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Northern Hemisphere climate variability during winter: Looking back on the work of Felix Exner

JAMES W. HURRELL* and CLARA DESER

National Center for Atmospheric Research[1], Boulder, Colorado, USA

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Abstract

We present a brief commentary on the landmark study of EXNER (1913), in which an analysis of the correlation between monthly anomalies of "polar pressure" and sea level pressure from numerous stations around the Northern Hemisphere during winter was presented. Exner's analysis still stands today as an excellent description of the spatial structure of the leading pattern of atmospheric variability over the extratropical Northern Hemisphere (NH); namely, the North Atlantic Oscillation (NAO). Moreover, Exner provided an accurate commentary on regional changes in surface air temperature driven by NAO variability. His quantitative analysis of these aspects represented a major step forward in the history of research on NH climate variability that, prior to his study, was primarily qualitative.

Keywords: climate variability, North Atlantic Oscillation, science history

1 Introduction

Contemporary atmospheric and climate scientists are very familiar with the North Atlantic Oscillation (NAO) as the most prominent and recurrent pattern of atmospheric variability over the middle and high latitudes of the Northern Hemisphere (NH), especially during the cold season months (November–April). The NAO refers to a redistribution of atmospheric mass between the Arctic and the subtropical Atlantic, and swings from one phase to another produce large changes in the mean wind speed and direction over the Atlantic, the heat and moisture transport between the Atlantic and the neighboring continents, and the intensity and number of storms, their paths, and their weather. As a result, winter weather over large regions of the NH, and especially continental regions around the Atlantic Ocean, is dominated by the NAO, impacting agricultural harvests, water management, energy supply and demand, and yields from fisheries, among many other things. It is worth noting that the original meaning of the term "oscillation" in the NAO acronym is that of a seesaw in space rather than time: that is, atmospheric mass "oscillates" between the Arctic and subtropical Atlantic, while NAO variations in time are irregular (HURRELL and DESER, 2009).

As a result of such pronounced impacts, the history of scientific research on the NAO is rich, with some of the earliest descriptions of it dating back to seafaring Scandinavians several centuries ago. As noted by VAN LOON and ROGERS (1978), for instance, the Danish priest and missionary to Greenland, Hans Egede Saabye (1746–1817), noted in his diary "In Greenland, all winters are severe, yet they are not alike. The Danes have noticed that when the winter in Denmark was severe, as we perceive it, the winter in Greenland in its manner was mild, and conversely." This temperature seesaw between Greenland and northern Europe is one of the classic characteristics of NAO variability, and the simultaneous, out-of-phase temperature variations it describes over regions far apart are commonly referred to as "teleconnections" in the modern meteorological literature. Teleconnections are a consequence of the transient behavior of atmospheric planetary-scale waves, so that anomalies in climate on monthly or seasonal time scales typically occur over large geographic regions. Some regions may be cooler or perhaps drier than average, while at the same time thousands of kilometers away, warmer and wetter conditions prevail.

The increasing availability of observed temperature measurements at stations scattered across the NH made it possible for such spatial and temporal variations in climate to be qualitatively described by climatologists as early as the 19th century. DOVE (1838; 1839), for instance, confirmed Saabye's observations by investigating 60 time series from stations all over the NH. He noted an opposition of monthly and seasonal northern European temperature anomalies with those from parts of North America, and he further noted that east-west variations in temperature anomalies across the NH were often more pronounced than north-south variations.

WANNER et al. (2001), STEPHENSON et al. (2003), and LUTERBACHER et al. (2008) provide much more complete accounts of these, and other early, qualitative studies of NH climate variability. As they also note, the paper by FELIX EXNER "Über Monatliche Witterungsanomalien auf der Nördlichen Halbkugel im Winter" (On Monthly Weather Anomalies in the Northern Hemisphere in Winter), published in *Sitzungs-*

*Corresponding author: James W. Hurell, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000, Colorado, USA, e-mail: jhurrell@ucar.edu

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berichte der Kaiserl, Akademie der Wissenschaften in 1913, represented a major step forward in the history of scientific research on NH climate variability and, in particular, the NAO. A short summary of this iconic paper appeared in *Meteorologische Zeitschrift* in 1914, and is translated in this issue. Exner (1913) made use of the statistical technique of correlation analysis, conceived by Galton (1888) and introduced into climate research by Sir Gilbert Walker (1909), to produce the first correlation map showing the spatial structure of the NAO. His quantitative analysis, based mainly on a decade of station records of sea level pressure (SLP) and temperature from 50 stations across the NH, is remarkable in that his findings are robust today, as we will show below. Moreover, many of the qualitative investigations of climate variability by Exner's predecessors, based on visual inspections of time series, led to the identification of many spurious relationships between climate variables (Stephenson et al., 2003).

Felix Maria Exner (1876–1930) was a pioneer in that he was the first to accurately depict not only the spatial structure of what we now know as the leading pattern of atmospheric variability over the NH, but he also provided a very insightful and accurate commentary on the role of the changing atmospheric circulation in driving regional variations in temperature. Moreover, by applying a lagged correlation analysis, Exner (1913) explored the utility of his findings for forecasting. To put Exner's research into perspective, it is useful to briefly examine some modern techniques for determining the spatial structure of the NAO, as well as the impact of NAO variability on surface climate.

2 Spatial structure of the NAO

There is no single way to "define" the NAO. One approach is through conceptually simple correlation maps (e.g., Fig. 5 of Hurrell and Deser, 2009), much like Exner (1913). Another technique, more often used today, is Empirical Orthogonal Function (EOF, or principal component) analysis. In this approach, the NAO is identified from the eigenvectors of the cross-covariance (or cross-correlation) matrix, computed from the time variations of the grid point values of SLP or some other climate variable. The eigenvectors, each constrained to be spatially and temporally orthogonal to the others, are then scaled according to the amount of total data variance they explain. This linear approach assumes preferred atmospheric circulation states come in pairs, in which anomalies of opposite polarity have the same spatial structure.

The NAO is the only teleconnection pattern evident throughout the year in the NH (Wallace and Gutzler 1981; Barnston and Livezey, 1987). During the boreal winter season (defined here as December-March), when the atmosphere is most active dynamically and perturbations grow to their largest amplitudes, the NAO accounts for more than one-third of the total variance in

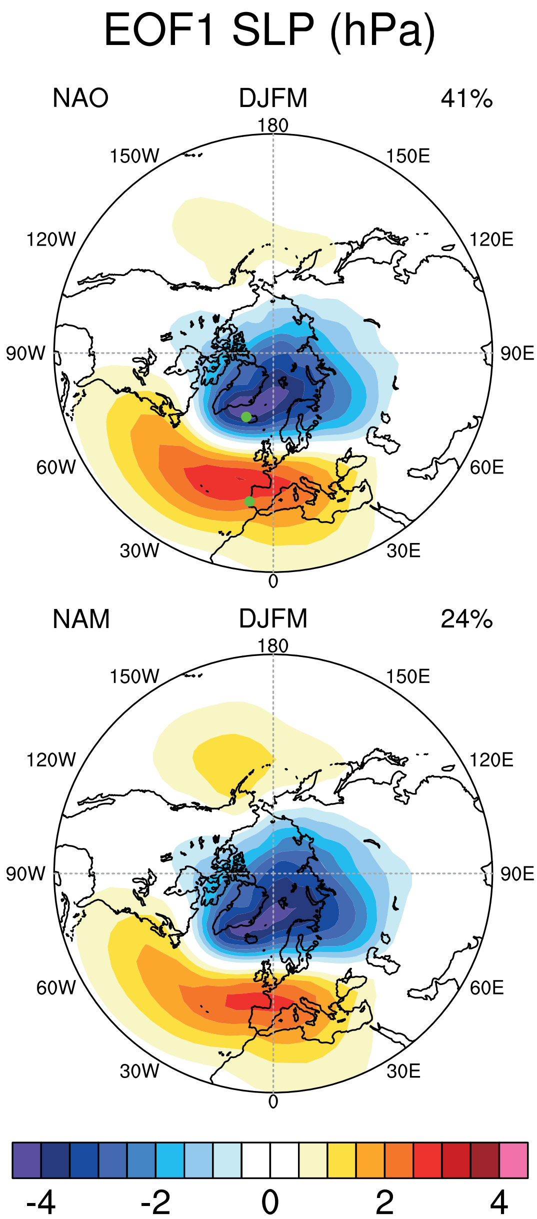

Figure 1: Leading empirical orthogonal function (EOF 1) of the winter (December-March) mean sea level pressure anomalies over (top) the North Atlantic sector (20°–70°N, 90°W-40°E) and (bottom) the Northern Hemisphere (20°–90°N), and the percentage of the total variance they explain. The patterns are displayed in terms of amplitude (hPa), obtained by regressing the hemispheric sea level pressure anomalies upon the leading standardized principal component time series. The data cover 1899–2013. The green dots in the top panel represent the locations of Lisbon, Portugal and Stykkisholmur, Iceland used in the station based NAO index of Hurrell (1995).

SLP fluctuations from one winter to the next over the North Atlantic (20°–70°N, 90°W–40°E). In the so-called "positive phase" (depicted in Fig. 1, upper panel), higher-than-normal surface pressures south of 55°N combine with a broad region of anomalously low pressure throughout the Arctic to enhance the climatological meridional pressure gradient. The largest amplitude anomalies occur in the vicinity of Iceland and across the Iberian Peninsula. The positive phase of the NAO is associated with stronger-than-average surface westerlies across the middle latitudes of the Atlantic onto Europe, with anomalous southerly flow over the eastern U.S. and anomalous northerly flow across the Canadian Arctic and the Mediterranean (Hurrell, 1995), very similar to the circulation anomalies described by Exner (1913).

A well-known shortcoming of EOF analysis, however, is that eigenvectors are mathematical constructs, constrained by their mutual orthogonality and the maximization of variance over the entire analysis domain. There is no guarantee, therefore, that they represent physical modes of the climate system. Moreover, the loading values of EOFs do not reflect the local behavior of the data: values of the same sign at two different spatial points in an EOF do not imply that those two points are significantly correlated. This means that the pattern structure of any particular EOF must be interpreted with care.

These issues have been at the center of a debate over whether or not the NAO is a regional expression of a larger-scale (hemispheric) mode of variability known as either the NH Annular Mode (NAM) or the Arctic Oscillation (AO; see Thompson and Wallace 2000). The NAM is defined as the first EOF of NH (20°–90°N) winter SLP data (Fig. 1, lower panel). It explains about one-quarter of the winter-mean (December-March) variance, and it is clearly dominated by the NAO structure in the Atlantic sector. Although there are some subtle differences from the regional pattern over the Atlantic and Arctic, the main difference is larger amplitude anomalies over the North Pacific of the same sign as those over the Atlantic. This feature gives the NAM an almost annular (or zonally-symmetric) structure that reflects a more hemispheric-scale meridional seesaw in SLP between polar and middle latitudes. Some have argued the NAM is a fundamental structure of NH climate variability, and that the "regional" NAO reflects the modification of the annular mode by zonally asymmetric forcings, such as topography and land-ocean temperature contrasts. It would then follow that the annular mode perspective is critical in order to understand the processes that give rise to NAM (or NAO) variations. For instance, the leading wintertime pattern of variability in the lower stratosphere is clearly annular (not shown), but the SLP anomaly pattern that is associated with it is confined almost entirely to the Arctic and Atlantic sectors and coincides with the spatial structure of the NAO (e.g., Deser, 2000).

3 Impact on surface climate

Changes in the mean atmospheric circulation patterns over the North Atlantic associated with the NAO are accompanied by changes in the intensity and number of storms, their paths, and their weather (Rogers, 1997). During winter, a well-defined storm track connects the North Pacific and North Atlantic basins, with maximum storm activity over both ocean basins. Positive NAO index winters are associated with a northeastward shift in the Atlantic storm track with enhanced activity from Newfoundland into northern Europe and a modest decrease in activity to the south. Positive NAO index winters are also typified by more intense and frequent storms in the vicinity of Iceland and the Norwegian Sea (see Fig. 12 in Hurrell and Deser, 2009).

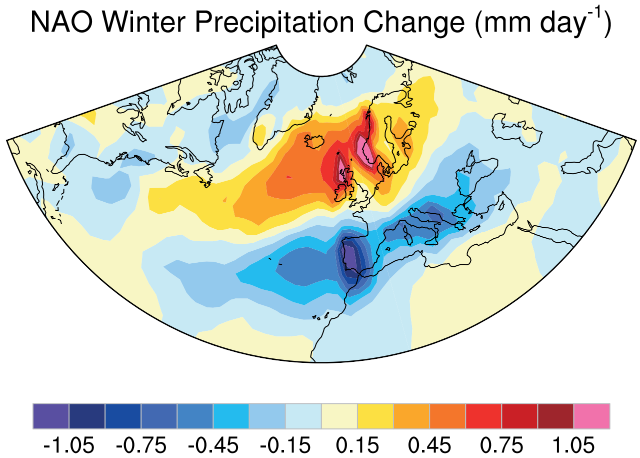

Figure 2: Changes in mean winter (December-March) precipitation (mm day^{-1}) associated with a plus one standard deviation departure of the NAO index, defined as the leading principal component time series associated with the top panel in Figure 1. The precipitation data cover 1979 through 2013 and are from the Global Precipitation Climatology Project (Adler et al. 2003).

Changes in the mean flow and storminess associated with swings in the NAO index are also reflected in pronounced changes in the transport and convergence of atmospheric moisture and, thus, the distribution of precipitation. Winters tend to be dry over much of central and southern Europe and northern portions of the Mediterranean, whereas more precipitation than normal falls from Iceland eastward to Scandinavia, during high NAO index periods (Fig. 2). Weaker magnitude drying also occurs over Greenland, the Canadian Arctic, and parts of the Middle East in association with high NAO index winters (Fig. 2).

The NAO also exerts a dominant influence on wintertime temperatures across much of the NH (Hurrell, 1995). Surface air temperature and sea surface temperature (SST) across wide regions of the North Atlantic Ocean, North America, the Arctic, Eurasia and parts of the Middle East are significantly correlated with NAO variability. When the NAO index is positive, for instance, enhanced westerly flow across the North Atlantic during winter brings relatively warm (and moist) maritime air over much of Europe and far downstream across Asia, while stronger northerlies over Greenland and northeastern Canada carry cold air southward and decrease land temperatures and SST over the northwest Atlantic (Fig. 3). Temperature variations over North Africa and the Middle East (cooling), as well as North America (warming), associated with the stronger clockwise flow around the subtropical Atlantic high-pressure

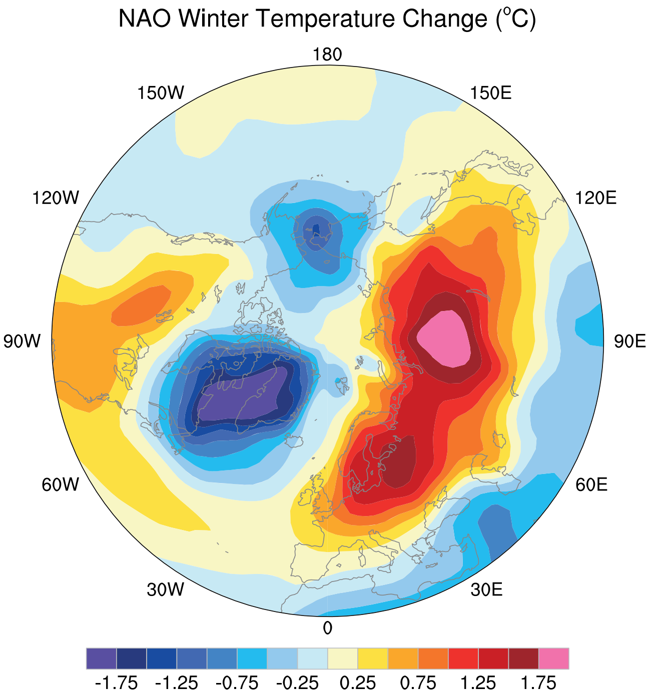

Figure 3: Changes in mean winter (December-March) air temperature (°C) associated with a plus one standard deviation departure of the NAO index, defined as the leading principal component time series associated with top panel in Figure 1. The temperature data cover 1980 through 2013 (Kalnay et al., 1996).

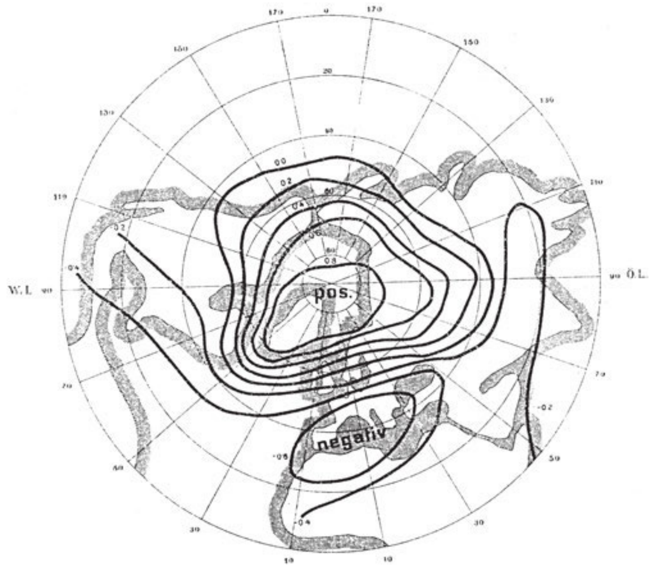

Figure 4: Map of the correlation coefficients between monthly anomalies of "polar pressure" and sea level pressure at around 50 sites of the Northern Hemisphere from 1887 to 1906 (from Exner, 1913).

center are also notable, and were well-described by Exner (1913).

The NAO also drives significant fluctuations in Arctic sea ice concentrations, which exhibit a seesaw in ice extent between the Labrador and Greenland Seas. These, as well as other impacts on surface climate and on both human and natural systems across the NH, are beyond the scope of this commentary but are described more completely by Hurrell and Deser (2009), as well as the many references within their paper. It is worth noting that the NAO's influence on surface climate may exhibit some changes over time, as documented in Osborn et al. (1999) and Hilmer and Jung (2000).

4 Summary and reflections on Exner (1913)

Felix Exner's correlation map of NH SLP anomalies is reproduced in Fig. 4. It shows the correlation coefficients between monthly mean pressure anomalies at the North Pole and those at roughly 50 other sites across the NH based on approximately one decade of measurements. The North Pole anomalies are approximated by the mean of the anomalies of two stations: Gjesvaer (northern Norway) and Markowo (northeastern Siberia). In his discussion of the map, Exner emphasized the annular appearance of the pattern and the strong local signatures in the North Atlantic and Mediterranean areas. In fact, his correlation pattern closely resembles the NAO (and NAM) spatial patterns in Fig. 1, which were found using the EOF analysis technique applied to a gridded analysis of NH SLP data covering more than a century (1899–2006). Exner (1913) also quite aptly described the spatial structure of the NAO-induced surface temperature anomalies illustrated in Fig. 3. In particular, he notes "the spatial distribution of the temperature anomalies resemble those expected if the air flow in areas with positive or negative pressure anomalies is similar to that in high- and low-pressure areas, transporting temperature [anomalies] to other places".

As mentioned earlier, Exner (1913) also used a lagged correlation analysis in an attempt to determine the relationships of non-simultaneous anomalies of air pressure and temperature at different stations, with implications for forecasting climate conditions a month or longer in advance. We will not summarize his major findings here, especially as Exner himself noted his efforts were only a preliminary attempt to identify forecast skill and his analysis mostly illustrated that it would be "desirable to continue these attempts".

A decade later, Walker (1923) made use of similar correlation techniques in an attempt to seasonally forecast the Indian summer monsoon and the flooding of the Nile. In so doing, he grouped world weather variations into several distinct patterns and noted his "Iceland Azores oscillation is not very closely related with that between the Pacific and Indian oceans" and suggested that "readers interested in northern relationships must in any case read Exner's interesting and important paper [Exner, 1913]". Walker later termed the North Atlantic correlations the "North Atlantic Oscillation", and his concept of the NAO became popular among contemporary meteorologists (see Wanner et al., 2001 and Stephenson et al., 2003 for further details).

It is furthermore noteworthy that Exner's (1913) pursuit of predictability continues to this day, more than a century later, motivated by the significant impact of the NAO on the climate and ecosystems of the NH (Hurrell and Deser, 2009). While modern science has established that most of the atmospheric circulation variability in the form of the NAO arises from the internal, nonlinear dynamics of the extratropical atmosphere (Hurrell et al. 2003) and is, therefore, largely unpredictable, considerable research continues around the idea that external forces might nudge the atmosphere to assume a high or low NAO index value over a particular month or season (Scaife et al., 2014). This is important, as even a small amount of predictability could be extremely useful. Moreover, one of the most urgent challenges is to advance our understanding of the interaction between the anthropogenic rise in greenhouse gas concentrations and the NAO (IPCC 2013). Finally, while the predictability of seasonal to interannual NAO variability will most likely remain low, some applications may benefit from the fact that this phenomenon leaves long-lasting imprints on surface conditions, in particular over the oceans.

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