The north atlantic oscillation : mechanisms and spatio-temporal variability

C. Cassou

THE NORTH ATLANTIC OSCILLATION :
MECHANISMS AND SPATIO-TEMPORAL VARIABILITY

Christophe Cassou
Cerfacs-CNRS, 42 Av. G. Coriolis, 31057 Toulouse Cedex 1
Email: cassou@cerfacs.fr

Abstract

Over the middle and high latitudes of the northern hemisphere, the most prominent mode of atmospheric variability is the North Atlantic Oscillation (NAO). The spatio-temporal characteristics of the NAO variability are reviewed in this lecture. The general state of knowledge on the complex dynamical processes governing the NAO is described. Emphasis is laid on teleconnections and ocean signals known to modulate the temporal excitation of the NAO.

Introduction

The NAO commonly refers to swings in the atmospheric pressure difference between the Arctic and the subtropical Atlantic. The seesaw pattern is clearly pronounced during the boreal winter season and is associated with changes in the mean wind speed and direction as well as in the number of storms, their intensity, their preferred paths and their associated weather over the neighbouring continents. Significant anomalies in ocean surface temperature and heat content, ocean currents and related heat transport, ocean deep convection and sea ice cover in subarctic seas etc., are also linked to a great extent to the NAO.

The NAO across time scales

The NAO is one of the oldest known weather patterns as some of the earliest descriptions of it were from seafaring Scandinavians several centuries ago (Stephenson et al 2003). There is no single way to define the NAO. The simplest one often referred to as "NAO index" has been proposed by Walker and Bliss (1932) and recently updated by Rogers (1984) and Hurrell (1995) among others; it is calculated as the difference in normalized mean sea level pressure (SLP) between Azores (or Portugal) and Iceland thus capturing the north-south redistribution of atmospheric mass between the two main centres of action in the North Atlantic sector. Most studies of the NAO focus on the boreal winter, when the atmosphere is most active dynamically and perturbations grow to their largest amplitude. In the so-called positive phase, higher-than-normal surface pressures south of 55^{o}N combine with deeper Iceland Low to enhance the climatological meridional pressure gradient leading to stronger-than-average surface westerlies across the middle latitudes and enhanced penetration of the mild and moist oceanic influence towards most of Europe. During NAO+, northward shifted storm track leads to cooler and drier conditions over the Mediterranean basin.

A disadvantage of station-based indices is that they are fixed in space. They do not account for the seasonal migration of the NAO centres of action and they are polluted by transient meteorological phenomena not related to the NAO, especially in summertime and autumn. An alternative approach is Empirical Orthogonal Function (EOF) analysis (Hurrell et al 2003); the NAO is often identified as the leading eigenvector computed from the time variations of gridpoint values of SLP or some other climate variables (geopotentiel, zonal wind etc.). The associated principal component is used to evaluate the temporal evolution of the NAO. While EOFs clearly capture the spatial and large-scale coherence of the NAO pattern, a well known shortcoming stands however in the linear constraints of the method ; EOFs assumes preferred atmospheric circulation states come in pairs in which anomalies of opposite polarity have the same spatial structure. A solution among others to overcome this simplification is to use classification techniques or clustering, which seek for recurrent patterns of a specific amplitude and sign. Objective analyses based on these methods are often used to identify number, spatial structure and frequency of occurrence of recurrent anomalous circulations referred to as "weather regimes". Travelling pressure systems or storms contribute to a significant fraction of the daily to interannual variability of the extratropical climate. Those are linked to the unstable nature of the upper-level westerly jet stream and interact with circulation patterns of large scale, or "weather regimes", in which they are embedded. Those regimes can be interpreted as quasi-stationary atmospheric circulations during which the character of the synoptic storms is unusually persistent (Reinhold and Pierrehumbert 1982). They are recurrent, spatially well defined and limited in number and ideally correspond to statistical-dynamical equilibria in the climate phase space. Over the North Atlantic-European (NAE) domain when applied to daily atmospheric circulation fields, they traditionally leads to four regimes (Vautard 1990). The two first regimes can be viewed as the negative and positive phases of the NAO (Fig.1). The third regime is named Atlantic Ridge and the fourth is often referred to as Scandinavian Blocking.

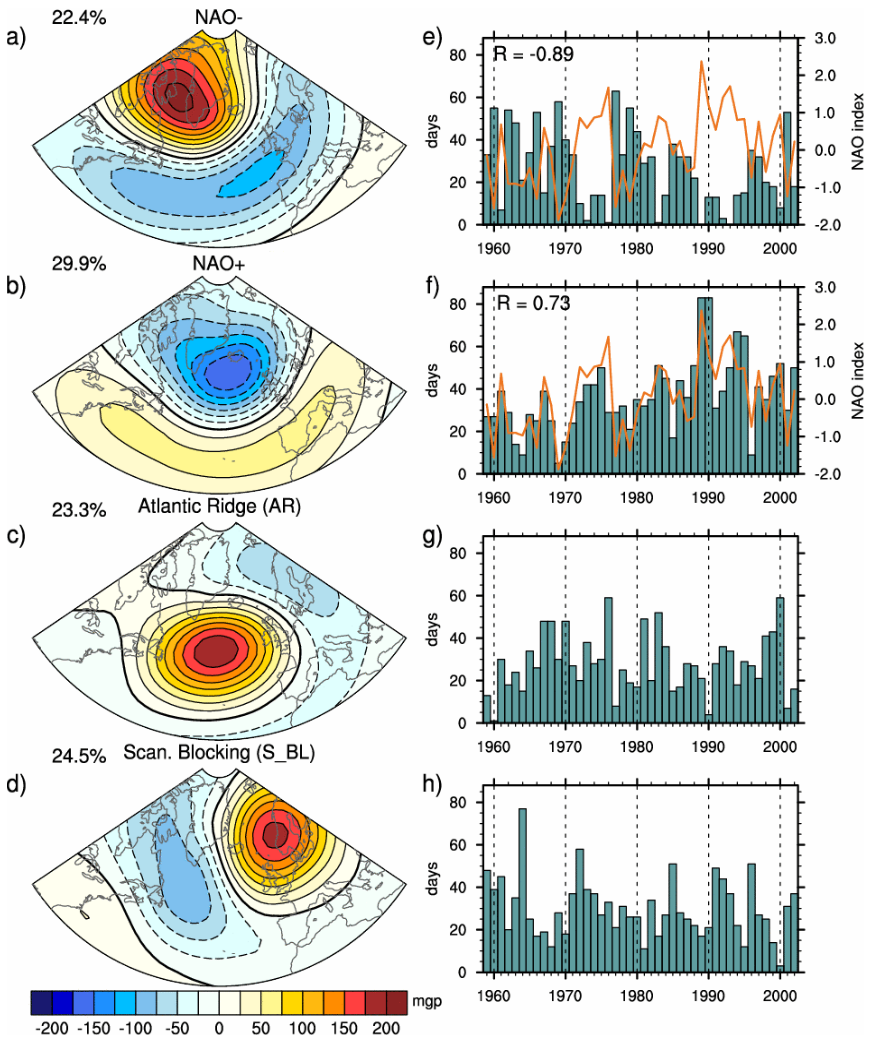

Figure 1: (a-d) Centroids of the four wintertime NAE Z500 weather regimes (m). Each percentage represents the mean frequency occurrence of the regime computed over 1958-2002 from 1 December to 31 March. Contour intervals are 25m. (e-h) Number of days of occurrence of each regime per winter from 1959 to 2002. The NAO index (orange curve) is superimposed on the upper two panels corresponding to the NAO regimes. Correlation (R) between the NAO index and the frequency of occurrence of the NAO regimes is provided. From Cassou et al. (2010).

The day-to-day meteorological fluctuations can be described in terms of temporal transition between regimes. The year-to-year (or longer timescale) climate fluctuations can be interpreted as changes in their frequency of occurrence provided the hypothesis of long term quasi-stationarity climate. This climate-oriented interpretation for weather regimes is shared with the so-called continuum paradigm elaborated for instance in Franske and Feldstein (2005) to better understand the low-frequency fluctuations of the northern hemisphere atmospheric teleconnections patterns. The NAO- and NAO+ regimes interannual occurrence (Fig.1ef) is strongly correlated to the traditional NAO index above discussed. Note however that spatial asymmetry between the two phases are clearly evidenced in winter by clustering techniques. Similar conclusions can de drawn for summertime.

Links between flow regimes and mean conditions over Europe have been documented from daily to decadal timescale as well as for weather (Cassou et al 2005) and climate extremes (Yiou et al 2007). 10-meter wind and air temperature composites derived from regime occurrence are also indicative of strong relationships between daily large-scale atmospheric circulation and ocean surface over the entire Atlantic basin. Evidence has been provided that a large fraction of the low frequency trends in the Atlantic observed at the surface over the last 50 years in winter can be tracked back to changes in the occurrence of weather regimes and their tropical counterpart (Fig. 2, Cassou et al 2010).

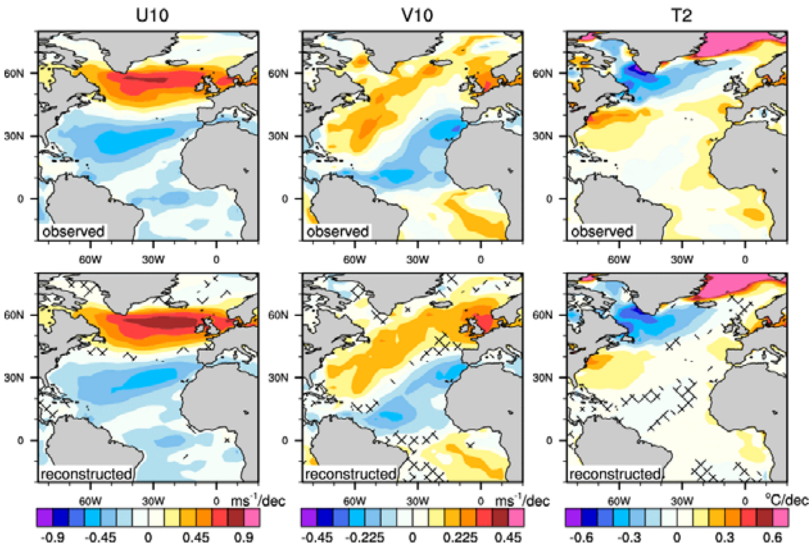

Figure 2: Linear trends computed over 1959-2002 for wintertime (a-c) ERA40 10-meter zonal (U10) and meridional (V10) wind and 2-meter temperature (T2) and for (d-f) reconstructed fields from multiple linear regression using NAE weather regime occurrences and tropical wind classes as predictors. Hashing stands for sign disagreement between observed and reconstructed trends. Contour intervals are 0.15 ms-1/decade, 0.075 ms^{-1}/decade for UV10 and V10 respectively, and 0.1^{o}C for T2. From Cassou et al. (2010).

Large-scale atmospheric circulation tendency are characterized by an intensification of the midlatitude westerlies and a concomitant strengthening of the Northeast trades. Northward displaced storm track is associated with prevalent southerlies north of 40^{o}N. The node for the wind trend corresponds to the mean position of the Azores High and is consistent with the positive trend in the NAO (Fig.1 and Hurrell et al 2003). Note that updated data until 2010 suggest though that the upward trend towards NAO+ enhanced occurrence is somehow reduced in the 2000's. The largest low-frequency changes for 2-meter temperature occur in the western part of the basin and strongly project on the North Atlantic tripole known to be forced by NAO dynamics (Deser and Timlin 1997).

The NAO governing processes

That the spatial pattern of the NAO remains largely the same throughout the year does not imply that it also tends to persist in the same phase for long. To the contrary, it is highly variable tending to change its phase from one week to the next, from one month to another, and its longer term behaviour clearly reflects the combined effect of residence time in any given phase and its amplitude therein. There is little evidence for the NAO to vary on any preferred time scale. The spectrum of the winter-mean NAO index reveals somewhat enhanced variance at quasi-biennial periods, a deficit of power at 3 to 6 year periods and slightly enhanced power in the 8-10 year band, but no significant peaks (Hurrell et al 2003). Note that those statistical characteristics are not stationary throughout the observed period.

It is now well recognized that the NAO type of variability arises from processes internal to the atmosphere in which various scales of motion interact with one another to produce quasi-random (and thus quasi unpredictable) variations. The variability of the extratropical flow can be divided into two broad classes: jet meandering, in which the latitude of the local zonal wind speed maximum in the upper troposphere exhibits pronounced north-south shifts; and jet pulsation, in which the local windspeed maximum exhibits marked strengthening and weakening without shifting latitude. Variability in the Atlantic zonal flow is characterized by both mechanisms because the subtropical jet is relatively weak and the baroclinic eddies tend to organize themselves in the poleward baroclinic zone ; the latter is particularly pronounced in the Atlantic due to the sharp meridional sea surface temperature (SST) gradient along the Gulf Stream/Labrador current, hence driving a purely eddy-driven jet. The NAO is thus associated with anomalous fluxes of zonal momentum of baroclinic waves across ~45^{o}N and fluctuates on preferred timescales of ~10 days resembling a first-order Markov process (Feldstein 2000). Positive feedbacks between the zonal flow and the eddies, as well as interactions with the stationary waves, play a key role in setting the basin-wide shape of the NAO.

An emerging view for explaining the jet variation and its link to the NAO has been recently proposed based on wave-breaking theory (e.g. Benedict et al 2004, Woollings et al 2010). Synoptic wave-breaking on the equatorward side of the jet tends to be anticyclonic, following the ambient background shear. This leads to poleward eddy fluxes of zonal momentum that act to push the jet to the North and to set NAO+ regimes. Similarly, cyclonic wave-breaking dominates on the poleward side of the jet and the associated momentum fluxes push it to the south and tend to excite NAO- regimes.

Finally, the coupling between the lower stratosphere and the troposphere could also play an active role in setting the phase and persistence of the NAO. Large amplitude anomalies in the strength of the zonal flow along ~60^{o}N frequently seem to originate in the stratosphere and descend into the troposphere. The downward propagating stratospheric circulation anomalies appear to modulate relatively high frequency tropospheric variability for period up to ~60 days following the initiation of the stratospheric signal. A stronger stratospheric polar vortex more frequently leads to NAO+ like anomalies and vice-versa, thus exerting a downward control on surface climate. Even if controversial, the annular shape of the stratospheric mode supports the view that the NAO could be the regional expression of a larger scale hemispheric mode of variability known as the Arctic Oscillation (Thompson et al 2003).

The NAO modulation by external factors

Progress in understanding low frequency variability and predictability of the midlatitude atmospheric circulation relies on the identification of specific causes responsible for the favoured occurrence of the associated weather regimes, their persistence and/or transition. In other words, which factors external to pure atmospheric dynamics at the origin of the NAO could modulate its strength and phase?

At intraseasonal timescale, recent studies (e.g. Cassou 2008) suggest that the main climate oscillation in the tropics –the Madden-Julian Oscillation (MJO)- controls part of the distribution and sequences of the four NAE winter weather regimes (Fig.1). The NAO regimes are the most affected. NAO+ events mostly respond to a midlatitude low frequency wave train initiated by the MJO in the western-central Pacific and propagating eastward. Precursors for NAO- are found in the eastern tropical Pacific-western Atlantic leading to changes along the North Atlantic Storm-track. Wave breaking diagnostics tend to support the MJO preconditioning and the role of the transient eddies in setting the phase of the NAO. These findings reconcile the oscillatory paradigm of the MJO with the episodic view of the North Atlantic dynamics via the regime approach and open some perspectives in terms of medium range predictability.

From seasonal to decadal timescale, evidence is provided that the ocean plays an active role in determining the evolution of the NAO (e.g. Hurrell et al 2003 for a review). While intrinsic atmospheric variability exhibits temporal incoherence, the ocean tends to respond to it with marked persistence of heat content anomalies that feedback to the local atmosphere. The level of retroaction of the anomalous extratropical SST upon the NAO is however under debate and is likely very dependent on the time scale. Adding to the complexity of local ocean-atmosphere interaction is the possibility of remote forcing of the NAO from the tropical oceans; the latter influence appears to be more robust. Several studies have concluded that NAO variability is closely tied to SST variations over the tropical Atlantic. Those involve changes in the meridional SST gradient across the equator, which affect the strength and location of the tropical convection along the Inter Tropical Convergence Zone, and thus ultimately the North Atlantic midlatitude circulation via the excitation of Rossby waves propagating northeastward from the anomalous diabatic heating source. At decadal timescale, the warming of the Indo-Pacific warmpool from the mid-1970's onwards could be responsible for part of the positive trend of the NAO at the end of the XXth century. At interannual timescale, the impact of El Niño Southern Oscillation (ENSO) on the NAO remains open to debate. The correlation between the two indices is not significant and the relationships might be asymmetrical; La Niña events seems to favour NAO+ phases while El Niño events might not induce systematic remote responses. In addition, the ENSO-NAO link might be indirect via the ENSO impact on tropical North Atlantic SSTs or via the ENSO influence on the stratospheric vortex as suggested by the latest literature (e.g Bell et al 2009).

One of most urgent challenge is to advance our understanding of the interaction between greenhouse gases forcing and the NAO. The response might be felt as a change in the residence frequency of the NAO+ regimes with respect to NAO- ones, leading to a weak positive trend according to the most recent results. However, the locations of both regimes in the NAO phase space may be also altered in warmer climate, moving towards more positive values of the NAO index; in that context, the background change thus contributes to the trend.

References

Bell C.J., Gray L.J., Charlton-Perez A.J., Joshi M.M. and Scaife A.A. (2009): Stratospheric communication of ENSO teleconnections to European Winter, *J. Clim*., **22**, 4083-4096.

Benedict J.J., S. Lee and S.B. Feldstein (2004): Synoptic view of the North Atlantic Oscillation. *J. Atmos. Sci.*, **61**, 121-144.

Cassou, C. L. Terray and A.S. Phillips (2005): Tropical Atlantic influence on European heat waves. *J. Clim.* , **18**, 2805-2811.

Cassou C. (2008) : Intraseasonal interaction between the Madden and Julian Oscillation and the North Atlantic Oscillation. *Nature*, **455**, doi:10.1038/nature07286

Cassou, C., M. Minvielle, L. Terray and C. Périgaud (2010). A statistical-dynamical scheme for reconstructing ocean forcing in the Atlantic. Part I: weather regimes as predictors for ocean surface variables. *Clim. Dyn*, doi:10.1007/s00382-010-0781-7.

Deser C. and M.S. Timlin (1997) Atmosphere-ocean interaction on weekly timescales in the North Atlantic and Pacific. *J. Clim*., **22**, 396-413

Franske C. and S.B. Feldstein (2005): The continuum and dynamics of the northern hemisphere teleconnection patterns. *J. Atmos. Sci*., **62**, 3250-3267.

Feldstein S.B. (2000): The time-scale, power spectra and climate noise properties of teleconnections patterns. *J. Clim*., **13**, 4430-4440.

Hurrell W. J. (1995): Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science*, **269**, 676-679.

Hurrell W.J., Kushnir Y., Otterson G. and M. Visbeck (2003): An overview of the North Atlantic Oscillation. *AGU Geophys. Mono*, **134**, doi:10.1029/134GM01.

Reinhold B. and R. Pierrehumbert (1982):Dynamics of weather regimes: quasi-stationary waves and blocking. Mon. Wea. Rev., 110, 1105-1145.

Rogers J.C. (1984): The association between the North Atlantic Oscillation and the Southern Oscillation in the northern hemisphere. *Mon. Wea. Rev.*, **112**, 1999-2015.

Stephenson D.B., Wanner H., Brönnimann S. and J. Luterbacher (2003): The history of scientific research on the North Atlantic Oscillation. *AGU Geophys. Mono*, **134**, doi:10.1029/134GM02.

Thompson D.W, S. Lee and M.P. Baldwin (2003): Atmospheric processes governing the Northern Hemisphere Annular Mode/North Atlantic Oscillation. *AGU Geophys. Mono*, **134**, doi:10.1029/134GM05.

Vautard R. (1990): Multiple weather regimes over the North Atlantic analysis of precursors and processors. Mon. Wea. Rev., 118, 2056-2081.

Walker G.T. and E.W. Bliss (1932): World weather V, *Mem. Roy. Met. Soc*., **4**, 53-84.

Woollings T., A. Hannachi, B. Hoskins and A. Turner (2010): A regime view of the North Atlantic Oscillation and its response to anthropogenic forcing. *J. Clim*., **23**, doi:10.1175/2009JCLI3087.1

Yiou, P., R. Vautard, P. Naveau and C. Cassou (2007): Inconsistency between atmospheric dynamics and temperatures during the exceptional 2006-2007 fall/winter and recent warming in Europe. *Geophys. Res. Lett*., **34**, doi:10.1029/2007GL031981.