# Summer North Atlantic Oscillation (SNAO) variability on decadal to palaeoclimate time scales

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### The summer North Atlantic Oscillation (SNAO)

The influence of the North Atlantic Oscillation (NAO) on climate in the North Atlantic region has been highlighted over the past few decades. Although most prominent during winter, the NAO is one of the few modes of variability that persist throughout the year, although there are systematic differences in its configuration through the seasons (Barnston and Livezey, 1987). This is related to seasonal variations of the North Atlantic jet stream which on average moves northwards in summer relative to winter. Consequently, the positive and negative nodes of the dipole NAO pattern have more northerly positions during summer. Until recently, most studies of the link between the NAO and climate have focused on winter, but after a thorough study of the summer NAO (SNAO) by Folland et al. (2009, henceforth F09), attention has also been directed to summer.

During summer the NAO pattern has its pressure centres located over the British Isles/Scandinavia and Greenland (Hurrell and Folland, 2002). Due to the lack of data from its northern node, SNAO has largely been defined until now from the variability of the southern node. F09 defined the SNAO as the first eigenvector of pressure at mean sea level (PMSL) anomalies (PMSLA) over the extratropical European–North Atlantic sector (25–70°N, 70°W–50°E) in July and August (JA). The SNAO time series shows large interannual to decadal variability as does the winter NAO, but the correlation between them is very low. The SNAO phase is strongly related to changes in Atlantic and European summer storm tracks (Dong et al., 2013). In its positive phase, the SNAO is associated with anticyclonic conditions over Northern Europe, yielding sunny, warm and dry conditions there. Accordingly, the positive phase of the SNAO is related to summer droughts from the UK to Scandinavia in particular, and a northerly position of the main storm track. In the negative SNAO phase, the storm track moves ~10° further south, giving cloudy, wet and cooler conditions over this region. The relationship with surface climate is surprisingly strong for southern Europe and more or less the opposite, especially in the eastern Mediterranean (Chronis et al., 2011). Climatic influences outside northwestern Europe have also been noted, e.g. eastern North America (Hardt et al., 2010) and East Asia (Linderholm et al., 2011).

On interannual to multidecadal timescales, SNAO variability can be linked to variations in North Atlantic surface temperature (SST). Observations and models indicate an association between the Atlantic Multidecadal Oscillation (AMO) ( Kerr, 2000) and the SNAO for periods greater than 10 years (F09) such that a cold (warm) phase of the AMO corresponds a positive (negative) phase of the SNAO, clearly seen in Sutton and Dong (2012).

Recently, the potential influence of Arctic climate change, particularly related to the large reduction in sea ice coverage, on mid-latitude circulation patterns has been studied (e.g. Overland and Wang, 2010; Francis and Skific, 2015). For instance, Wu et al. (2013) suggested that winter sea ice concentration conditions west of Greenland influences the following summer atmospheric circulation over northern Eurasia. Using observations, Knudsen et al. (2015) found a link between anomalous Arctic sea ice melt and changes in midlatitude atmospheric patters during summer, as did Screen (2013) using an atmospheric general circulation model. Petrie et al. (2015), using a fully coupled climate model, found that sea ice loss together with increased SST in the Labrador Sea affects the summer atmospheric circulation over the North Atlantic region.

Within an ongoing International CLIVAR Climate of the 20th Century (C20C) Project (Kinter and Folland, 2011) and a project supported by the Swedish Research council, studies have been underway to describe SNAO variability on decadal to multicentury timescales, mechanisms behind its variability and its potential predictability. Recent work has extended the definition of the SNAO to include June in addition to July and August, and new data sets allow this definition to be extended spatially to include data from the whole Arctic. This work, to be reported elsewhere, does not change the fundamental spatial or temporal character of the SNAO but it is better aligned to important aspects of seasonal forecasting

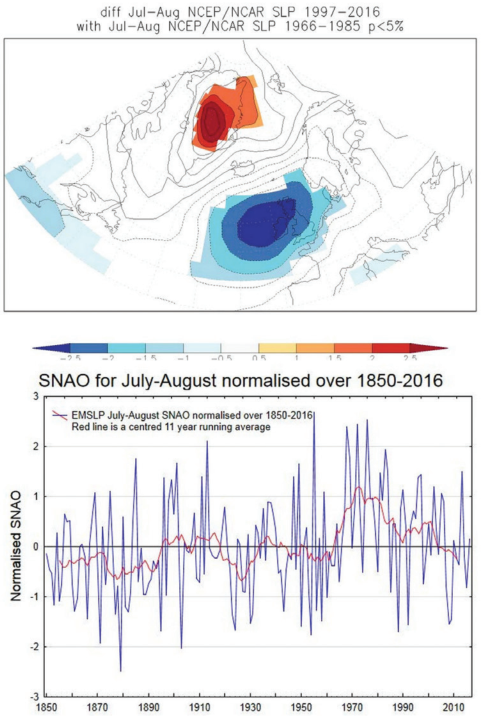

**Figure 1: (Top Panel)** Differences in pressure at mean sea level over the North Atlantic and Europe in July and August between the two decades 1997-2016 and the two decades 1966-1985, together with significances of these differences at the 5% level. **(Bottom Panel)** Variations in the July and August SNAO, 1850-2016

research. Here we confine ourselves to the JA SNAO as discussed in F09 and show a key result that indicates that over the last 5 decades the JA SNAO emerges naturally as a key component of JA atmospheric circulation change. Fig. 1 (top panel) shows the difference in pressure at mean sea level using the NCEP Reanalysis between the two most recent decades 1997-2016 and the two decades 1966-1985. These periods have been chosen to illustrate the character of a large decline in the JA SNAO (Fig 1, bottom panel). This shows that the last half century contains the largest coherent fluctuation of the SNAO since 1850 with a large decline in its value since the 1970s. However the recent relatively negative level of the SNAO is quite similar to its average level in the late nineteenth century, so that the very positive levels of the 1970s in particular are the more unusual. Fig 1 (top panel) shows that the difference pattern appears to be very like the negative pattern of the SNAO. Thus the SNAO, defined from an eigenvector analysis over the much longer period 1881-2003 and explaining about 28% of the mean July and August variance over this period, dominates the changing pattern of interdecadal July and August decadal pressure at mean sea level since the 1970s over the North Atlantic and Europe. In fact the centres of difference over Greenland and near the United Kingdom are both significant at the 0.1% level. The negative centre over the UK has, for instance, led to markedly wetter late summers over England and Wales in the most recent decade in contrast to expected long term changes found in many papers towards more anticyclonic, dry, conditions arising from anthropogenic warming (e.g. F09). Research is underway, including the use of CMIP5 models, to attempt to explain this large short term change in climate, particularly sea surface temperatures in the Atlantic and the global tropics and possible influences of changing Arctic sea ice extents (Screen, 2013; Petrie et al., 2015). Other aspects of the behaviour of the SNAO on interannual to century time scales are summarised annually in State of the Climate publications (e.g. Allan and Folland, 2016).

## SNAO variability during the last millennium

Several studies have shown that tree growth variations across Europe are linked to SNAO-like atmospheric circulation patterns (e.g. Seftigen et al., 2013), suggesting the suitability of using tree-ring data to reconstruct the SNAO before the observational record. Indeed, F09 used tree-ring data from western Norway and northern UK to produce a reconstruction of the JA SNAO back to 1706 CE, verified by long instrumental records from the UK. Using a tree-ring network with much larger spatial distribution, the reconstruction was extended back to 1441 CE, providing opportunities to study e.g. associations between the SNAO and European/Sahel drought (Linderholm et al., 2009) and associations between the SNAO and summer climate in East Asia in a long-term context (Linderholm et al., 2013). Here we present a preliminary new reconstruction where the target season was extended to JJA. This should also help from a tree-ring perspective as the growth of trees in northwestern Europe is influenced by temperature or precipitation in June as well. This reconstruction, based only on tree-ring data from the southern node region of the SNAO (i.e. UK and Fennoscandia), which extends back to 1200 CE, is shown in Fig. 2. In light of the potential influences of Arctic sea ice as noted above, it is also compared to northeastern Canadian summer sea ice cover (SIC) variations inferred from coralline algae (Halfar et al., 2013), and a multi-proxy reconstruction of the AMO (Mann et al., 2009). On multidecadal timescales, a sustained period of negative SNAO during the Little Ice Age (LIA) coincided with high SIC (note that SIC is inverted in Fig. 2). Also the positive SNAO in the twentieth century corresponds to a significant decrease in SIC. However, no stable association between the SNAO and summer SIC during the last six centuries is evident. This may be because none actually exists, despite an apparent influence, where reduced Arctic sea ice extents favour the negative SNAO implied by Screen (2013), or the variation of drivers not studied here is more important. To better assess the potential influence of Arctic sea ice on the SNAO in a long-term context, additional SIC proxies are needed. The long-term evolution of the AMO is in general (except for the 1200s) quite similar to that of the SNAO: negative (positive) multidecadal phases of the the AMO correspond to periods of negative (positive) SNAO. Our tentative comparison suggests that both long-term changes in the AMO and SIC are of opposite signs in their apparent influences on the recent shorter-term

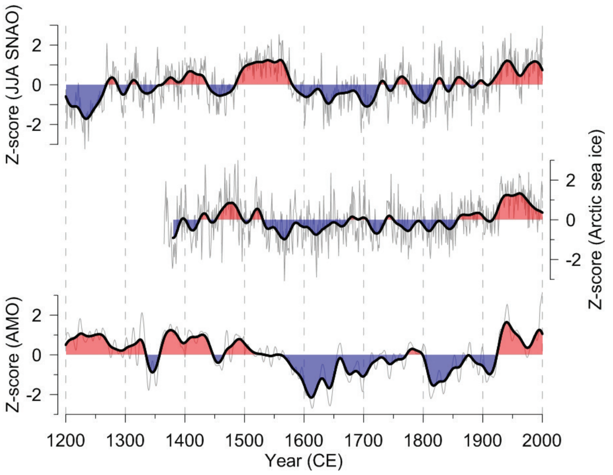

**Figure 2:** A preliminary reconstruction of the JJA SNAO, based on tree-ring data from Fennoscandia and the UK, (upper panel) compared to inferred (inverted) sea ice variability in the eastern Canadian Arctic (middle panel), derived from coralline alge and representing the region 85-60°W, 55-73°N, (Halfar et al., 2013, data available at www.ncdc.noaa.gov/paleo-search/study/15454), and a reconstruction of the AMO (lower panel, Mann et al. (2009)). All records have been z-scored. Thick lines represent 30-year variability. Note that positive algal proxy anomalies correspond to below normal sea ice coverage.

behaviour of the SNAO. Still, this apparent contradiction may be due to the data used here. For instance, the AMO index used here was derived from a gridded reconstruction of temperatures mainly based on terrestrial proxies only. The recent increase in the spatiotemporal representation of palaeoclimate proxies, e.g. within the PAGES 2k initiative, provides new the opportunities for improving the multicentury reconstruction of indices like the AMO and different Arctic sea ice parameters.

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