{16,43}. This picture is pretty much consistent with phase 2 of the MJO (Fig. 2, main text); the displacement of the Pacific synoptic-scale storm-track activity in phase 3 (Supplementary Fig. 5a) could thus be interpreted as a lagged response to MJO kicks, initiated in phase 2 and further reinforced as the tropical heating moves eastward in phase 3.

**Supplementary Figure 5**

*Supplementary Figure 5*: Composites of anomalous kinetic energy estimated from 2-6 day band pass filtered wind to retain high frequency eddy activity, for (a) phase 3 and (b) phase 6 at lag 0. Shading interval is every 6 m\textsuperscript{2} s\textsuperscript{-2}. Thick black contours represent the mean climatological kinetic energy. Contour is every 6 m\textsuperscript{2} s\textsuperscript{-2} starting at 160 m\textsuperscript{2} s\textsuperscript{-2}.

Enhanced (diminished) convection dominates the far-western (central-eastern) part of the Pacific during phase 3 and the related anomalous upper-level divergent flow generates an anomalous Rossby wave vorticity source (RWS) in the subtropics consistent downstream with the eastward extension of the Pacific jet stream. RWS can be written\textsuperscript{27,44}

\[
RWS = -\nabla \cdot [\nabla (\xi + f)] - \nabla \cdot (\xi + f) \nabla \cdot \nabla = \text{ADV} + \text{STR}
\]

including contributions from both the advection of absolute vorticity (ADV) and vortex stretching (STR) by the divergent wind. ADV generally dominates in the subtropics and is considered as the main vector for tropical-extratropical connection\textsuperscript{18,26}, while STR is more pronounced on the northern flank of the subtropical jet and is mostly controlled by eddy activity. Supplementary Fig. 6a shows that, a few days post to MJO kicks of phase 3, subtropics (south of 30\degree N) are clearly dominated by enhanced ADV located in the western-central Pacific accompanying the eastward displacement of the convection. A sink for ADV is located along the North American coast while a wave-like pattern is found downstream along the North Atlantic jet stream. Additional results (not shown) suggest that the latter can be interpreted as the signature of pre-existing quasi-stationary wave activity initiated in phase 2 of the MJO, which appears to be reinforced in Phase 3 by enhanced convection and associated RWS in western Pacific. The Pacific sources/sinks fade away at greater lags for phase 3 (Supplementary Fig. 6c), while the midlatitude Atlantic signals remain intact with a slight eastward propagation though.
Supplementary Figure 6: Composites of anomalous ADV term computed at 300hPa for (ab) phase 3 and (cd) phase 6 averaged from lag 0 to +5 days (left panels) and from lag +6 to +12 days (right panels). Shading interval is every 0.25 $10^{-11}$ s$^{-1}$. Thick black contours represent the mean climatological jet (zonal wind at 300hPa). Contour is every 6 m s$^{-1}$ starting at 22 m s$^{-1}$. RWS terms have been computed using spherical harmonics retaining spatial structures higher than truncature 21 (about 3.8° lon/lat$^{2}$).

The interaction between the altered background flow and the synoptic storm activity tends to favor AWB leading in fine to NAO+ regimes (Fig.4b, main text). In this paper, AWB and CWB are crudely estimated by the sign of the meridional eddy momentum fluxes averaged over the entire North Atlantic storm-track (100°W-10°W/30°N-60°N, Supplementary Fig.5) following Rivière and Orlanski (2007)$^{22}$. Note that a larger domain compared to the latter paper is chosen here to better extract the mean statistical properties of the wave breakings that potentially occur over a broad region. This choice appears to be more relevant for climate studies as opposed to case events (Rivière, personal communication). Two band pass filters are used$^{22}$ (2-6 days for very high frequency eddies and 2-12 days for additional intermediate frequency eddies) and only days where strong wave breakings occur are retained for counting in Figure 4 (+/- 1 standard deviation of the eddy momentum flux index). Fig.4b confirms that both intermediate and high-frequency transient eddies breaking are important for NAO+ in agreement with Feldstein (2003)$^{23}$.

A different picture emerges for phase 6 of the MJO leading to NAO- favored occurrence after about 10-12 days. Supplementary Fig.5b shows that the Pacific storm-track is not altered in the vicinity of the North American coast. Slackened storminess is confined to the central
Pacific and no junction can be found between the North Atlantic and North Pacific jet streams. Enhanced eddy activity dominates the North Atlantic storm-track, especially along its polar flank stretching northeastward from the southern tip of Greenland towards Spitzberg. The southwest-northeast tilt is consistent with SBL circulations that are favored at short lag time during Phase 6 (Fig.3, main text). Storms are confined offshore during SBL regimes, skirt Europe and prematurely move to subpolar latitudes in the Greenland Sea. This further supports recent conclusions\(^{24,25,29}\) that NAO- events may arise from the influence of Scandinavian blocking events favored before their onset and acting as a preconditioning process. In that case, the tropical MJO forcing upon NAO- regimes would be indirect and viewed as one of the trigger of the preferred sequence NAO+ to SBL to NAO-. Such a sequence has been suggested by Vautard (1990)\(^3\) and a more basic computation of the transition between regimes in our classification over 1974-2007 confirms his result. We found that 41% of NAO+ regimes transit to SBL and that 36% of SBL go towards NAO-. Those two transitions are dominant, while the least likely are self-transitions for all the regimes. Our findings provide some evidence that a fraction of the so-called 30-50 day oscillation found in the North Atlantic dynamics\(^3\) could be related to MJO.

A more direct route connecting MJO to NAO- regimes can be suggested too, following the forced Rossby wave paradigm similarly to Phase 3/NAO+ relationship. The Rossby wave source is not located in the western tropical Pacific in Phase 6, but in the eastern tropical Pacific-westernmost tropical Atlantic following the eastward displacement of the MJO. Consistently with the anomalous divergent wind (Fig.4f, main text), enhanced northward advection of vorticity occurs off the Pacific Mexican coast and in the Caribbean basin to a lower extent, providing a Rossby wave source\(^27\) at the entrance of the North Atlantic jet together with enhanced momentum transport along its southern flank (Supplementary Fig.6b). Convergence clearly appears around 25\(^\circ\)S-30\(^\circ\)S and 60\(^\circ\)W-70\(^\circ\)W and provides evidence for reinforced local Hadley cell, following e.g. Tyrrell et al (1999)\(^{26}\) interpretations. This intensification favors the equatorward displacement and reinforcement\(^{44}\) of the subtropical jet consistent with a negative phase of the NAO. The strengthened descent branch of the localized Hadley cell is documented to be very important in the generation of Rossby waves at upper levels. The stretching term of RWS takes over at such latitudes as also found in our case post MJO phases (not shown).

Evidence for forced Rossby wave initiated in the eastern tropical Pacific and propagating northeastward towards Europe in response to anomalous upper-level divergence has been extensively illustrated in earlier studies\(^{17,28,45,46}\). All the ingredients seem to be present here to consider this process as a serious candidate for the MJO-NAO- link, in addition to the SBL preconditioning effect. The pair of cyclonic circulation anomalies straddling the equator at upper-levels prior to onset the signature of midlatitude anomalies is clear in Fig. 2 (main text). The location of the anomalous tropical divergence around 90\(^\circ\)W is documented to be optimal for tropical-North Atlantic connection (see Fig. 2b from Ambrizzi and Hoskins 1997\(^{45}\), or Fig.6 in Hoskins and Ambrizzi 1993\(^{28}\)). Finally, the perturbation of the local Hadley cell is very efficient to link tropical/extratropics dynamics\(^{44}\). That said, ADV values in phase 6 appear much weaker than in phase 3 and support the hypothesis that the direct tropical forcing for the former phase may be less efficient than for the latter, at least in terms of forced Rossby waves.

Forced Rossby waves should be interpreted as catalysts for the full development of NAO regimes involving a strong interaction with transient eddies via wave breaking. Fig.4d (main text) confirms the dominance of CWB prior to the maturation of NAO- events and after phase.
6 of the MJO, and highlights the primary role of very high-frequency storms versus intermediate-frequency transients by contrast to NAO+. For phase 6, the moisture reservoir located at the entrance of the North Atlantic storm track expanding from the tropical eastern Pacific and westernmost Atlantic is expected to favor explosive development of synoptic eddies at low-level and consequently to fuel CWB leading to NAO- regimes. Note that such a mechanism does not seem to be present for phase 3 and subsequent NAO+ regimes (Fig.4e). The amplification role played by synoptic eddies explains the reinforcement of anomalous ADV along the North Atlantic jet-stream about a week after the MJO and concomitant with the maturation of NAO- events (Supplementary Fig.6d). Subtropical ADV anomalies fade away with lags, while midlatitude cores develop in a standing way and are characterized by a clear southeast-northwest tilt consistently with dominant CWBs. The opposite is found for Phase 3 (supplementary Fig. 6ab) with a tendency for clock-wise rocking of the anomalous centers as a function of lag and in agreement with favored AWBs.

In summary, we have presented here a novel interpretation for the occurrence of the NAO regimes in response to MJO forcing. Based on lagged composites, we have shown that precursors for NAO events detailed in recent literature are in fact partly linked to specific MJO phases. The asymmetry of these precursors as a function of the NAO sign is shown to be consistent with the MJO forcing. Forced Rossby waves initiated in the tropics by MJO variability are viewed as adjustment of the mean background flow in the North Atlantic leading to either AWB or CWB. The latter is speculated to be also influenced by moisture anomalies controlled by the MJO and located in the subtropics, while the former is more altered by upper-level wave-train remotely initiated in the Pacific. The role of the transient eddies therefore appears primordial for the complete maturation of the NAO regimes in relation with the MJO phase. The NAO regimes can thus be interpreted as the consequence of a complex chain. For NAO-, it is even more difficult because of the possible concomitance of a direct (tropical-extratropical connection) and an indirect (properties of the extratropical dynamics) mechanism. If the latter was dominant, we think that the anomalous occurrences for NAO- during phases 6-7 of the MJO would be much less significant (they are as strong as for NAO+ during phases 3-4) because the preferred sequence NAO+ to SBL to NAO- is indeed present, but not overwhelming (as expected). Therefore a large body of the initial response to MJO phase 3 starting with NAO+ is lost with time. We thus believe that the strong anomalous occurrence for NAO- during phase 6-7 of the MJO “needs” the direct tropical-extratropical mechanism that could be interpreted a “young” forcing enhancing an “old” and evanescent signal. In any case, the two mechanisms should not be viewed as competing but more as complementary because of the time scale resonance between the eastward propagation of the MJO and the preferred sequence of the North Atlantic regimes.

Finally, we have reproduced the same analysis as for Fig.3 (main paper) but for summertime in order to assess the seasonality of the MJO-North Atlantic connection. May-September regimes are considered over 1974-2006 and combined to summer RMMI. We find that the summer North Atlantic regimes occurrence is only marginally altered by MJO variations whatever the regimes and lags considered. This further reinforces the primary role of the mean atmospheric state in general to act as a “door of connection” for efficiently exporting the signal from the tropics to the higher latitudes. Summertime jet-stream and storm track might be too weak and too northward displaced to sustain the MJO-North Atlantic regimes connection. In addition, the tropical forcing is mostly embedded in the zonal belt of the easterlies, which prevents the excitation of forced Rossby wave trains in both North Pacific and North Atlantic during summer.
3. A very simple statistical model for the sign prediction of the daily NAO regimes and the daily NAO index: a benchmark.

Predicting the temporal behavior of the NAO at medium-range lead times (week to month to season) has been a trendy challenge over the past decade or so. Here we construct a simple *generalized linear model* (GLM) based on the MJO-NAO relationship suggested by our analyses, to forecast the phase of the NAO regimes as a first step, and to forecast the NAO daily index as a second step. Results from this most simple statistical model could be treated as benchmarks for operational weather prediction centers.

In statistics, GLM is a generalization of ordinary least squares regression. The linear model is given by $Y=X\beta+\epsilon$ with $E(Y)=X\beta$. The expected value for GLM is simply $g(E(Y))=X\beta$, where $g$ is referred to as the link function. The latter thus provides the relationship between the linear predictors and the mean of the distribution function. The choice for the link function $g$ is somewhat arbitrary but should correspond to the statistical properties of the predicted variable.

Our first goal here is to forecast the sign of the NAO regimes. In other words, the “event” to be assessed is “Reg = NAO- or Reg = NAO+”. This event could be of greatest interest considering the relationship between weather regimes and occurrences of extreme shown in Supplementary Fig.2, or weather regimes and mean characteristics. We select the days where NAO regimes are excited and create a dichotomous variable $Y$ taking 0 for NAO- days with a probability $p$ of appearance and taking 1 for NAO+ days with a probability $1-p$ of appearance. The model is such that for each day, there is a set of explanatory variables $X$ or predictors (phases and amplitudes of the MJO in our case) that might inform the final probability for $Y$ (sign of the NAO regimes). $Y$, or response variable, is binomially distributed and the most commonly canonical link function used in that case for GLM is the so-called *logit* function given by:

$$\ln\left(\frac{p}{1-p}\right) = X\beta$$

GLMs with this setup are logistic regression models and allow predicting a discrete outcome (0 for NAO-, 1 for NAO+ in our case) from a set of variable that may be continuous, discrete, dichotomous or a mix of any of these, like in our case where we combine the 8 phases of the MJO and the amplitude for predictors.

The model skill is summarized in Supplementary Fig. 7 showing the percentage of correct forecasts for the sign of the NAO regimes, when they occur as a function of lags similarly to Fig.3 (main paper). Red stars correspond to the model skill when the entire period is used to build the GLM model while barplots provide an estimate of the model skill used in a cross-validation mode (1000 randomly sub samplings to assess the significance of the results with the learning period excluded from the forecast period). Consistently with the physical mechanism documented in the main paper, we find a steady increase of the model success as a function of lags with maximum values reached between 10 and 12 days, before a moderate decrease of the score for higher lead times. This further tends to reinforce the forcing nature of the MJO on the sign of the NAO regimes as detailed throughout the paper. At best, 70% of the NAO days are correctly predicted at lag +12 days which is considered as very significant and valuable at such a time scale. Persistence given by the green curve is beaten from lag +4.
A Wald test is used to test the statistical significance of each coefficient $\beta$ of the linear combination. We found that the $\beta$ values associated with phases 2-4 and phases 6-7 of the MJO are the most significant with p-values increasing with lags ($p>0.001$ for lags 9-13). Consistently, a slight increase in skill (~72% at lag+12 days) is obtained when non-significant phases are excluded in GLM predictors (backward elimination, orange square in Supplementary Fig.7). Interestingly, the $\beta$ coefficient associated with the amplitude of the MJO is marginally significant ($p=0.05$) and tends to show that the amplitude, at least the one estimated like in WH04\textsuperscript{15}, is not a crucial exploratory variable for the sign of the NAO regimes in this very crude forecast model. Consistently, eliminating it in GLM does not degrade significantly the skill score (blue dot at lag +12 days).

Supplementary Figure 7

Supplementary Figure 7: Percentage among a total of 3150 days of correct prediction of the sign of the NAO regimes as a function of lags based on the GLM model built from the MJO-NAO connection detailed in the main paper. Red stars (blue dot) correspond to the skill of the model when both phases and amplitude (only phases) of the MJO are used in the statistical model as predictors. Barplots show the model performance in a cross-validation mode. The orange square shows GLM skill at lead-time +12 days when only phases that pass the Wald test are retained as predictors (backward elimination). Green triangles stand for persistence. The level of significance at 99% is assessed through Monte Carlo test (1000 random resampling).

As a first crude attempt, the prediction of the daily NAO index (NAOI) is now estimated based on the linear regression model (LM in the following). All days are now considered and not only the days where the NAO regimes were excited like previously. The daily NAO index is extracted from http://www.cpc.noaa.gov/products/ and the reader is invited to refer to this website for its definition and computation. Similarly to the NAO regimes, we find a steady increase of the skill score between the LM predicted values and observed ones (not shown).
Supplementary Fig. 8 summarizes our findings and further highlights the simplicity and the limitations of the model. Observed values are plotted against predicted ones that tend to be aligned around 8 values because of the discrete nature of the predictors (phases of the MJO) used in the model. By construction, LM tends to predict the mean value of the NAO index for each MJO phase. Adding the amplitude as additional predictor in the model introduces a slight departure to these mean values but do not add more in terms of skill for NAOI as already envisioned from NAO regimes. Because of the discrete properties of the forecast, traditional verification strategies cannot be fully applied in our context, except in terms of table of contingency and basic correlation between predicted and observed values, even if the latter score, traditionally interpreted as potential predictability, should be considered here with great caution.

Maximum skill is reached at lag +12 days with a probability of predicting the correct sign equal to 0.60 and a correlation equal to 0.24 over the full 1974-2007 period. 0.60 corresponds to the sum of occurrences in upper-right and lower-left quadrants in Supplementary Fig.8. For comparison to operational weather forecast models, we computed the skill score of LM over 2000-2005 (1974-1999 treated as the learning period). Considering all days, the hit rate for correct sign climbs to 0.63 corresponding to a correlation equal to 0.30 for lags greater than +9 days. This value is comparable to the state-of-the-art dynamical models used in operational forecast, even if caution is required about this strict comparison because the predicted NAO index is a continuous variable in numerical weather prediction (NWP) systems, but quasi-discrete in our case.

**Supplementary Figure 8**

![Supplementary Figure 8](image-url)

**Supplementary Figure 8:** Predict NAOI index (X-axis) by LM versus observed NAOI at 12-day lead-time with (without) amplitude+phase (phases only) used as predictors in red (blue). The percentage of occurrence is given for each quadrant. Successes (failures) are highlighted in green (orange). The dashed horizontal lines represent the upper and lower terciles of observed NAOI.
The daily NAOI is now subdivided into three equiprobable categories or terciles following traditional approaches in seasonal forecasting. The probability of being in the upper tercile given that the observation is in the upper tercile (NAOI > 0.54) is first investigated based on GLM. Values less than the upper tercile are converted to 0 while values that exceed the upper tercile are set to 1. A conditional probability equal to 0.46 is obtained using GLM and appears to be a substantial improvement compared to the expected 0.33. A weaker score (0.38) is found for the lower tercile (NAOI < -0.37). As a final step, days that belong to lower and upper terciles are treated together assigning 0s and 1s respectively, while days that belong to the medium tercile are discarded. This computation aims at comparing the previous score obtained from regimes (Supplementary Fig. 7), to the one using operational NAOI considering the fact that 71% of days when NAO regimes are excited, fit in one of the two terciles. Note though that a strict comparison is biased because NAO- and NAO+ regimes are not equally distributed (Fig.1, main text). The probability of predicting the correct NAOI sign in that case is equal to 0.67 compared to 0.70 for regimes.

Our results are consistent with values estimated from simple Gaussian climate models used to understand and measure the skill of seasonal forecast systems. Because of the extreme simplicity of GLM, we thus suggest that its prediction skill may be treated as “benchmarks to beat” for the next generation NWP models. We are convinced that a correct representation of the MJO-NAO relationship in models would contribute to a significant step forward in medium-range to seasonal forecasts. The rapid loss of information of the initial MJO conditions in NWP is speculated to partly explain the poor quality of the present extratropical forecast. Statistical models seem to perform better in this regard and a combination between NWP and those models could be very much of use to produce at least a qualitative forecast. The poor representation of tropical-extratropical connections because of mean state errors in NWP (position and strength of jets and related stationary waves activities, strength and feedbacks of synoptic-scale storms etc) is also expected to be a limiting factor.
Supplementary Notes


