Coupling between Greenland blocking and the North Atlantic Oscillation pattern

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1] Through the adoption of a bidimensional blocking index based on geopotential height, it is shown that the blocking frequency over Greenland is not only a key element in describing the North Atlantic Oscillation (NAO) index, but it also operates as an essential element in modulating its pattern. When Greenland blocking is lower than average, the first Empirical Orthogonal Function (EOF) of the 500 hPa geopotential height over the Euro-Atlantic region no longer resembles the NAO. Moreover, the typical trimodal variability observed in the Atlantic eddy-driven jet stream is reduced to a bimodal variability. Consistent with this result, we link the eastward displacement of the NAO pattern observed in recent years to the decreasing frequency of Greenland Blocking. Considering the large bias seen in the simulated blocking frequency in climate models, such strong coupling might have important consequences in the analysis of the NAO in climate simulations. Citation: Davini, P., C. Cagnazzo, R. Neale, and J. Tribbia (2012), Coupling between Greenland blocking and the North Atlantic Oscillation pattern, Geophys. Res. Lett., 39, L14701, doi:10.1029/2012GL052315.

1. Introduction

[2] The North Atlantic Oscillation (NAO) is a major regional pattern of wintertime variability in the Northern Hemisphere. The NAO index describes a dipolar oscillation in surface pressure between the subtropical high-pressure and the mid-latitude low-pressure in the North Atlantic [Hurrell, 1995].

[3] Traditionally, the NAO index has been measured as the pressure difference between the Azores (or Portugal) and Iceland [Walker and Bliss, 1932]. More recently, following the concept of teleconnection patterns, it has been defined as the Principal Component (PC) time series of the leading Empirical Orthogonal Functions (EOF) in Euro-Atlantic sector mean sea level pressure [Wallace and Gutzler, 1981].

[4] Observations show a recent positive trend in the wintertime NAO index, especially through the 1980s and 1990s [Hurrell, 1995]. Furthermore, the NAO pattern as represented by different method (e.g., rotated and non-rotated EOFs analysis, regression analysis, etc.) shows an eastward displacement [e.g., Hilmer and Jung, 2000; Jung et al., 2003]. Other studies investigate the origin of this migration [e.g., Luo and Gong, 2006].

[5] The origin of the NAO remains a widely debated question. Recent studies have reconnected the origin of the NAO to Rossby Wave Breaking (RWB) events, defined as the reversal of the potential temperature gradient measured at the tropopause level [McIntyre and Palmer, 1983]. They argued that the NAO phase is modulated by a succession of cyclonic and anticyclonic RWB events [Benedict et al., 2004; Strong and Magnusdottir, 2008]. Other studies have investigated the links between the NAO and blocking activity [e.g., Croci-Maspoli et al., 2007]. Blocking is defined as a persistent (more than 5 days) anticyclonic high-pressure system, diverting or blocking the migratory cyclones [Rex, 1950] and tightly coupled with RWB events [Pelly and Hoskins, 2003; Berrisford et al., 2007]. Woollings et al. [2008] showed that blocking events and its associated Rossby-Wave Breaking events over Greenland are strongly anticorrelated with the NAO index. They suggested that the NAO may be arising from the succession of blocked and non-blocked days.

[6] The NAO phase has also been connected with displacements of the tropospheric jet stream. Woollings et al. [2010] observed a trimodal variability of the low-level jet stream and showed that the southward displacements of the jet stream are tightly coupled with the occurrence of blocking over Greenland and to the NAO. P. Davini et al. (European Blocking and Atlantic Jet Stream Variability in the NCEP/NCAR Reanalysis and the CMCC climate model, submitted to Journal of Climate, 2012) noted that blocking occurring on the equatorward side of the jet are linked to the northward displacements of the jet.

[7] The purpose of this work is to try to bridge the gap between the statistical interpretation of the North Atlantic Oscillation (i.e., EOF and teleconnectivity maps) and the actual atmospheric and physical phenomena occurring over the Euro-Atlantic sector. Therefore, we aim to determine the relevant physical events influencing the North Atlantic Oscillation. Specifically we will address the role of blocking over Greenland in influencing the NAO phase and pattern using data from the NCEP/NCAR Reanalysis.

2. Data and Method

[8] In this study Northern Hemisphere data from the NCEP/NCAR Reanalysis [Kalnay et al., 1996] have been analyzed for the winter (DJF) season from 1951 to 2005. Data presented here use a horizontal resolution of 2.5° × 2.5°. In order to detect atmospheric blocking a bidimensional
blocking index based on daily geopotential height measured at 500 hPa is used [Tibaldi and Molteni, 1990; Scherrer et al., 2006]. For every grid point of coordinates \((\lambda_0, \Phi_0)\) we define:

\[
GHGS(\lambda_0, \Phi_0) = \frac{Z500(\lambda_0, \Phi_0) - Z500(\lambda_0, \Phi_S)}{\Phi_0 - \Phi_S},
\]

(1)

\[
GHGN(\lambda_0, \Phi_0) = \frac{Z500(\lambda_0, \Phi_N) - Z500(\lambda_0, \Phi_0)}{\Phi_N - \Phi_0}
\]

(2)

where \(\Phi_0\) ranges from 30°N to 75°N and \(\lambda_0\) ranges from 0° to 360°. \(\Phi_S = \Phi_0 - 15°, \Phi_N = \Phi_0 + 15°\). Therefore an Instantaneous Blocking (IB) is identified if:

\[
GHGS(\lambda_0, \Phi_0) > 0 \quad \text{and} \quad GHGN(\lambda_0, \Phi_0) < -10 \text{ m}/\text{lat}.
\]

(3)

In order to ensure that spatial and temporal scales are significant to detect a blocking event, some constraints have been applied to the Instantaneous Blocking previously defined: an IB must be extended for at least 15° of continuous longitude. Finally, a Blocking Event is defined when blocking is occurring within a box of 10° lon \(\times\) 5° lat around that point for at least 5 days. This method allows the computation of single event duration as well as the average values of duration of the Blocking Events for each grid point. The index is described in Davini et al. [2012].

[10] The Jet latitude index (JLI) is used as a measure of the variability in the position of the Atlantic eddy-driven jet stream, following the approach of Woollings et al. [2010]. The JLI describes the daily low-level variability of the tropospheric winds over the Atlantic basin, and it is defined as the latitude where the maximum of the zonally averaged zonal wind between 60°W and 0° is located. Values are averaged between 925 and 700 hPa and a 5-day running mean is applied.

[11] Finally, in order to define the NAO and the main teleconnection pattern over the Euro-Atlantic sector the Empirical Orthogonal Functions (EOFs) of the monthly mean Z500 over the Atlantic sector (90°W–40°E, 20°–85°N) are computed. The leading EOF is defined as the NAO, while the second EOF describes the Eastern-Atlantic pattern (EA) [Wallace and Gutzler, 1981]. The associated PC describes each EOF time series.

3. Greenland Blocking and NAO Coupling

[12] In order to investigate the impact of the Greenland Blocking on the NAO patterns, we define the “Greenland Region” as a box placed between 70°–20°W and 62.5°–72.5°N, centered on the climatological blocking frequency relative maximum over Greenland. For each day, if at least a single grid point in the box is blocked, the whole sector is considered blocked. In this way, a daily binary time series can be defined and compared with the NAO index. From this time series a large and significant anticorrelation (−0.7 on monthly basis) emerges, which is in agreement with Woollings et al. [2008].

[13] After computing the total number of blocking days from the daily blocking index for each DJF season, we split the database into three different categories according to the index terciles. We define “High Greenland Blocking” years (HGB, blocked days over Greenland >30 days, 18/55 years), “Low-Greenland Blocking” years (LGB, blocked days <15 days, 16/55 years) and “Neutral Greenland Blocking” years (NGB, when the blocking frequency is in between the two thresholds). For convenience, the case in which no selection is been applied (i.e., the whole data set) has been defined as “Original Greenland Blocking” (OGB). Since results for the NGB and OGB category are very similar for every analysis here performed, we decided to report the OGB case only.

[14] The blocking climatology and the main Euro-Atlantic EOFs are again computed according to the subset defined as OGB, HGB and LGB. Results are shown in Figure 1. The first column shows the EOF and blocking for the OGB case (DJF 1951–2005). The North Atlantic Oscillation and the East-Atlantic pattern are clearly evident in the upper and lower panels (contours), while the blocking frequency (shading) shows the canonical blocking pattern [Scherrer et al., 2006; Davini et al., 2012].

Figure 1. Linear regression patterns on Z500 monthly anomalies for the (top) first and (bottom) second EOF for the 3 different categories of GB frequency. Red contours show positive values, blue contours the negative ones. Blocking frequency, expressed as percentage of blocked days, is shown by the gray scale.
The second column reports the patterns for the HGB case. As expected the blocking frequency is almost doubled over Greenland. Moreover, blocking frequency is also higher at all high latitudes suggesting a strong linkage in wave breaking activity on the poleward side of the jet. The pattern of the first EOF is pretty similar to the OGB case, but it shows a westward shifted shape, with smaller zonal extensions especially for its positive center of action. The EA pattern is remarkably similar to the one of the original case.

The EOFs of the LGB case reveal a very different NAO-blocking relationship. In particular the first EOF pattern is no longer NAO-like. Such pattern broadly corresponds to the EA pattern shown in the OGB case, but some significant differences are present (larger global teleconnectivity, tripolar anomalies and northward displacement). Interestingly, a “NAO-like” pattern is detectable in the second EOF, even though it is notably north-eastward shifted, weaker and no longer linked to the occurrence of Greenland Blocking (monthly correlation coefficient between NAO and GB is ~0.07). Therefore, in the absence of Greenland Blocking, the NAO-like pattern associated to the zonal variability is no longer the dominant mode of regional variability over the Euro-Atlantic.

Obviously, the stratified sampling of the data set performed in order to compute the subset is by construction affecting the EOF-based NAO patterns. It is important to point out that, if the NAO is defined as the one present in the OGB case, the HGB case represents years with negative NAO index while the LGB case represents years with positive NAO phase. This is due to the strong anticorrelation present between the NAO and GB.

It is useful to highlight how this approach shares some features with the one used in Croci-Maspoli et al. [2007]. They excluded from their data set the days when blocking is occurring over the Euro-Atlantic sector (80°W–60°E, 20°N–80°N) and then they performed an EOF analysis. They found that the first two EOFs were switched, with the EA pattern explaining more variance. Consequently, they linked the blocking occurrence to the NAO. Our approach provides further information on the localization of this blocking-NAO dependence, suggesting that without GB blocking the NAO is no longer the first EOF.

Adopting the JLI, Woollings et al. [2010] showed the presence of a strong link between NAO, GB and jet displacements. We apply the same methodology in order to shed light on the connection between the EOF-related statistical variability and the dynamical variability of the jet stream. We especially aim at investigating the behaviour of the Atlantic jet stream under the anomalous EOF1 present in the LGB case. The JLI PDF for the three Greenland blocking categories (OGB, HGB and LGB) during the different phases of the NAO and EA is hereafter analyzed. The positive and negative phases have been defined as the days exceeding the positive and negative terciles of the PC time series of each EOF (with a 5-day persistence criteria). The JLI PDFs for the three categories are reported in Figure 2. It shows that the variability of the Atlantic jet is lead by a trimodal PDF in latitude (black line). The NAO phase distinguishes between the central peak and the equatorward-displaced peak (blue and green lines), while the EA variability distinguishes between the central peak and the poleward displacement of the jet (orange and red dashed lines). This analysis is consistent with Woollings et al. [2010], in which they showed that both leading EOFs are needed to completely describe the jet variability.

The JLI PDF for the HGB case is shown in the central panel of Figure 2. This confirms the link between the negative phase of the NAO and the southern latitudinal position of the jet stream, as pointed out by many studies [e.g., Woollings et al., 2010]. Increased GB frequency is associated with increased equatorward displacements of the jet. On the other hand, the JLI variability related to the EOF2 (i.e., EA) is similar to the OGB case, here again distinguishing from the central peak and poleward displaced peak.

The LGB case (Figure 2, bottom) shows that with few Greenland Blocking events the equatorward displacements completely disappear. Interestingly, the first and the second EOF both describe the variability between the neutral state of the jet and the poleward displaced ones. This implies that without Greenland Blocking the variability over
the Euro-Atlantic is no longer trimodal, but it is limited to a bimodal pattern. Importantly, this more limited mode of variability precludes the existence of a zonal NAO-like pattern (Figure 1, right).

4. Eastward Shift of the NAO

[22] In comparing the EOF1 pattern of the HGB case and the OGB case it is possible to notice that in the latter both the centers of action are shifted eastward with respect to the HGB case. Moreover, the zonal extension of the positive center of action of the OGB case is wider and extends into Western Europe. We speculate that the eastward shift of the NAO pattern is connected with the reduction of the Greenland Blocking frequency.

[23] In order to confirm this hypothesis, we created 35 subsets of 20 years each from the yearly time series of GB (covering the 55 years), characterized by decreasing values of the average yearly GB frequency. The subset with the highest average GB frequency has been created choosing the 20 years with the highest GB frequency in the whole data set. We created the other subsets in the following way: first, we removed the highest-frequency GB year from the previous subset. Hence, we added the highest-frequency GB year that was not part of the previous subset in order to still have 20 years in the new subset. This was repeated 34 times in order to span the whole 55 years.

[24] For each subset we performed an EOF analysis and we identified the location of the minimum and maximum of the linear regression of EOF1. Therefore we were able to detect the geographical shift of the center of action of the NAO as a function of the GB frequency.

[25] In the upper panel of Figure 3 it is clearly evident that with progressively higher GB frequency the NAO shifts to the West, especially for its negative center of action that becomes centered over the Labrador Sea (similar to the HGB case). When the GB frequency is reduced, the negative center of action shifts to the East, reaching Iceland and hence moving to the South. The overall Eastward shift is about 30°.

[26] The movement in the positive center of action is more complex. With high values of GB, it is placed approximately over the Azores. With decreasing values, it is subjected to a small westward displacement but its position remains almost stationary over the Central Atlantic. When a threshold value is reached (about 20 blocked days) it abruptly moves to Central Europe. At this stage, EOF1 is no longer representing a zonal mode of variability, but rather a teleconnection pattern more similar to the classical EA.

[27] Consequently, we argue that the EOF-based North Atlantic Oscillation may be interpreted as the statistical result of the succession of different GB events, and that its pattern and intensity are primarily linked to the frequency of the GB itself. If GB events are more frequent, the incidences of an equatorward-displaced jet are also more frequent and hence the main mode of variability over the Euro-Atlantic sector is mainly associated with the GB occurrence. Alternatively, when the GB frequency decreases, other phenomena become more relevant in determining the NAO pattern and sign.

Figure 3. (top) EOF1 centers of action shift in function of the GB frequency. Circles represent the position of the negative center of action, diamonds the position of the positive one. See text for details. (bottom) GB yearly frequency measured as number of blocked days (black line) and its 5-year running mean (red line). The blue line is the 5-year running mean of the yearly averaged NAO index.
[28] A logical consequence of this geographical dependence of the NAO pattern to the occurrence of the Greenland blocking may be an explanation of the observed eastward shift during the 1980s and the 1990s. Figure 3 (bottom) shows the Greenland Blocking yearly frequency, its 5-year running mean and the 5-year running mean of the NAO index. Even though blocking is a very noisy and variable field, it is evident that GB has reached a minimum during the 1980s and 1990s. Since the reduction of the GB frequency leads to an eastward shifted NAO, the variability in the GB activity observed in the NCEP/NCAR Reanalysis suggests that this eastward shift of the NAO is very likely related to the GB variability.

5. Concluding Remarks

[29] In this work, the connection and the coupling between the North Atlantic Oscillation and the occurrence of Greenland Blocking have been analyzed in 55 years (1951–2005) during the DJF season of the NCEP/NCAR Reanalysis. Starting from the anticorrelation observed between the NAO phase and the GB, we analyzed the relationship between the GB occurrence and the NAO pattern, showing that in years with high GB frequency (i.e., negative NAO index) the NAO signal is strengthened and shifted westward. Additionally, we showed that with low GB frequency (i.e., positive NAO index), the first EOF of the Euro-Atlantic sector no longer represents a zonal mode of variability and is more similar to the East-Atlantic pattern.

[30] Furthermore, we reconcile these findings with the Atlantic jet stream displacements. With a high frequency of GB, the increasing number of observed southward jet displacements suggests that the NAO, canonically defined as a zonal mode of variability, is strongly linked to the GB occurrence and its associated jet displacements. Conversely, if the number of GB days is smaller than average, the southward displacement of the jet no longer exists. We were finally able to relate the variability of the NAO pattern and its recent eastward shift with the changes of the Greenland blocking frequency.

[31] Similar results are obtained studying the NAO pattern variability following the teleconnectivity approach defined by Wallace and Gutzler [1981] (not shown).

[32] This GB-dependent interpretation of the North Atlantic Oscillation, suggested by Woollings et al. [2008], is in agreement with studies that connect the NAO to the occurrence of cyclonic and anticyclonic wave breaking [e.g., Benedict et al., 2004]. Due to the strong similarities between the RWB and the blocking [Pelly and Hoskins, 2003] and the predominance of cyclonic wave breaking over Greenland [Davini et al., 2012], our interpretation is also consistent with the NAO-RWB mechanism. Therefore we conclude that the Greenland blocking (and the associated Rossby Wave Breaking and southward displacement of the jet) is the primary physical mechanism leading to the North Atlantic Oscillation.

[33] Indeed, since the EOF defines the main mode of variability over the defined sector, we speculate that the NAO is obtained by the combination of GB and the blocking on the equatorward side of the jet. This area, characterized by blocking and associated anticyclonic RWB, extends from the Azores up to Scandinavia and it is associated with poleward displacements of the jet stream (Davini et al., submitted manuscript, 2012). In the HGB case, GB is able to explain the majority of the variance of the low frequency Z500 field. Therefore, the pattern of the first EOF is very similar to the pattern of anomalies associated with GB days [Woollings et al., 2008; Davini et al., 2012]. As the GB frequency decreases, GB is no longer dominating the Euro-Atlantic variability, and therefore loses its “centrality” in the EOF1-NAO pattern. The EOF1 pattern appears zonally elongated and it is subjected to an eastward shift because it is also affected by the blocking at the equatorward side of the jet. Finally, if GB events almost disappear, the variability of the jet is then only linked to the blocking on the equatorward side of the jet. It is then assumed that the new NAO pattern takes the shape of the northward-eastward displaced anomalies as the EOF2 does in the LGB case. This suggests that the NAO pattern is obtained by the combination of GB and by the equatorward RWB, but with different weights.

[34] The dynamical mechanism behind the change in the blocking frequency and the consequent shift of the NAO patterns is an important topic, but it is beyond the scope of this study. Our analysis supports the interpretation of Luo and Gong [2006] that argued that NAO eastward shift in the 1980s and 1990s is linked to a stronger zonal mean flow over the Atlantic. Indeed, we found larger values of the jet speed (measured via the JLI) for the LGB case than for HGB case (not shown).

[35] To summarize, caution should be used when studying the NAO via EOF analysis as it may lead to misleading results, especially in climate models. Many models [e.g., Gillett et al., 2003] show a shifted first EOF pattern and significant bias in blocking activity [Scaife et al., 2010]. Therefore, we argue that a biased blocking representation in climate models, especially over Greenland, can totally offset the pattern of the North Atlantic Oscillation and lead to the analysis of a mode of variability which is fundamentally different from the one observed in the Reanalysis.

[36] It may be more physically relevant to return to the original definition of the NAO, based on the difference of measured SLP between Iceland and Azores. This definition will probably provide less information than a full EOF approach, but it will be more focused on the effective climate variability due to the changes in the RWB and blocking activity between high and low latitudes.

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