

# Modes of Variability affecting southwestern Europe

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## Introduction

Atmospheric variations may result from external forcing, but also naturally from internal interactions between components of the climate system. A closer inspection of the spatial structure of the atmospheric variability, in particular on seasonal and longer time-scales, shows that it occurs predominantly in preferred large-scale and geographically anchored spatial patterns, known as teleconnection patterns (TP). TP can vary in intensity and position at seasonal, interannual and decadal time scales (Wallace and Gutzler, 1981; Trenberth et al., 1998; Quadrelli and Wallace, 2004). They are regional in nature and shaped by wave processes, reflecting zonal mean anomalies and connections via other components of the climate system, especially the ocean (Liu and Alexander, 2007). Thus, TP are related to circulation types (Casado et al., 2008) and have an impact on other atmospheric surface variables such as temperature and precipitation.

Southwestern Europe, where the Iberian Peninsula is located, is mainly under the influence of the subtropical Azores high pressure system. This subtropical anticyclone exhibits meridional displacements along the seasonal cycle, inducing changes in the mean climatic conditions of this area.

The most important TP affecting the southwestern Europe is the North Atlantic Oscillation (NAO; Trigo et al., 2002), which is associated with changes in the meridional gradient between the subpolar and subtropical pressure systems. NAO explains a large part of the precipitation variability over Europe, mainly in winter, in such a way that positive phases of this oscillation are associated with an increase of precipitation over northern Europe and a decrease towards the south-western European continent. NAO also affects temperature, winds and other variables impacting climate and society. Apart from NAO, other TP affecting Europe are the East Atlantic/Western Russia (EA/WR), East Atlantic (EA) and Scandinavian (SCAND)

patterns (García-Herrera and Barriopedro, 2017).

The atmosphere responds to other components of the climate system through excited Rossby waves and localized eddy-mean flow interactions, which can both result in regional teleconnection patterns (Liu and Alexander, 2007). Due to the large heat capacity of water when compared to the atmosphere, ocean subsurface can store energy for several months and release it later as latent and sensible heat fluxes which, in turn, can alter the global circulation of the atmosphere, triggering in this way, teleconnections. Sea surface temperature (SST) variability is used as a measure of the associated oceanic energy to be released. This is the basis of seasonal to decadal predictability (s2d). In particular, El Niño is the leading natural variability mode at global scale, determining most of the year-to-year global climate variability, including its impact on southwestern Europe (Brönnimann et al., 2007). Its Atlantic counterpart, with similar dynamics, is the Atlantic Niño, which is the main source of SST variability in the Tropical Atlantic at interannual time scales (Polo et al., 2008). Both, Atlantic and Pacific Niños are very much linked and cannot be considered as independent modes of variability (Rodríguez-Fonseca et al., 2009; Martín-Rey et al., 2014; Martín-Rey et al., 2015; Polo et al., 2015). Also, Tropical North Atlantic (TNA) variability cannot be isolated from ENSO (García-Serrano et al., 2017) and has a significant influence on the atmospheric circulation of the Atlantic-European sector and in particular in the Iberian Peninsula in both early winter and spring (Rodríguez-Fonseca et al., 2006).

Climate models are generally able to simulate the gross features of many of the modes of variability, and to provide useful tools for understanding how they might change in the future (Müller and Roeckner, 2008; Handorf and Dethloff, 2009). The most recent IPCC report includes a

chapter devoted to the analysis of climate phenomena, in particular the main modes of variability, and their relationship with current and future regional climate (IPCC, AR5, Christensen et al., 2013).

In the former CLIVAR-Spain assessment, Rodríguez-Fonseca and Rodríguez-Puebla (2010) discussed the studies about atmospheric teleconnection patterns affecting the Iberian Peninsula, including possible predictability, with special emphasis in the NAO, and analyzing interactions with the ocean. Since then, a great progress has been made on the development of applications on subseasonal to decadal forecasts (s2s and s2d, Vitart et al., 2012). The availability of results from the Climate system Historical Forecasting Project (CHFP; Tompkins et al., 2017) and the Coupled Model Intercomparison Project (CMIP5), together with very active investigations in both operational and research communities, have improved and will continue to enhance our abilities to make skillful predictions and projections in the region. The present review collects most of the works dealing with TP affecting the Euro-Mediterranean region done from 2010, with special attention to internal vs. forced variability, predictability at different timescales and future projections.

#### **Patterns affecting Southwestern Europe atmospheric variability and potential precursors**

New studies have been done in the last years relating NAO with winter precipitation, winds and temperature, including extremes over the western Mediterranean region (Vicente-Serrano et al., 2009; Lorenzo et al., 2008; Jerez et al., 2013; Casanueva et al., 2014; Vicente-Serrano et al., 2009; Lorenzo et al., 2008). Also during this season, recent studies have found how positive phases of the NAO could act as precursors of explosive cyclones affecting Europe (Gómara et al., 2014).

Apart from NAO, recent studies point to combinations with other TP, as SCAND and EA, to explain climate variability in the region (Comas-Bru and MacDermott, 2014). From a more regional perspective, patterns such as the Mediterranean Oscillation (MO) and the Western Mediterranean Oscillation (WeMO) (Martin Vide and López-Bustins, 2006; Vicente-Serrano et al., 2009; Lana et al., 2016) are also important in the description of the atmospheric variability of the southwestern Europe. Together with the NAO, the westerly index (Barriopedro et al., 2014), a measure of the frequency of westerly winds over the English Channel, have been found to explain the drought variability across Europe (Vicente-Serrano et al. 2016).

In seasons other than winter, the NAO presents a less zonal structure due to the weakening of the extratropical jet, and other TP may be more influential on European climate (García-Herrera and Barriopedro, 2017). For example, during autumn, global atmospheric patterns

project better on an EA-like pattern, whose structure and associated impacts depend on the background mean flow, therefore experiencing low-frequency oscillations. Thus, its annular structure has been active in the most recent decades, while a wave-4 pattern was dominant in the decades before (King et al., 2017). As compared to the winter NAO, the leading mode of variability in high-summer (July-August), also known as the summer NAO, is more regional and shifted northwards. Different to the winter NAO, its largest impacts over the Iberian Peninsula are detected, although weak, in maximum temperatures (Favà et al., 2016).

There is a clear non-stationary relationship between the winter NAO and European precipitation (Hertig et al., 2015). Several hypotheses have been formulated to explain this non-stationarity, including modifications in the meridional pressure gradient (Zveryaev, 2006), North Atlantic air-sea dynamics and variability in the Atlantic Meridional Overturning Circulation (AMOC) (Walter and Graf, 2002; Gómara et al., 2016), solar activity (Gimeno et al., 2003) and variability in the NAO pressure centers (Haylock et al., 2007; Vicente-Serrano and Lopez-Moreno, 2008).

In winter, the NAO is also modulated by ENSO, whose teleconnections over Europe might involve both a tropospheric pathway and a stratospheric one (Butler et al., 2014). The persistence of the wintertime ENSO signal in the stratosphere and air-sea interactions in the North Atlantic allow the winter ENSO signal to persist until the following spring (Herceg-Bullick et al., 2017). In this season, although El Niño influence on the North Atlantic has been related to a negative phase of the NAO (Brönnimann et al., 2007; Vicente Serrano et al., 2008; García-Serrano et al., 2011), this influence has been found to be non-stationary on time, depending on the slowly variant background of the ocean (Greatbach et al., 2004; Zanchettin et al., 2008; López-Parages and Rodríguez-Fonseca, 2012; López-Parages et al., 2015; López-Parages et al., 2016; King et al., 2017). In this way, the state of multidecadal variability of the north Atlantic SST determines the effectiveness of ENSO teleconnection. Moreover, two ENSO flavours have been reported, referred to as Eastern Pacific (EP) and Central Pacific (CP), with different winter teleconnections over Europe (Calvo et al., 2017). Their influence on southwestern Europe has also changed with time, being the EP warm events during negative Atlantic Multidecadal Oscillation (AMO) periods the combination with the largest impacts on European rainfall (López-Parages et al., 2016). Also, the Tropical North Atlantic region (TNA) has a significant influence on the atmospheric circulation in the Atlantic-European sector and in particular in the Iberian Peninsula in early winter and spring, also in relation to ENSO (Frankignoul et al., 2003; Rodríguez-Fonseca et al., 2016; King et al., 2017).

The impact of the Atlantic Niño decaying phase is mainly determined by the climatological jet stream's position and intensity, showing an arching pattern over the North Atlantic region during summer–autumn, and a zonally oriented wave train during autumn–winter (García-Serrano, 2011). Nevertheless, summer Atlantic Niño presents different impacts on summer Mediterranean climate depending on the state of the rest of the tropical oceans (Losada et al., 2012). Mediterranean SST anomalies also influence the Northern Hemisphere atmospheric circulation (García-Serrano et al., 2013; Sahin et al., 2015) affecting late summer temperatures.

Finally, at decadal time scales, the AMO (Ortiz Bevia et al., 2016; Zampieri et al., 2017) has been found to influence the length of the summer in southern Europe (Peña-Ortiz et al., 2015) and weather regimes at Mediterranean region in summer. Also, a coupling between Indian and southern European summer rainfall has been found after the late 1970s (Lin et al., 2017).

In addition to the ocean, other predictors are being defined for the better assessment of TP. The stratosphere (Scaife, 2005; Palmeiro et al., 2017), the Madden Julian Oscillation (Cassou, 2008; Schwartz et al., 2017), Eurasian snow cover (Orsollini et al., 2016), and the Arctic sea-ice extension (García-Serrano et al., 2015) have been pointed out to be determinant for the correct assessment of predictability in the Euro-Atlantic sector at subseasonal timescales.

### **Predictions and Future Projections**

The evidence for potential seasonal predictions of the winter NAO has recently increased (Scaife et al., 2014; Athanasiadis et al., 2017), while a similar progress has not been achieved for other seasons or TP. Multiple studies have shown a potential for improved North Atlantic predictability at seasonal timescales based on two main predictors: ENSO and sudden stratospheric warming (SSW) events (Barriopedro and Calvo, 2014; Domeisen et al., 2015; Butler et al., 2016).

There are suggestions of extended skillful predictions of the NAO one year ahead with two sources of skill for the second-winter forecasts: the climate variability in the tropical Pacific region and the effect of solar forcing on the stratospheric polar vortex strength (Dunstone et al., 2016).

Multi-model decadal prediction exercises (Doblas-Reyes et al., 2013) have demonstrated the large potential for useful interannual-to-decadal prediction of European climate (Guemas et al., 2015; Lienert et al., 2017). The forecast information comes mainly from the warming trend in the case of temperature, but also from the AMO.

The Mediterranean is considered a 'hot spot' for climate change, due to the expected warming and drying of the

region. While thermodynamically-induced changes due to greenhouse gases (GHG) forcing are robust, there are considerable uncertainties in the future projections of atmospheric circulation and variables related with dynamical processes, e.g., precipitation (Shepherd, 2014), so that large ensemble simulations are essential to estimate the probabilistic distribution. Regarding future projections of TP, Gonzalez-Reviriego et al. (2014) have found a positive trend for the NAO and a negative trend for the SCAND pattern under future SRES A1B climate change scenario. This result is in line with recent multi-model studies of NAO (Gillett and Fyfe, 2013) showing a small positive response of boreal winter NAO indices to GHG forcing. NAO will continue to influence precipitation and temperature in coming decades (López-Moreno et al., 2011), with the positive winter NAO trend in the future potentially leading to an increase in the frequency of dry conditions in the Iberian Peninsula. Moreover, as the simulations indicate a steady increase in temperature (see Serrano and Camino, this issue), winters classified as "cold" in the 21st century will be noticeably rarer compared with recent decades.

Bladé et al. (2012a, 2012b) examined the future summer NAO trend in CMIP3 models. They found an overall positive trend, albeit with a large spread in magnitude, which accounts for a large fraction of the projected multi-model mean precipitation reduction in northwest Europe. These changes should also lead to modest precipitation increases in the Iberian Peninsula, where the observed correlation between the SNAO and summer precipitation is weakly positive, partially offsetting some of the thermodynamically-induced drying in the region. However, this effect is not captured by the CMIP3 models, because those models do not correctly represent the surface signatures of the summer NAO.

Climate regime shifts are projected under future scenarios including a strengthening and eastward extension of the North Atlantic storm track towards western Europe (Feng et al., 2014). The atmosphere-ocean coupling shapes distinct responses of Atlantic Niño under GHG forcing (Mohino and Losada, 2015) with uncertainties in ocean circulation changes accounting for much of the projected spread in storm tracks (Woollings et al., 2012).

Regional future projections indicate a generalized increase of heatwaves and drought severity in the region (Jacob et al., 2014; Vicente-Serrano et al., 2014). Despite this, Atmospheric Rivers (ARs), which trigger intense precipitation and floods over continental areas, are projected to transport an increased amount of vertically integrated water vapor, producing extreme precipitation along the Atlantic European Coasts from the Iberian Peninsula to Scandinavia (Ramos et al., 2016). In relation to explosive cyclones, although most of them occur north of southwestern European region, abrupt southward shifts of the NAO, modulated by changes in the AMOC,

could lead to more frequent events over the subtropical European regions (Gómara et al., 2016).

Similarly to the last decades, in the 21st century, multidecadal fluctuations of the oceans are expected to act as a switch for global teleconnections, enhancing predictability during certain decades (López-Parages et al., 2015). In this way, the decadal variability that will accompany the projected forced changes in the Mediterranean region should be considered in the development of future climate outlooks (Mariotti et al., 2015).

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