Annex 1: What is NAO?

Abdel Hannachi and Martin Stendel

The atmospheric circulation in the European/Atlantic sector, which also determines the regional climate of the North Sea region, can be described mainly by the North Atlantic Oscillation (NAO), the zonality or meridionality of the atmospheric flow and the frequency of atmospheric blocking. The NAO is the dominant mode of near-surface pressure variability over the North Atlantic Ocean and Europe, including the 'NOSCCA region', impacting a considerable part of the northern hemisphere (Hurrell et al. 2003). In its positive phase, the pressure difference between the two main centres of action—the Azores High and the Icelandic Low—is enhanced compared to the climatological average, resulting in a stronger than normal westerly air flow (Hurrell 1995). The storm-track extends north-eastward with more storms over the North Sea and northern Europe. These regions have therefore warmer and wetter than average conditions, especially during winter, whereas the Mediterranean region is generally drier and colder than normal. In contrast, during the negative phase of the NAO, the pressure difference between the Azores High and Icelandic Low is reduced, the storm track is more zonal and shifted southward, extending into the western Mediterranean, and the resulting air flow is weaker than normal (Xoplaki 2002; Xoplaki et al. 2004). For strongly negative NAO indices, the flow can even reverse when there is higher pressure over Iceland than over the Azores, with the consequence of harsh winters over large parts of Europe, such as occurred in 2009/2010 (Ouzeau et al. 2011). The strength of the NAO follows an annual cycle with maximum values in January and minimum values in May (Jones et al. 1997; Furevik and Nilsen 2005). Although the largest amplitude and explained variance occur in winter, the impact of the NAO on the North Sea region is present all year round.

Figure A1.1 shows the variability of the NAO over the past 190 years. From a long-term perspective, the behaviour of the NAO appears irregular. However, extended periods of positive or negative NAO indices are apparent. From the mid-1970s to the mid-1990s, positive index values prevailed (e.g. Hurrell et al. 2003). After the mid-1990s, however, there was a tendency towards more negative NAO indices, in other words a more meridional circulation, and it should be noted that the winter of 2010/2011 had the most negative NAO index in the record (Jung et al. 2011; Pinto and Raible 2012).

Fingerprints of the NAO have been known since at least the days of the Scandinavian sailors (Haine 2008), and from the mid-18th century it was noted (Egede 1745; Cranz 1765) that surface air temperatures in Greenland and Scandinavia vary in opposite phase (Stephenson et al. 2003; Pinto and Raible 2012). Depending on the season, the NAO pattern explains between 40 and 60 % of the total variance in sea-level pressure (SLP) over the North Atlantic Ocean (Wanner et al. 2001; Bojariu and Gimeno 2003; Hurrell et al. 2003).

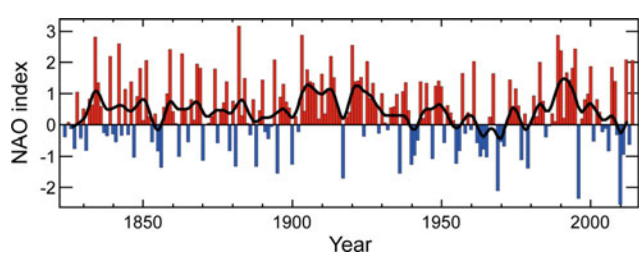

Fig. A1.1 North Atlantic Oscillation (NAO) index for boreal winter (DJFM) 1824/1825 to 2012/2013, calculated as the difference of the normalised station pressures of Iceland and Gibraltar (which is a good measure for the strength of the Azores High) from the monthly means of the period 1951–1980 (Jones et al. 1997, updated at www.cru.uea.ac.uk/~timo/datapages/naoi.htm). The *solid black line* is a 5-year running mean

A. Hannachi (✉)
Department of Meteorology, Stockholm University, Stockholm, Sweden
e-mail: a.hannachi@misu.su.se

M. Stendel
Department for Arctic and Climate, Danish Meteorological Institute (DMI), Copenhagen, Denmark
e-mail: mas@dmi.dk

M. Quante and F. Colijn (eds.), *North Sea Region Climate Change Assessment*,
Regional Climate Studies, DOI 10.1007/978-3-319-39745-0

The North Atlantic sea-surface temperature (SST) responds to changes in large-scale atmospheric flow, particularly the NAO. For example, during positive NAO events, there is enhanced cooling of North Atlantic SST north of 45° N. The resulting negative SST anomaly affects air-sea interaction between about 30° and 45°N, leading to positive SST anomalies in this lower latitude band (Marshall et al. 2001). The correlation between the North Atlantic SST anomalies and the NAO index leads to a dipole pattern, known as the Bjerknes' North Atlantic SST dipole (Bjerknes 1962, 1964). The southern lobe of this dipole extends across the Atlantic to the North Sea and thus the NOSCCA region, where the correlation is at a maximum (see Visbeck et al. 2003: their Fig. 2). The NAO affects a whole spectrum of atmospheric and environmental processes, including tropospheric wind (Thompson et al. 2000; see also Fig. 2.2), precipitation (Lamb and Peppler 1987; Zorita et al. 1992; Hurrell and van Loon 1997), ocean surface characteristics (e.g. Moliarini et al. 1997), storminess (Rogers 1997; Serreze et al. 1997), North Atlantic/European atmospheric blocking frequency (Nakamura 1996; Woollings et al. 2010a, b; Häkkinen et al. 2011) and Sverdrup and Ekman transport (Visbeck et al. 2003).

Many approaches have been used to define the spatial structure of the NAO. Historically, (normalised) SLP differences between Iceland and Lisbon (Hurrell 1995), the Azores (Rogers 1997) or Gibraltar (Jones et al. 1997; Vinther et al. 2003) have been used. Several researchers use one-point correlation maps to identify regions of maximal negative correlation near or over Iceland and over the Azores extending to Portugal (e.g. Wallace and Gutzler 1981; Kushnir and Wallace 1989; Portis et al. 2001; Hurrell and Deser 2009). A related approach uses principal components and identifies the NAO by the eigenvectors of the cross-correlation matrix which is computed from the temporal variation of the grid point values of SLP, scaled by the amount of variance they explain (e.g. Barnston and Livezey 1987), or clustering techniques (e.g. Cassou and Terray 2001a,b). Several researchers use unrotated (Horel 1981; Thompson and Wallace 1998; Woollings et al. 2010b) or rotated empirical orthogonal functions (EOFs) (Cheng et al. 1995; Hannachi et al. 2007). Other techniques, such as NAO indices over latitudinal belts (e.g. Li and Wang 2003), optimally interpolated patterns, trend EOFs (Hannachi 2007a, 2008) and cluster analyses (Cheng and Wallace 1993; Kimoto and Ghil 1993; Hannachi 2007b, 2010) have also been proposed. Seasonality can also be taken into account by defining a seasonally and geographically varying NAO index (Portis et al. 2001). All these definitions lead to slightly different NAO indices; but the indices all resemble each other and are in fact highly correlated with each other (Leckebusch et al 2008).

All these definitions have in common that they are based on direct observations or analyses. However, it is also possible to use proxy data to extend the indices back in time. Several reconstructions exist that cover roughly the last millennium. These are based on early instrumental observations (Jones et al 1997; Luterbacher et al. 1999), ship logs (Küttel et al. 2009; Wheeler et al. 2009), other documentary data (Glaser et al. 1999; Luterbacher et al. 2001, 2004), climate field reconstructions (Jones and Mann 2004; Casty et al. 2007), ice cores (Appenzeller et al. 1998), speleothems (Trouet et al. 2009) or strontium/calcium ratios in coral (Goodkin et al. 2008). Multi-proxy reconstructions also exist, based on tree rings and snow accumulation records (Glueck and Stockton 2001) or on tree rings and stable isotope ratios (Cook et al. 2002).

A model-based reconstruction of past atmospheric circulation patterns is in principle possible. While climate models are able to capture the broad spatial and temporal features of the NAO (Gerber et al. 2008), the patterns of variability exhibit substantial differences between models and in comparison to observations (Xin et al. 2008; Casado and Pastor 2012; Handorf and Dethloff 2012). In particular, most models overestimate persistence on time scales from sub-seasonal to seasonal (Gerber et al. 2008). With few exceptions (Selten et al. 2004; Semenov et al. 2008), many climate models are unable to simulate the amplitude of changes in the observed NAO trend since the 1960s (Scaife et al. 2008, 2009; Stoner et al. 2009). This and the apparent underestimation of vertical coupling between troposphere and stratosphere in most models make it difficult to determine the extent to which the underestimation of trends is due to model deficiencies and the extent to which it mirrors anthropogenic forcing (Sigmond and Scinocca 2010; Karpechko and Manzini 2012; Scaife et al. 2012). Further uncertainties arise because there are indications that NAO variability may depend on the mean state of the atmosphere (Branstator and Selten 2009; Barnes and Polvani 2013). It has also been proposed that higher wave numbers could lead to resonance effects and therefore increased persistence of circulation regimes (Coumou et al. 2014), thus corroborating earlier findings, such as those by Kyselý and Huth (2006); see also Rutgersson et al. (2014). It remains an open question how far these drivers of NAO variability are related to changes in the Arctic, such as the decrease in sea ice.

A comparison of the different reconstructions can shed some light on the ability to reconstruct past atmospheric circulation patterns. Pinto and Raible (2012) made such a comparison (after applying a low-pass filter and normalisation) and found reasonable agreement between different reconstructions since the beginning of the 20th century, but also for a few periods in the more distant past (in particular between 1620 and 1720). As these studies rely on different numbers of proxies, different calibration methods and very different types of proxies, including growing-season data to estimate winter NAO, this is not unexpected (e.g. Schmutz et al. 2000). Furthermore, it is also unclear how valid the implicit assumption is that the relation between proxies and the NAO does not change over time.

References

Appenzeller C, Stocker TF, Anklin M (1998) North Atlantic Oscillation dynamics recorded in Greenland ice cores. Science, 282:446–449

Barnes EA, Polvani L (2013) Response of the midlatitude jets and of their variability to increased greenhouse gases in the CMIP5 models. J Climate 26:7117–7135

Barnston AG, Livezey RE (1987) Classification, seasonality and persistence of low frequency atmospheric circulation patterns. Mon Wea Rev 115:1083–1126

Bjerknes J (1962) Synoptic survey of the interaction of the sea and atmosphere in the North Atlantic. Vilhekm Bjerknes Centenary Volume, vol. XXIV, Geofys Publ 3:115–145

Bjerknes J (1964) Atlantic air-sea interactions. Adv Geophys 10:1–82

Bojariu R, Gimeno L (2003) Predictability and numerical modelling of the North Atlantic Oscillation. Earth Sci Rev 63:145–168

Branstator G, Selten F (2009) “Modes of Variability” and climate Change. J Climate 22:2639–2658

Casado MJ, Pastor MA (2012) Use of variability modes to evaluate AR4 climate models over the Euro-Atlantic region. Clim Dyn 38:225–237

Cassou C, Terray L (2001a) Dual influence of Atlantic and Pacific SST anomalies on the North Atlantic/Europe winter climate. Geophys Res Lett 28, 3195–3198

Cassou C, Terray L (2001b) Oceanic forcing of the wintertime low-frequency atmospheric variability in the North Atlantic European sector: A study with the ARPEGE mode. J Climate 14:4266–4291

Casty C, Raible CC, Stocker TF, Wanner H, Luterbacher J (2007) A European pattern climatology 1766-2000. Clim Dyn 29:791–805

Cheng X, Wallace JM (1993) Cluster analysis of the Northern Hemisphere wintertime 500 hPa height field: Spatial patterns. J Atmos Sci 50:2674–2696

Cheng X, Nitsche G, Wallace JM (1995) Robustness of low-frequency circulation patterns derived from EOF and rotated EOF analysis. J Climate 8:1709–1720

Cook ER, D’Arrigo RD, Mann ME (2002) A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation index since A.D. 400. J Climate 15:1754–1764

Coumou D, Petoukhov V, Rahmstorf S, Petri S, Schellnhuber HJ (2014) Quasi-resonant circulation regimes and hemispheric synchronization of extreme weather in boreal summer. Proc Natl Acad Sci 111:12331–12336

Cranz D (1765) Historie von Grönland enthaltend die Beschreibung des Landes und der Einwohner ec. insbesondere die Geschichte der dortigen Mission der Evangelischen Brüder zu Neu Herrnhut und Lichtenfels. Ebers (Barby)

Egede SH (1745) History of Greenland – A description of Greenland: showing the natural history, situation, boundaries, and face of the country; the nature of the soil; the rise and progress of the old Norwegian colonies; the ancient and modern inhabitants; their genius and way of life, and produce of the soil; their plants, beasts, fishes, etc. (translated from Danish), Pickering Bookseller, London

Furevik T, Nilsen JEØ (2005) Large-scale atmospheric circulation variability and its impacts on the Nordic Seas ocean climate – a review. In Drange H, Dokken T, Furevik T, Gerdes R, Berger W (eds.) The Nordic Seas: An Integrated Perspective. Geophys Mon Ser 158, AGU

Gerber EP, Polvani LM, Ancukiewicz D (2008) Annular mode time scales in the Intergovernmental Panel on Climate Change Fourth Assessment Report models. Geophys Res Lett 35:L22707. doi:10.1029/2008GL035712

Glaser R, Brázdil R, Pfister C, Dobrovolný P, Barriendos Vallvé M, Bokwa A, Camuffo D, Kotyza O, Limanówka D, Rácz, Rodrigo FS (1999) Seasonal temperature and precipitation fluctuation in selected parts of Europe during the sixteenth century. Clim change 43:169–200

Glueck MF, Stockton CW (2001) Reconstruction of the North Atlantic Oscillation, 1429-1983. Int J Climatol 21:1453–1465

Goodkin NF, Hughen KA, Doney SC, Curry WB (2008) Increased multidecadal variability of the North Atlantic Oscillation since 1781. Nature Geoscience 1:844–848

Haine T (2008) What did the Viking discoverers of America know of the North Atlantic Environment? Weather 63:60–65

Häkkinen S, Rhines PB, Worthen DL (2011) Atmospheric blocking and Atlantic multidecadal ocean variability. Science 334:655–659

Handorf D, Dethloff K (2012) How well do state-of-the-art atmosphere-ocean general circulation models reproduce atmospheric teleconnection patterns? Tellus A 64:19777 http://dx.doi.org/10.3402/tellusa.v64i0.19777

Hannachi A (2007a) Pattern hunting in climate: a new method for trends in gridded climate data. Int J Climatol 27:1–15

Hannachi A (2007b) Tropospheric planetary wave dynamics and mixture modeling: Two preferred regimes and a regime shift. J Atmos Sci 64:3521–3541

Hannachi A (2008) A new set of orthogonal patterns in weather and climate: Optimally interpolated patterns. J Climate 21:6724–6738

Hannachi A (2010) On the origin of planetary-scale extratropical circulation regimes. J Atmos Sci 67:1382–1401

Hannachi A, Jolliffe IT, Stephenson DB (2007) Empirical orthogonal functions and related techniques in atmospheric science: A review. Int J Climatol 27:1119–1152

Horel JD (1981) A rotated principal component analysis of the interannual variability of the Northern Hemisphere 500 mb height field. Mon Wea Rev 109:2080–2902

Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation, regional temperatures and precipitation. Science 269:676–679

Hurrell JW, Deser C (2009) North Atlantic climate variability: The role of the North Atlantic Oscillation. J Mar Sys 78:28–41

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

Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (2003) An overview of the North Atlantic Oscillation. In: The North Atlantic Oscillation: Climatic significance and environmental impact, Geophysical Monograph Series 134:1–36, AGU

Jones PD, Mann ME (2004) Climate over past millennia. Rev Geophys 42:RG2002 doi:10.1029/2003RG000143

Jones PD, Jonsson 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

Jung T, Vitart F, Ferranti L, Morcrette JJ (2011) Origin and predictability of the extreme negative NAO winter of 2009/10. Geophys Res Lett 38, L07701, doi:10.1029/2011GL046786

Karpechko AY, Manzini E (2012) Stratospheric influence on tropospheric climate change in the Northern Hemisphere. J Geophys Res 117:D05133 doi:10.1029/2011JD017036

Kimoto M, Ghil M (1993) Multiple flow regimes in the northern hemisphere winter. Part II: Sectorial regimes and preferred transitions. J Atmos Sci 16:2645–2673

Kushnir Y, Wallace JM (1989) Low-frequency variability in the Northern Hemisphere winter: Geographical distribution, structure and time dependence. J Atmos Sci 46:3122–3142

Küttel M, Xoplaki E, Gallego D, Luterbacher J, García-Herrera R, Allan R, Barriendos M, Jones PD, Wheeler D, Wanner H (2009) The importance of ship log data: reconstructing North Atlantic, European and Mediterranean sea level pressure fields back to 1750. Clim Dyn 34:1115–1128

Kyselý J, Huth R (2006) Changes in atmospheric circulation over Europe detected by objective and subjective methods. Theor Appl Climatol 85:19–36

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

Leckebusch GC, Weimer A, Pinto JG, Reyers M, Speth P (2008) Extreme wind storms over Europe in present and future climate: a cluster analysis approach. Meteorol Zeit 17:67–82

Li J, Wang JXL (2003) A new North Atlantic Oscillation index and its variability. Adv Atmos Sci 20:661–676

Luterbacher J, Schmutz C, Gyalistras D, Xoplaki E, Waaner H (1999) Reconstruction of monthly NAO and EU indices back to AD 1657. Geophys Res Lett 26:2745–2748

Luterbacher J, Xoplaki E, Dietrich D, Jones PD, Davies TD, Portis D, Gonzalez-Rouco JF, von Storch H, Gyalistras D, Casty C, Wanner H (2001) Extending North Atlantic oscillation reconstructions back to 1500. Atm Sci Lett 2:1-4

Luterbacher J, Dietrich D, Xoplaki E, Grosjean M, Wanner H (2004) European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303:1499–1503

Marshall J, Johnson H, Goodman J (2001) A study of the interaction of the North Atlantic Oscillation with the ocean circulation. J Climate 14:1399–1421

Moliarini RL, Mayer DA, Festa JF, Bezdek HF (1997) Multiyear variability in the near-surface temperature structure of the midlatitude western North Atlantic Oscillation. J Geophys Res 102: 3267–3278

Nakamura H (1996) Year-to-year and interdecadal variability in the activity of intraseasonal fluctuations in the Northern Hemisphere wintertime circulation. Theor Appl Climatol 55:19–32

Ouzeau G, Cattiaux J, Douville H, Ribes A, Saint-Martin D (2011) European cold winter 2009–2010: How unusual in the instrumental record and how reproducible in the ARPEGE-Climate model? Geophys Res Lett 38:L11706. doi:10.1029/2011GL047667

Pinto JG, Raible CC (2012) Past and recent changes in the North Atlantic oscillation. Clim Change 3:79–90

Portis DH, Walsh JE, El-Hamly M, Lamb PJ (2001) Seasonality of the North Atlantic Oscillation. J Climate 14:2069-2078

Rogers JC (1997) North Atlantic storm-track variability and its association to the North Atlantic Oscillation and climate variability of Northern Europe. J Climate 10:1635–1647

Rutgersson A, Jaagus J, Schenk F, Stendel M (2014) Observed changes and variability of atmospheric parameters in the Baltic Sea region during the last 200 years. Clim Res 61:177–190

Scaife AA, Folland CK, Alexander LV, Moberg A, Knight JR (2008) European climate extremes and the North Atlantic Oscillation. J Climate 21:72–83

Scaife AA, Kucharski F, Folland CK, Kinter J, Brönnimann S, Fereday D, Fischer AM, Grainger S, Jin EK, Kang IS, Knight JR, Kusunoki S, Lau NC, Nath MJ, Nakaegawa T, Pegion P, Schubert S, Sporyshev P, Syktus J, Yoon JH, Zeng N, Zhou (2009) The CLIVAR C20C project: selected twentieth century climate events. Clim Dyn 33:603–614

Scaife AA, Spangehl T, Fereday DA, Cubasch U, Langematz U, Akiyoshi H, Bekki S, Braesicke P, Butchard N, Chipperfiels MP, Gettelman A, Hardiman SC, Michou M, Rozanov E, Shepherd TG (2012) Climate change and stratosphere-troposphere interaction. Clim Dyn 38:2089–2097

Schmutz C, Luterbacher J, Gyalistras D, Xoplaki E, Wanner H (2000) Can we trust proxy-based NAO index reconstructions? Geophys Res Lett 27:1135–1138

Selten FM, Branstator GW, Dijkstra HA, Kliphuis M (2004) Tropical origins for recent and future Northern Hemisphere climate change. Geophys Res Lett 31:L21205. doi:10.1029/2004GL020739

Semenov VA, Latif M, Jungclaus JH, Park W (2008) Is the observed NAO variability during the instrumental record unusual? Geophys Res Lett 35:L11701. doi:10.1029/2008GL033273

Serreze MC, Carse F, Barry RG, Rogers JC (1997) Icelandic low cyclone activity: climatological features, linkages with the NAO and relationships with recent changes in the Northern Hemisphere circulation. J Climate 10:453–464

Sigmond M, Scinocca JF (2010) The influence of the basic state on the Northern Hemisphere circulation response to climate change. J Climate 23:1434–1446

Stephenson DB, Wanner H, Brönnimann S, Luterbacher J (2003) The history of scientific research on the North Atlantic Oscillation. In: Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (eds) The North Atlantic Oscillation: Climatic Significance and Environmental Impact. AGU Geophys Monogr Series 134

Stoner AMK, Hayhoe K, Wuebbles DJ (2009) Assessing General Circulation Model simulations of atmospheric teleconnection patterns. J Climate 22:4348–4372

Thompson DWJ, Wallace JM (1998) The Arctic oscillation signature in the wintertime geopotential height and temperature fields. Geophys Res Lett 25:1297–1300

Thompson DWJ, Wallace JM, Hegerl GC (2000) Annual modes in the extratropical circulation: Part II: Trends. J Climate 13:1018–1036

Trouet V, Esper J, Graham NE, Baker A, Scourse JD, Frank DC (2009) Persistent positive North Atlantic Oscillation mode dominated the medieval climate anomaly. Science 324:78–80

Vinther BM, Andersen KK, Hansen AW, Schmith T, Jones PD (2003) Improving the Gibraltar/Reykjavik NAO index. Geophys Res Lett 30:2222, doi:10.1029/2003GL018220

Visbeck M, Chassignet EP, Curry RG, Delworth TL, Dickson RR, Krahmann G (2003) The ocean's response to North Atlantic Oscillation variability In: Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (eds) The North Atlantic Oscillation: Climatic Significance and Environmental Impact. AGU Geophys Monogr Series 134

Wallace JM, Gutzler DS (1981) Teleconnections in the geopotential height field during the Northern Hemisphere winter. Mon Wea Rev 109:784–812

Wanner H, Brönnimann S, Casty C, Gyalistras D, Luterbacher J, Schmutz C, Stephenson DB, Xoplaki E (2001) North Atlantic Oscillation - concepts and studies. Surv Geophys 22:321–381

Wheeler D, Garcia-Herrera R, Wilkinson CW, Ward C (2009) Atmospheric circulation and storminess derived from Royal Navy logbooks: 1685 to 1750. Clim Change 110:257–280

Woollings TJ, Hannachi A, Hoskins B (2010a) Variability of the North Atlantic eddy-driven jet stream. Q J Roy Met Soc 136:856–868

Woollings TJ, Hannachi A, Hoskins B, Turner A (2010b) A regime view of the North Atlantic Oscillation and its response anthropogenic forcing. J Climate 23:1291–1307

Xin XG, Zhou TJ, Yu RC (2008) The Arctic Oscillation in coupled climate models. Chin J Geophys Chinese Edition 51:337–351

Xoplaki E (2002) Climate variability over the Mediterranean. PhD thesis, University of Bern, Switzerland

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

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 Climate 5:1097–1108