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Sergio M. Vicente-Serrano
Ricardo M. Trigo *Editors*

Hydrological, Socioeconomic and Ecological Impacts of the North Atlantic Oscillation in the Mediterranean Region

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Introduction

Sergio M. Vicente-Serrano and Ricardo M. Trigo

This book is a collection of the main contributions in a thematic workshop devoted to the hydrological, socioeconomic, and ecological impacts of the NAO in the Mediterranean area that was held in Zaragoza (Spain), in May 2010, in the framework of the European Science Foundation (ESF) Mediterranean Climate Variability and Predictability (MedCLIVAR) program (http://www.medclivar.eu/).

According to the latest IPCC report, the Mediterranean basin represents one of the most important "hot spots" of climate change in the world, with recent trends towards a hotter and drier climate being related to changes in atmospheric circulation patterns. Previous work has shown that the interannual variability of Mediterranean climate is mostly associated to changes in certain relevant atmospheric circulation patterns (Dünkeloh and Jacobeit, 2003; Zorita et al., 1992; Xoplaki et al., 2003, 2004; Pauling et al., 2006; Trigo et al., 2006). Such changes can have significant impacts in the climate of this region but also on the natural environment and several socioeconomic activities. Among these patterns, the North Atlantic Oscillation (NAO) is the only one which shows a clear signal throughout the whole year, although with stronger intensity and extension during winter due to the stronger meridional gradients (Lamb and Peppler, 1987; Hurrell et al., 2003). During this season changes in the NAO phase lead to shifts in the location of the centers of action and in the associated storm tracks (Trigo, 2006).

The NAO is responsible for most of the climatic variability in the North Atlantic, modifying direction and intensity of the westerlies, the track of the polar depressions and the location of the anticyclones (Hurrell, 1995; Wanner et al., 2001). During the positive phases, the Azores subtropical high is reinforced, leading to sunny and dry weather in the Mediterranean region (Trigo et al., 2002). On the contrary, during the negative winters, cyclones move southward increasing precipitation on the western Mediterranean (Hurrell and Van Loon, 1997; García-Herrera et al., 2001; Moses et al., 1987). Cloudiness, temperature and solar radiation are also highly modulated by the NAO index (Trigo et al., 2002).

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The NAO behavior is characterized by a remarkable interannual variability, which is evident in long instrumental (Jones et al., 1997) but equally in paleo records (Cook et al., 2002; Luterbacher et al., 2002). In the instrumental period, the NAO has shown important decadal variability and a decreasing trend between 1940 and 1970. Nevertheless, the most unusual period was observed between the 1970s and 1990s when the NAO showed an increasing tendency towards positive phases (Osborn et al., 1999), coincident with severe drought conditions in the Mediterranean (López-Moreno and Vicente-Serrano, 2008; Sousa et al., 2011) and a reinforced NAO influence on climate (Vicente-Serrano and López-Moreno, 2008a). High variability has been recorded during the first decade of the twenty-first century, including extreme seasonal values of the NAO index. As usual, extreme winter NAO values are at the root of large climate impacts on different natural hazards (e.g. floods, droughts, landslides) but also several important socio-economic areas such as agriculture, renewable energies production, water resources. Thus the winter 2001 (2005) was characterised by several monthly negative (positive) values of NAO inducing an abnormally wet (dry) year in western Mediterranean (García-Herrera et al., 2007). However, the recent winter 2010 was characterised by the most negative NAO winter value ever recorded, and it has caused notable climate anomalies and impacts namely a colder than usual central Europe (Cattiaux et al., 2010) and a wetter than usual Western Mediterranean region (Vicente-Serrano et al., 2011).

The complexity of the NAO behaviour and their impact has attracted the attention of a wide variety of scientific communities, with more than 3800 papers published on different NAO features during the last decade (SCOPUS database, visit: 15/11/2010). The association between the NAO and the Mediterranean climate variability has been well documented, showing that it is one of the main forcing factors in the region. Its impact on extreme events such as droughts, severe precipitations or heat and cold waves has been well established (e.g. Gallego et al., 2006; Garcia-Herrera et al., 2007; Della-Marta et al., 2007; López-Moreno and Vicente-Serrano, 2008). These changes have also an impact on the availability of water resources throughout the entire basin, affecting, not only river flows but also storage availability in lakes and reservoirs and snow cover (Trigo et al., 2004; Karabörk et al., 2005; López-Moreno et al., 2007; Küçük et al., 2009). The ecological dynamics of the region is also greatly affected, as has been shown through satellite imagery and tree rings (Gouveia et al., 2008; Vicente-Serrano and Heredia, 2004; Roig et al., 2009). This has an impact on the quality and quantity of crops and in the migration and welfare of animal populations (Gimeno et al., 2002; Rubolini et al., 2007). The marine environment is also affected by NAO through changes in sea level and fisheries dynamics (Woolf et al., 2003; Lloret et al., 2001; Maynou, 2008). Other reported impacts are landslides (Zêzere et al., 2008), air pollution and human health (Dayan and Lamb, 2008).

Current climate change scenarios obtained with state-of-the-art General Circulation Models (GCMs) predict large modifications in the NAO behaviour in the next decades, however a clear change towards more positive or negative NAO values has not been yet universally established (Solomon et al., 2007). Nevertheless, the majority of the GCMs indicate as the most probable outcome an increase of the NAO values, with a decreased gradient of the Sea Level Pressures and more frequent positive NAO phases (Osborn et al., 1999; Osborn, 2004; Demuzere et al., 2009). However, the increase likelihood of positive NAO mode does not eliminate the high inter-annual variability, thus the possibility of occurrence of extreme negative values, which can trigger large impacts (Vicente-Serrano et al., 2011). In addition, GCMs predict a more robust and stable link between NAO and surface climate variables (Raible et al., 2006; Vicente-Serrano and López-Moreno, 2008b), suggesting that future climate variability, and their related impacts in the Mediterranean region might be controlled even more by the NAO pattern under a warmer world.

The NAO impacts on Northern Europe have been well reviewed and compiled (Hurrell et al., 2003), but no similar work has been attempted for the Mediterranean, which is the other key area impacted by NAO (Trigo et al., 2006). The aim of the book "Hydrological, socioeconomic and ecological impacts of the North Atlantic Oscillation in the Mediterranean region" is to serve as an updated reference text that covers the wide range of evidences on the NAO impacts in the Mediterranean regions and from a multidisciplinary perspective. We hope that this volume constitutes a unique document to present the state of the art of the numerous studies undertaken on the Hydrological, Socioeconomic and Ecological impact of the NAO, collecting the expertise of researchers from several complementary earth science fields (Geography, Hydrology, Remote-sensing, Climatology, Agriculture, Energy), but that have been lacking a common ground.

The first book chapter provides an updated overview on the internal spatial and temporal variability of the NAO and how external forcing factors may affect the future NAO pattern. Tim J. Osborn shows how multi-model ensemble of simulations under increasing anthropogenic forcing strengthens earlier findings of a shift in the mean state of the winter atmospheric circulation towards positive NAO conditions, but he indicates that if a shift towards positive NAO conditions is a realistic response to increasing anthropogenic forcing, then this signal has not yet emerged from the natural variability. He discuss that anthropogenic forcing could be altering the temporal or spatial character of the interannual NAO variability, though only relatively small changes in pattern are evident when considering a multi-model ensemble.

Some of the book chapters focus on the NAO impacts on climate extreme events, like droughts, which will also have subsequent environmental, hydrological and socioeconomic impacts. The paper by Sergio M. Vicente-Serrano and co-authors show the influence of the NAO on droughts in the entire Mediterranean region, focussing on the use of the Standardized Precipitation Evapotranspiration Index, a multi-scale drought indicator that allows to determine how the effects of the winter NAO are propagated for further months when long time scales of drought are analysed.

In terms of the hydrological impacts of the NAO, Ricardo M. Trigo presents that the strong control exerted by NAO on precipitation is very significant between October and March, being extensive to the river flow of major Iberian rivers, such as Douro/Duero, Tejo/Tagus and Guadiana. Correlation coefficient values computed between Iberian winter river flow and contemporaneous (and lagged) winter NAO index show that the large inter-annual variability of the rivers flow is largely modulated by the NAO phenomena. In fact this mode controls inter-annual and decadal variability of both precipitation and river flow of large sectors of Iberia. In the East of the Mediterranean region the hydrological variability of river discharges and lake levels is also determined by the NAO. Ercan Kahya documents the impact of the NAO on the hydrology of eastern Mediterranean countries, such as Turkey, Iran, Kuwait, Oman, and Israel from a general perspective. Patterns of precipitation, streamflow, and lake levels in Turkey are discussed to show the NAO impacts. He devotes special attention to the NAO influences on the formation of streamflow homogeneous region and on the probability distribution functions of critical droughts. The results of his analyses clearly shows that the NAO signals are quite identifiable in various hydrologic variables in Turkey.

The NAO also affects the water stored in the form of snow with evident hydrological but also tourist implications, since the winter snow tourism represents an important income source for several mountain chains located around the Mediterranean basin. Juan I. López-Moreno and collaborators analyse the influence of NAO on the interannual evolution of winter temperature, precipitation and snowpack in these Mediterranean mountains. They show that the snow cover response to winter NAO may differ spatially as a consequence of the different influence of winter NAO on precipitation and temperature. In Switzerland, they show how the influence of NAO on snow is significant at the lowest elevation areas, where temperature is the main control on snowpack accumulation, but in the Pyrenees the highest correlation with snow is found at high elevations where precipitation controls mainly the accumulation of snow related to the NAO control of the interannual variability of precipitation.

Primary activities over land and sea are also being largely affected by NAO. On the one hand, several Mediterranean fisheries reveal inter-annual variations closely related to the NAO variability. Francesc Maynou shows that the NAO explains a large part of the variability in population abundance of red shrimp *Aristeus antennatus* in the western Mediterranean Sea, with a lag of 2–3 years. Moreover, the stocks of hake also respond to the NAO since positive NAO years enhance hake fishery production through increasing the individual size of recruits, as well as the individual weight and abundance of adult hake. The NAO signal is also observed in the crop productions as Simone Orlandini and collaborators illustrate. They stress that besides common meteorological information supplied by local stations, the use of the NAO may allow to forecast agricultural yields and production quality in regions of the Mediterranean basin.

The dynamic of ecosystems of the Mediterranean region is also largely determined by the NAO. In their chapter, Célia Gouveia and Ricardo Trigo analyse the relationship between NAO, vegetation dynamics and carbon absorption over Iberian Peninsula. They provides strong evidence that positive (negative) values of winter NAO induce low (high) vegetation activity in the following spring and summer seasons. These features are mainly associated with the impact of NAO on winter precipitation, together with the strong dependence of the spring and summer vegetation activity on water availability during the previous winter. Jesus J. Camarero quantified the tree growth responses to NAO index across a climatic gradient in Northeastern Spain, considering ten tree species with contrasting habitats and plausibly different growth responses to climate. He shows that climatic variables and NAO indices explained on average 40.1 and 15.9% of the growth variance, respectively. He also shows how the growth responses to climate and NAO also changed through time, illustrating how long tree-ring chronologies of different species may serve as valuable monitors of the responses of forests to winter NAO. In terms of animal communities, Oscar Gordo and collaborators review more than 60 studies that have demonstrated the effects of the NAO on both terrestrial and aquatic Mediterranean ecosystems. They show how the NAO affects the condition and diet of mammals and disease-related mortality in amphibians and how the birds communities are affected by NAO impacts on the availability and extent of their habitat and by influencing dispersal decisions of individuals. Thus, they illustrate how the NAO plays an essential role in the migration of birds throughout the Mediterranean basin, and it is probably a reason for the observed advance of arrival dates during the spring in Europe.

Moreover, the environmental NAO impacts are also evident in terms of air quality and contaminants dispersion. Uri Dayan presents simulations of transport of anthropogenic CO for high and low phases of the NAO. He shows the different spatial and temporal influence played by the positive and negative phases of the NAO mode when controlling the dust tranport to the Mediterranean: the positive phase during summer over the western region and the negative one regulating dust transport over the Eastern Mediterranean in winter. He indicates that positive phases imply a reduced import of European trace gases, an enhancement of long range transport of air pollutants from North American sources and conditions in favor of mobilization and transport of North African dust mainly to the western part of this fragile basin.

Geomorphological processes in the Mediterranean region are also being largely affected by the NAO. The erosive capacity of rainfall is the factor that triggers different surface processes that finally determine soil erosion. Marta Angulo-Martínez and Santiago Beguería illustrate in a western Mediterranean area how the erosive power of rainfall is stronger during the negative phase of NAO and weaker during positive NAO conditions, a finding very useful in the implementation of soil conservation strategies. In addition, soil intensity and magnitude also triggers mass movements and landslides. José Luís Zêzere and Ricardo Trigo show that NAO have an impact on the landslide events that have occurred in the region located just north of Lisbon between 1956 and 2010. Thus, they show how many months with landslide activity are characterized by negative average values of the NAO index and high values of average precipitation (above 95 mm/month).

The volume ends showing the influence of the NAO on a key economic sector that at present is increasing its economic importance. David Pozo-Vazquez and collaborators explore the influence of the NAO on the solar and wind energy resources in the Mediterranean area, in particular, and over the whole North Atlantic area, in general. They show that interannual variability of the solar and wind energy resources in the Mediterranean area can reach values above 20% in winter and 10% in the annual case associated with changes in the NAO phase. They results are of interest regarding the estimation of the expected interannual variability of the wind farms and solar plants production in the study region.

The set of chapters of this books provides the most complete overview about the impacts of the NAO in the Mediterranean region, highlighting the importance of this phenomenon not only in terms of the understanding of climate processes in the region, but also to know in depth the derived impacts that are affecting our environment, economy and natural resources.

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References

Cattiaux J, Vautard R, Cassou C, Yiou P, Masson-Delmotte V, Codron F (2010) Winter 2010 in Europe: a cold extreme in a warming climate. Geophys Res Lett 37. doi:10.1029/2010GL044613

Cook E, D'Arrigo RD, Mann ME (2002) A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation Index since A.D. 1400. J Clim 15:1754–1764

Dayan U, Lamb D (2008) Influence of atmospheric circulation on the variability of wet sulfate deposition. Int J Climatol 28:1315–1324

Della-Marta PM, Luterbacher J, von Weissenfluh H, Xoplaki E, Brunet M, Wanner H (2007) Summer heat waves over western Europe 1880–2003, their relationship to large-scale forcings and predictability. Clim Dyn 29:251–275

Demuzere M, Werner M, van Lipzig NPM, Roeckner E (2009) An analysis of present and future ECHAM5 pressure fields using a classification of circulation patterns. Int J Climatol 29: 1796–1810

Dünkeloh A, Jacobeit J (2003) Circulation dynamics of mediterranean precipitation variability 1948–98. Int J Climatol 23:1843–1866

Gallego MC, García JA, Vaquero JM, Mateos VL (2006) Changes in frequency and intensity of daily precipitation over the Iberian Peninsula. J Geophys Res D: Atmos 111:D24105. doi:10.1029/2006JD007280

García-Herrera R, Paredes D, Trigo RM, Trigo IF, Hernández H, Barriopedro D, Mendes MT (2007) The outstanding 2004–2005 drought in the Iberian Peninsula: the associated atmospheric circulation. J Hidrometeorol 9:483–498

García-Herrera R, Gallego D, Hernández E, Gimeno L, Ribera P (2001) Influence of the North Atlantic Oscillation on the Canary Island precipitation. J Clim 14:3889–3903

Gimeno L, Ribera P, Iglesias R, de la Torre L, Garcia R, Hernandez E (2002) Identification of empirical relationships between indices of ENSO and NAO and agricultural yields in Spain. Clim Res 21:165–172

Gouveia C, Trigo RM, DaCamara CC, Libonati R, Pereira JMC (2008) The North Atlantic Oscillation and European vegetation dynamics. Int J Climatol 28:1835–1847

Hurrell J (1995) Decadal trends in North Atlantic Oscillation and relationship to regional temperature and precipitation. Science 269:676–679

Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (2003) The North Atlantic Oscillation: climate significance and environmental impact. Geophysical monograph series, vol 134. American Geophysical Union, Washington, DC

Hurrell J, Van Loon H (1997) Decadal variations in climate associated with the North Atlantic Oscillation. Clim Change 36:301–326

Jones PD, Jónsson T, Wheeler D (1997) Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. Int J Climatol 17:1433–1450

Karabörk MÇ, Kahya E, Karaca M (2005) The influences of the southern and North Atlantic Oscillations on climatic surface variables in Turkey. Hydrol Process 19:1185–1211

Küçük M, Kahya E, Cengiz TM, Karaca M (2009) North Atlantic Oscillation influences on Turkish lake levels. Hydrol Process 23:893–906

Lamb PJ, Peppler RA (1987) North Atlantic Oscillation: concept and application. Bull Am Meteorol Soc 68:1218–1225

Lloret J, Lleonart J, Solé I, Fromentin J-M (2001) Fluctuations of landings and environmental conditions in the north-western Mediterranean sea. Fisheries Oceanogr 10:33–50

Luterbacher J, Xoplaki E, Dietrich D, Jones PD, Davies TD, Portis D, González-Rouco JF, von Storch H, Gyalistras D, Casty C, Wanner H (2002) Extending North Atlantic Oscillation reconstructions back to 1500. Atmos Sci Lett 2:114–124

López-Moreno JI, Beguería S, Vicente-Serrano SM, García-Ruiz JM (2007) The influence of the NAO on water resources in Central Iberia: precipitation, streamflow anomalies and reservoir management strategies. Water Resour Res 43:W09411. doi:10.1029/2007WR005864

López-Moreno JI, Vicente-Serrano SM (2008) Extreme phases of the wintertime North Atlantic Oscillation and drought occurrence over Europe: a multi-temporal-scale approach. J Clim 21:1220–1243

Maynou F (2008) Influence of the North Atlantic Oscillation on Mediterranean deep-sea shrimp landings. Clim Res 36:253–257

Moses T, Kiladis N, Díaz H, Barry R (1987) Characteristics and frequency of reversals in mean sea level pressure in the north Atlantic sector and their relationship to long term temperature trend. J Climatol 7:13–30

Osborn TJ (2004) Simulating the winter North Atlantic Oscillation: the roles of internal variability and greenhouse gas forcing. Clim Dyn 22:605–623

Osborn TJ, Briffa KR, Tett SFB, Jones PD, Trigo RM (1999) Evaluation of the North Atlantic Oscillation as simulated by a coupled climate model. Clim Dyn 15:685–702

Pauling A, Luterbacher J, Casty C, Wanner H (2006) Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. Clim Dyn 26:387–405

Raible CC et al (2006) Climate variability-observations, reconstructions, and model simulations for the Atlantic-European and Alpine region from 1500–2100 AD. Clim Change 79:9–29

Roig FA, Barriopedro D, Herrera RG, Patón Domínguez D, Monge S (2009) North Atlantic Oscillation signatures in western Iberian tree-rings. Geogr Ann 91:141–157

Rubolini D, Ambrosini R, Caffi M, Brichetti P, Armiraglio S, Saino N (2007) Long-term trends in first arrival and first egg laying dates of some migrant and resident bird species in northern Italy. Int J Biometeorol 51:553–563

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (2007) Climate change 2007: the physical science basis. Cambridge University Press, Cambridge, UK and New York, NY

Sousa P, Trigo RM, Aizpurua P, Nieto R, Gimeno L, Garcia-Herrera R (2011) Trends and extremes of drought indices throughout the 20th century in the Mediterranean. Nat Hazards Earth Syst Sci 11:33–51

Trigo IF (2006) Climatology and interannual variability of storm-tracks in the Euro-Atlantic sector: a comparison between ERA-40 and NCEP/NCAR reanalyses. Clim Dyn 26:127–143

Trigo RM et al (2006) Relations between variability in the Mediterranean region and Mid-Latitude variability. In: Lionello P, Malanotte-Rizzoli P, Boscolo R (eds) The Mediterranean climate: an overview of the main characteristics and issues. Elsevier, Amsterdam, pp. 179–226

Trigo RM, Osborn TJ, Corte-Real JM (2002) The North Atlantic Oscillation influence on Europe: climate impacts and associated physical mechanisms. Clim Res 20:9–17

Trigo RM, Pozo-Vazquez D, Osborn TJ, Castro-Diez Y, Gamiz-Fortis S, Esteban-Parra MJ (2004) North Atlantic Oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. Int J Climatol 24:925–944

Vicente-Serrano SM, Heredia A (2004) NAO influence on NDVI trends in the Iberian Peninsula (1982–2000). Int J Remote Sens 25:2871–2879

Vicente-Serrano SM, López-Moreno JI (2008a) The nonstationary influence of the North Atlantic Oscillation on European precipitation. J Geophys Res Atmos 113:D20120. doi:10.1029/2008JD010382

Vicente-Serrano SM, López-Moreno JI (2008b) Differences in the nonstationary influence of the North Atlantic Oscillation on European precipitation under different scenarios of greenhouse gases concentrations. Geophys Res Lett 35:L18710. doi:10.1029/2008GL034832

Vicente-Serrano SM, Trigo RM, López-Moreno JI, Liberato MLR, Lorenzo-Lacruz J, Beguería S, Morán-Tejeda E, El Kenawy A (2011) Extreme winter precipitation in the Iberian Peninsula in 2010: anomalies, driving mechanisms and future projections. Clim Res 46:51–65

Wanner H et al (2001) North Atlantic Oscillation—concepts and studies. Surv Geophys 22:321–382

Woolf DK, Shaw AGP, Tsimplis MN (2003) The influence of the North Atlantic Oscillation on sea-level variability in the North Atlantic region. Global Atmos Ocean Syst 9:145–167

Xoplaki E, González-Rouco JF, Luterbacher J, Wanner H (2003) Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs. Clim Dyn 20:723–739

Xoplaki E, González-Rouco JF, Luterbacher J, Wanner H (2004) Wet season Mediterranean precipitation variability: influence of large-scale dynamics and trends. Clim Dyn 23:63–78

Zêzere JL, Trigo RM, Fragoso M, Oliveira SC, Garcia RAC (2008) Rainfall-triggered landslides in the Lisbon region over 2006 and relationships with the North Atlantic Oscillation. Nat Hazards Earth Syst Sci 8:483–499

Zorita E, Kharin V, Von Storch H (1992) The atmospheric circulation and sea surface temperature in the North Atlantic area in winter: their interaction and relevance for Iberian precipitation. J Clim 5:1097–1108

Variability and Changes in the North Atlantic Oscillation Index

Tim J. Osborn

Abstract Most – or perhaps even all – of the observed variations in the winter North Atlantic Oscillation (NAO) index can be explained as internally-generated climate variability. The influence of external forcing factors on the observed NAO behaviour is still an open question. Two sea level pressure datasets yield different results for the strength of the winter NAO trend from the 1960s to the 1990s, though these trends from both datasets lie outside the 90% range of trends generated by the internal variability of climate models, and the latter is more precisely known now that over 8000 years of simulation under constant forcing is available for analysis. Similarly, a much expanded, multi-model ensemble of simulations under increasing anthropogenic forcing strengthens earlier findings of a shift in the mean state of the winter atmospheric circulation towards positive NAO conditions. There is considerable inter-model spread in both the magnitude of this response to increased forcing and in its regional structure, but of the 21 climate models analysed here, none showed an overall decrease in the mean level of the NAO index. If a shift towards positive NAO conditions is a realistic response to increasing anthropogenic forcing, then this signal has not yet emerged from the natural variability: observations since the 1990s show a return to lower values, and the 2009/2010 winter had the record negative NAO index in a record lasting almost two centuries. It is possible that anthropogenic forcing could be altering the temporal or spatial character of the interannual NAO variability, though only relatively small changes in pattern are evident when considering the multi-model ensemble as a whole and there is only weak evidence for an increase in the interannual variance.

Keywords Internal variability · External forcing · North Atlantic Oscillation index · Temperature

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1 Introduction

The interannual variability of the North Atlantic Oscillation (NAO) represents between 20 and 30% of the Northern Hemisphere winter atmospheric sea-level pressure (SLP) variance, and an even greater part of the variance in the Atlantic-European sector (e.g. Hurrell and Deser, 2009). For example, defining the NAO index as the leading principal component of winter (December to February or December to March, as here, are typically used) SLP in the domain 15–90°N and 110°W–70°E represents around 40% of the variance in this domain (Figs. 1a and 2a), updated from Osborn (2004). Taking instead a station-based index – simply the difference between standardised or raw SLP records near the Azores High and Iceland Low pressure systems can yield a longer record, but captures slightly less variance (because the principal component was optimised to maximise the variance captured). The Gibraltar minus Iceland record first developed by Jones et al. (1997) and updated here (Fig. 1b) now contains 187 complete winters (only those since 1887 are shown here).

This is all well established, as are the links between the NAO and some aspects of surface climate (Trigo et al., 2002; López-Moreno and Vicente-Serrano, 2008; and

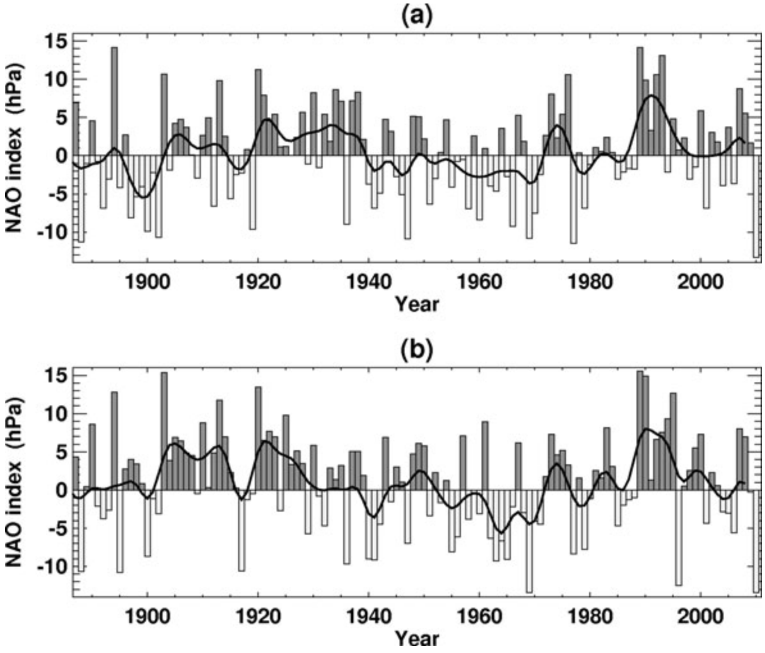

Fig. 1 Two alternative observed timeseries of the winter NAO index. (**a**) The leading principal component timeseries of Atlantic-European SLP, using the HadSLP2r dataset (Allan and Ansell, 2006). (**b**) The difference between Gibraltar and southwest Iceland SLP observations. The values represent the absolute pressure difference (hPa) between winter-mean values (**a**) from the maxima and minima of the EOF pattern, and (**b**) from Gibraltar and Iceland

many others). More recent research, coupled with longer observational records that enable empirical relationships to be better established, is increasing this knowledge and also extending it to new areas such as the consequences of NAO variability for various natural and societal systems. See the rest of this volume for many examples. What is considerably more uncertain is the link between internally-generated variability and externally-forced change, and whether the signature of the latter is evident in the observed record. The positive trend in the NAO index from the 1960s to the 1990s, evident in Fig. 1, has been a particular focus of such work (Osborn et al., 1999; Gillett et al., 2003; Osborn, 2004), though more general changes in the mean level of the NAO index have also been considered (Selten et al., 2004).

Others have investigated changes in the spatial structure of the NAO pattern (Fig. 2a). For example, a tendency for an eastward shift or extension of the NAO signature is apparent during part of the observed record (1978–1997 compared with 1958–1977; Jung et al., 2003) and also in the response to increased greenhouse gas concentrations simulated by some climate models (Ulbrich and Christoph, 1999). Multi-model analyses (Osborn, 2004; Kuzmina et al., 2005) suggest that such a result is model dependent, though the multi-model mean response in both cases did show a small north-eastward shift (Fig. 2b–d). A reconsideration of this is worthwhile using more recent climate models that typically have finer resolution and increasingly sophisticated representations of some physical and dynamical processes.

In addition to possible shifts in the mean level of the NAO index – i.e. corresponding to a change in the mean atmospheric circulation that has a structure that correlates positively with the NAO pattern (Fig. 2a) – or in the pattern of interannual NAO variability, it is feasible that external forcing could influence the *amplitude* of temporal variability. This is of topical interest because the winter 2009–2010 NAO index had a record low value in the 187-year record (Osborn, 2011). Though this could simply be a random event arising from internal variability, it is also important to assess the evidence for externally-forced changes in NAO variance which could alter the likelihood of such extreme events.

This chapter is structured as follows: Section 2 provides a brief description of the observed and climate model simulated datasets used in this study, while Section 3 compares the observed record with the range of internal variability simulated by the

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Fig. 2 Spatial patterns of SLP variability associated with the winter NAO, estimated from the regression coefficients between local SLP and the NAO principal component index. (**a**) Observed pattern using HadSLP2r (Allan and Ansell, 2006). (**b**) Average simulated pattern from 7 older climate models used by Osborn (2004), using pre-industrial or twentieth-century control runs. (**c**) As (**b**), but using the 2050–2099 period under a scenario with increasing CO_2 concentrations (1% year^{-1}). (**d**) Difference (**c**) minus (**b**). (**e**) Average simulated pattern from 22 CMIP3 climate models, using the 1922–1999 period under historic forcing (anthropogenic only or anthropogenic and natural). (**f**) As (**e**), but using the 2050–2099 period under the SRES A1B scenario of increasing anthropogenic forcing. (**g**) Difference (**f**) minus (**e**). Note that the contour interval is 4 times smaller in *panel* (**d**) than in *panels* (**b**) and (**c**), and is 10 times smaller in *panel* (**g**) than in *panels* (**e**) and (**f**)

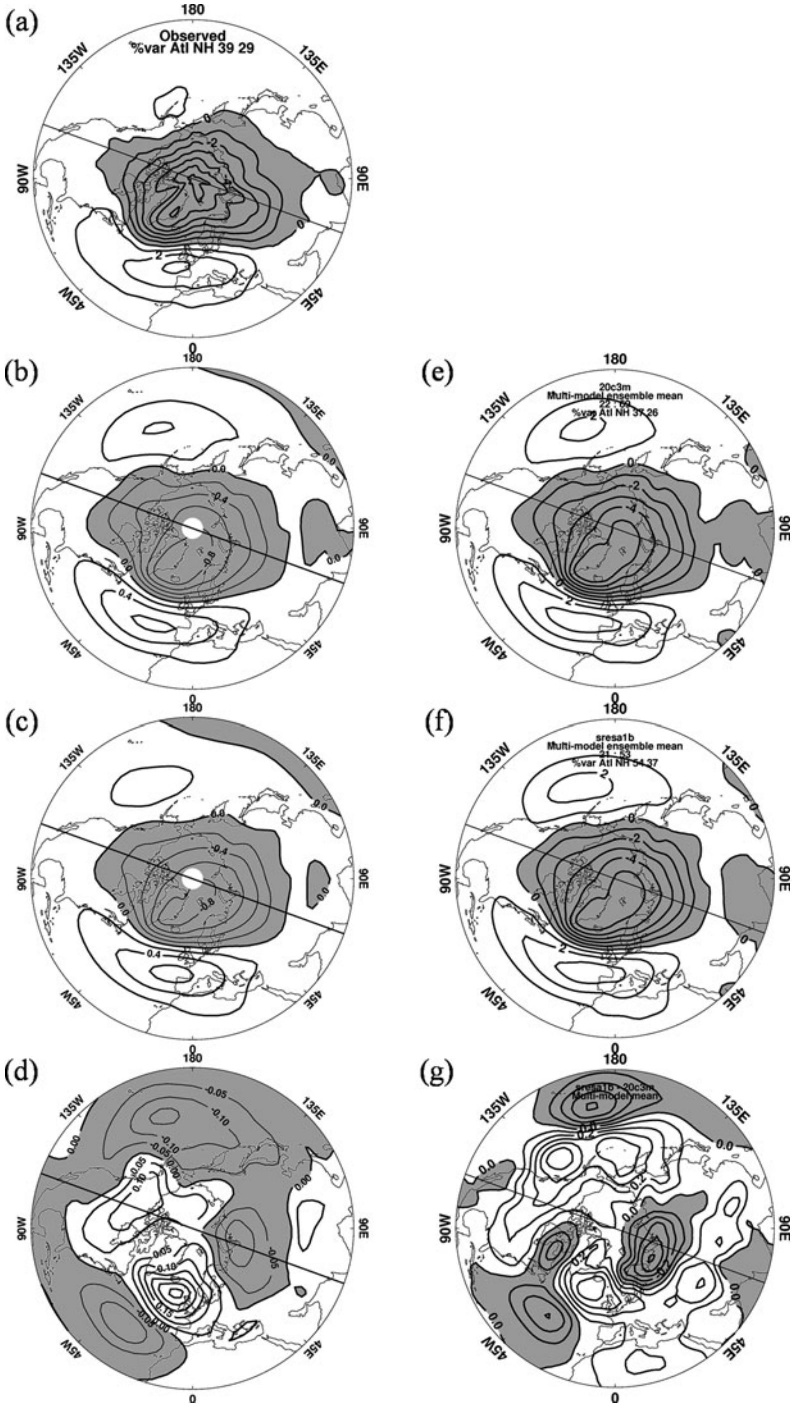

Fig. 2 (continued)

climate models. Then the simulated response to increasing greenhouse gases and other anthropogenic forcings is described, for the mean circulation (Section 4), the pattern of interannual variability (Section 5) and the amplitude of temporal variance (Section 6), before some concluding remarks in Section 7.

2 Observed and Simulated Data

2.1 Observed Data, NAO Pattern and NAO Index

Monthly-mean SLP fields from 1850 to 2010 from the HadSLP2r dataset (Allan and Ansell, 2006) were used. These consist of fields on a 5° latitude by 5° longitude grid based on ship and weather station observations till 2004, with near-real-time updates from 2005 to 2010 using NCEP/NCAR reanalysis data adjusted so that its climatological average matches the observed data. The EOF analysis used to define the NAO index was applied to the period from 1922 to 1999, because 1922 is the first year in the record when at least 20% of the Northern Hemisphere grid boxes contain at least 30 observations per month (Allan and Ansell, 2006). Note that the HadSLP2r dataset falls back below this threshold from 1941 to 1948; the dataset is spatially complete because it is based on interpolation from the available observations, but nevertheless the values of the NAO index prior to 1922 and between 1941 and 1948 should be considered with more caution.

The spatial pattern of the NAO (Fig. 2a, the leading EOF of the December-to-March seasonal mean SLP) is similar to the pattern found by Hurrell and Deser (2009) who used a longer period, a smaller spatial window focussed on the North Atlantic, and a different SLP dataset (Trenberth and Paolino, 1980, dataset with updates). One difference is in the relative strengths of the northern and southern parts of the dipole, which are more equal in Hurrell and Deser's pattern (bottom panel of their figure 8) compared with that shown in Fig. 2a here, perhaps because the EOF has not been calculated with area-weighting of the SLP data here. Hurrell and Deser (2009) also show that using the shorter December-to-February season (compare the top-left panel of their figure 6 with their figure 8) results in stronger loadings over the North Pacific – which is of interest because most climate models show an EOF pattern with that feature.

The observed NAO index obtained by projecting the HadSLP2r seasonal mean data fields onto the leading EOF is quite similar to the Gibraltar minus Iceland index (Fig. 1). This is in contrast to the earlier analysis of Osborn (2004), where the trend from the 1960s to the 1990s was more pronounced and the early 1990s values were distinctly higher than the preceding century. Osborn (2004) used SLP data based on the UK Met Office analyses, updated from Jones (1987). Hurrell and Deser (2009) use the leading EOF of the Trenberth and Paolino (1980) SLP data to obtain an NAO index that shows a more intermediate result. Although these NAO indices are highly correlated, they do have different characteristics (e.g. the strength of multi-decadal variations compared with shorter term variability) that can influence the statistical significance of trends. Further investigation is needed of the differences between these SLP datasets (e.g. whether the reduced-space optimal interpolation algorithm used for HadSLP2r affects the amplitude of long-term variations).

2.2 Simulated Data and NAO Patterns

Osborn (2004) reported an analysis of the NAO as simulated by seven climate models whose primary references were published between 1997 and 2000 (table 1 of Osborn, 2004). Here, I report results of similar analyses applied to models that have been developed or improved more recently, using 22 models from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007). The focus is on the multi-model-mean results; detailed results from individual models will be presented elsewhere. The 22 models used here are listed in Table 1. The simulations used are control runs under constant pre-industrial forcings, those under historic transient forcing, beginning between 1850 and 1900 and extending to between 1999 and 2003, and those

Table 1 CMIP3 simulated data used in the analyses presented here

Model	Control run (year)	Historic forcing	Runs	Future forcing (SRES A1B)	Runs
bcc_cm1	–	1871–2003	4	–	–
bccr_bcm2_0	250	1850–1999	1	2000–2099	1
cccma_cgcm3_1	1001	1850–2000	5	2001–2200	5
cccma_cgcm3_1_t63	350	1850–2000	1	2001–2200	1
cnrm_cm3	390	1860–1999	1	2000–2200	1
csiro_mk3_0	380	1871–2000	3	2001–2200	1
gfdl_cm2_0	500	1861–2000	3	2001–2200	1
gfdl_cm2_1	500	1861–2000	3	2001–2200	1
giss_aom	502	1850–2000	2	2001–2100	2
giss_model_e_h	400	1880–1999	5	2000–2099	4
giss_model_e_r	500	1880–2003	9	2004–2200	5
iap_fgoals1_0_g	150	1850–1999	3	2000–2199	3
inmcm3_0	331	1871–2000	1	2001–2200	1
ipsl_cm4	–	1860–2000	1	2000–2100	1
miroc3_2_hires	100	1900–2000	1	2001–2100	1
miroc3_2_medres	500	1850–2000	3	2001–2200	1
				2001–2100	2
mpi_echam5	506	1860–2000	3	2001–2200	3
				2001–2100	1
mri_cgcm2_3_2a	350	1851–2000	5	2001–2200	1
				2001–2100	4
ncar_ccsm3_0	830	1870–1999	8	2000–2199	1
				2000–2099	3
ncar_pcm1	350	1890–1999	3	2000–2200	2
				2000–2099	2
ukmo_hadcm3	341	1860–1999	2	2000–2199	1
ukmo_hadgem1	–	1860–1999	2	2000–2099	1

under the SRES A1B future scenario of increasing greenhouse gas concentrations and other anthropogenic forcing to 2100. For most models, the SRES A1B simulations are extended beyond 2100 with fixed forcings, and model output up to 2200 is used here.

Multiple simulations under the same forcing, but different initial conditions and hence different realisations of internal variability, are available in some cases. These initial-condition ensembles are used by analysing the individual ensemble members separately, and then averaging the results to produce an ensemble mean. Table 1 indicates the availability of simulations, including the size of initial-condition ensembles, for each of the models used here.

Osborn (2004) explained the advantages of regridding all datasets to a common grid prior to analysis, so here all simulated data are regridded to the grid of the HadSLP2r observational data. The same methods described in Osborn (2004) for calculating and scaling the principal component NAO index time series from an EOF analysis of each model simulation are used here – refer to that paper for a detailed description.

The simulated spatial pattern of the NAO, when averaged across the 22 climate models with twentieth century simulations (Fig. 2e), bears a very close resemblance to the observed NAO pattern (Fig. 2a). As with the earlier models (Fig. 2b), the teleconnection between the NAO and the North Pacific is stronger than observed, resembling the Northern Annular Mode more closely (Miller et al., 2006). Note that the NAO is defined here from an EOF analysis of only the Atlantic half of the hemisphere, but the pattern shown in the maps is from the pattern of regression coefficients between the principal component NAO index and SLP from across the entire northern hemisphere. With this exception, the similarity with the observed pattern provides some justification for using these model experiments to investigate NAO behaviour.

3 Comparing the Observed Record with Internally-Generated Climate Variability

The detection of climate changes that might be caused by some external forcing requires the comparison of an observed record with an estimate of the variations that might typically be expected to arise from internal variability. In most cases, the amplitude of internal variability increases with decreasing timescale, so that even where a real climate change is present the likelihood of detecting it is rather small within a short (e.g. sub-decadal) record. But longer-term trends must be compared with an estimate of internally-generated variability on multi-decadal timescales, and a multi-century record is required to provide an adequate sample of such variations. The instrumental record is not long enough and is also “contaminated” by any responses to natural or anthropogenic forcings, rather than being a “pure” representation of internal variability. In most detection studies, therefore, the internal climate variability is estimated from climate model simulations, using