The North Atlantic Oscillation:
Climatic Significance and Environmental Impact

James W. Hurrell
National Center for Atmospheric Research
Climate and Global Dynamics Division, Climate Analysis Section
P.O. Box 3000, Boulder, CO 80307-3000, USA.
Tel: 1-303-497-1383; Fax: 1-303-497-1333
Email address: jhurrell@ucar.edu

Introduction

Simultaneous variations in weather and climate over widely separated points on earth have long been noted in the meteorological literature. Such variations are commonly referred to as “teleconnections”. In the extratropics, teleconnections link neighboring regions mainly through the transient behavior of atmospheric planetary-scale waves. Consequently, some regions may be cooler than average, while thousands of kilometers away warmer conditions prevail. Though the precise nature and shape of these structures vary to some extent according to the statistical methodology and the data set employed in the analysis, consistent regional characteristics that identify the most conspicuous patterns emerge.

Over the middle and high latitudes of the Northern Hemisphere (NH), roughly a dozen distinct teleconnection patterns can be identified. One of the most prominent is the North Atlantic Oscillation (NAO), which refers to changes in the atmospheric sea level pressure difference between the Arctic and the subtropical Atlantic. Although it is the only teleconnection pattern evident throughout the year in the NH, the climate anomalies associated with the NAO are largest during the boreal winter months when the atmosphere is dynamically the most active.

A time series (or index) of nearly 150 years of wintertime NAO variability and the spatial pattern of the oscillation are shown in **Figures 1** and **2**. In the positive index phase, higher than normal surface pressures south of 55°N combine with a broad region of anomalously low pressure throughout the Arctic. Because air flows counterclockwise around low pressure and clockwise around high pressure in the NH, this phase of the oscillation is associated with stronger-than-average westerly winds across the middle latitudes of the Atlantic onto Europe, with anomalous southerly flow over the eastern United States and anomalous northerly flow across western Greenland, the Canadian Arctic, and the Mediterranean.

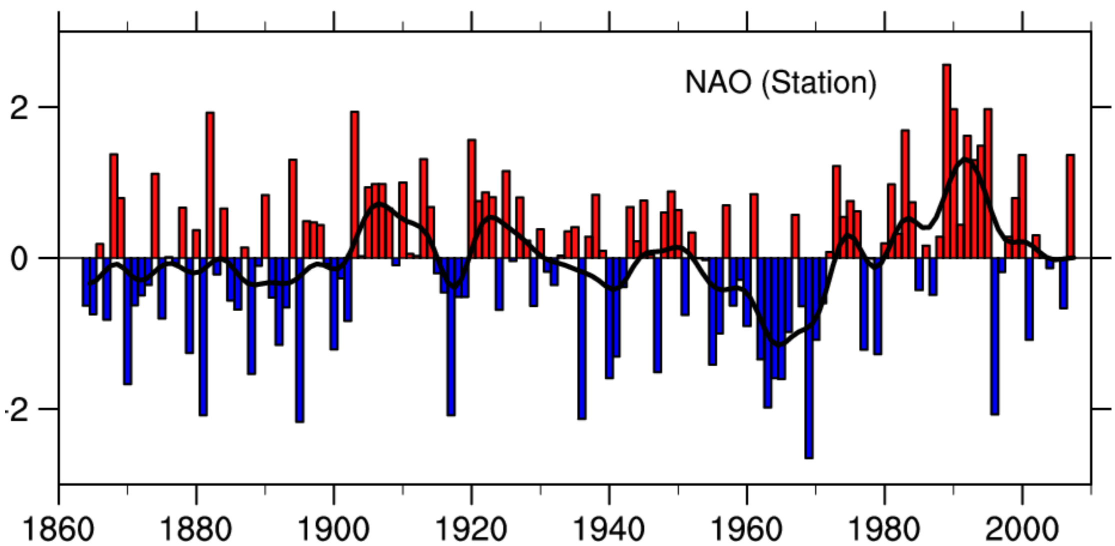

Figure 1. *Index of the boreal winter (December-March) mean NAO constructed as the difference in sea level pressure between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland from 1864 through 2007. The mean winter sea level pressure data at each station were normalized by division of each seasonal pressure by the long-term mean (1864-1983) standard deviation. The heavy solid line represents the index smoothed to remove fluctuations with periods less than 4 years. The indicated year corresponds to the January of the winter season (e.g., 1990 is the winter of 1989/1990).*

Impacts of the NAO

Swings in the NAO produce changes in wind speed and direction over the Atlantic that significantly alter the transport of heat and moisture. During positive NAO index winters, enhanced westerly flow across the North Atlantic moves relatively warm and moist maritime air over much of Europe and far downstream across Asia, while stronger northerlies carry cold air southward and decrease land and sea surface temperatures over the northwest Atlantic (**Figure 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 center are also notable.

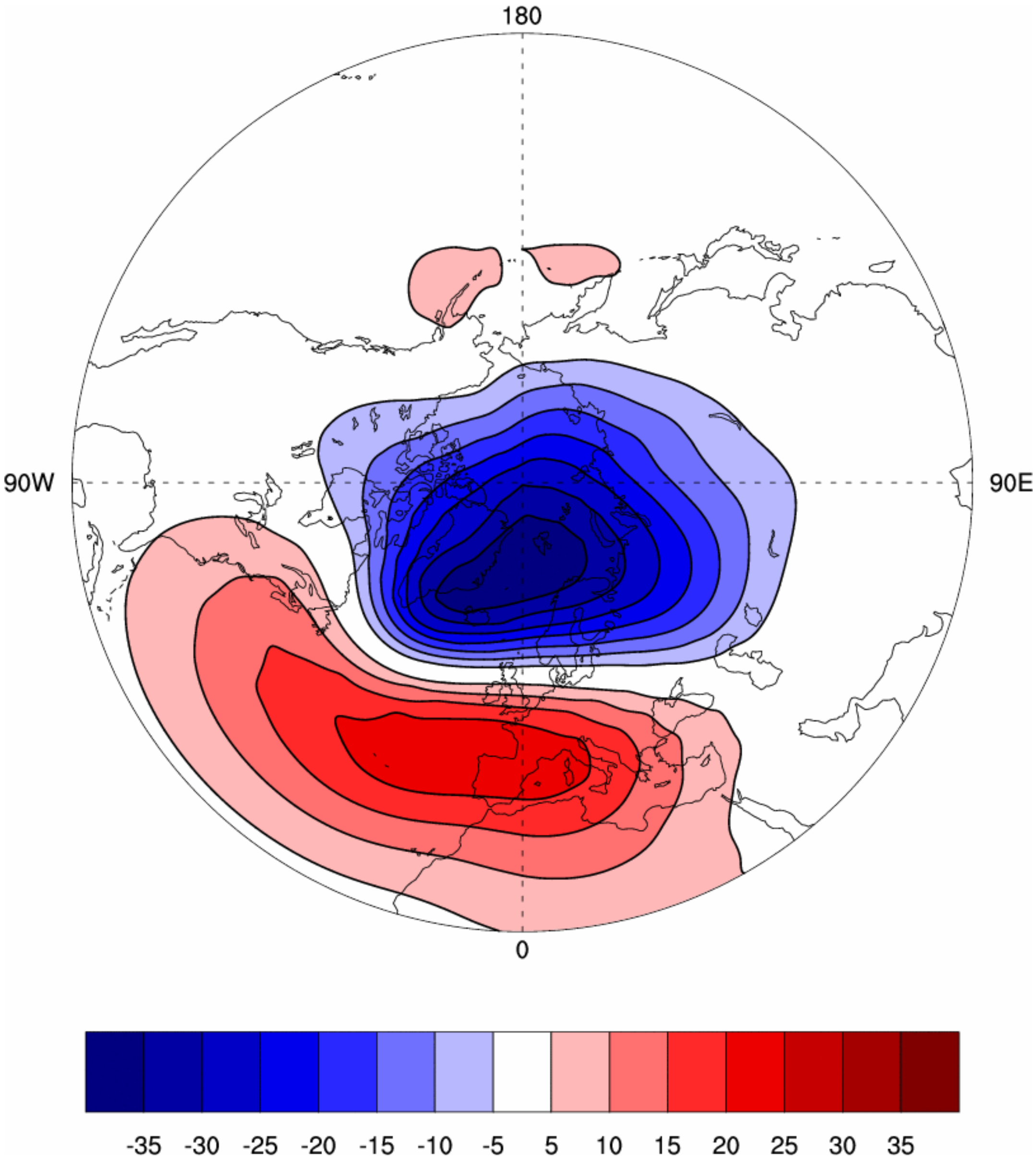

Figure 2. *Change in winter (December-March) surface pressure corresponding to a unit deviation of the NAO index over 1900 to 2005. The contour increment is 0.5 hPa.*

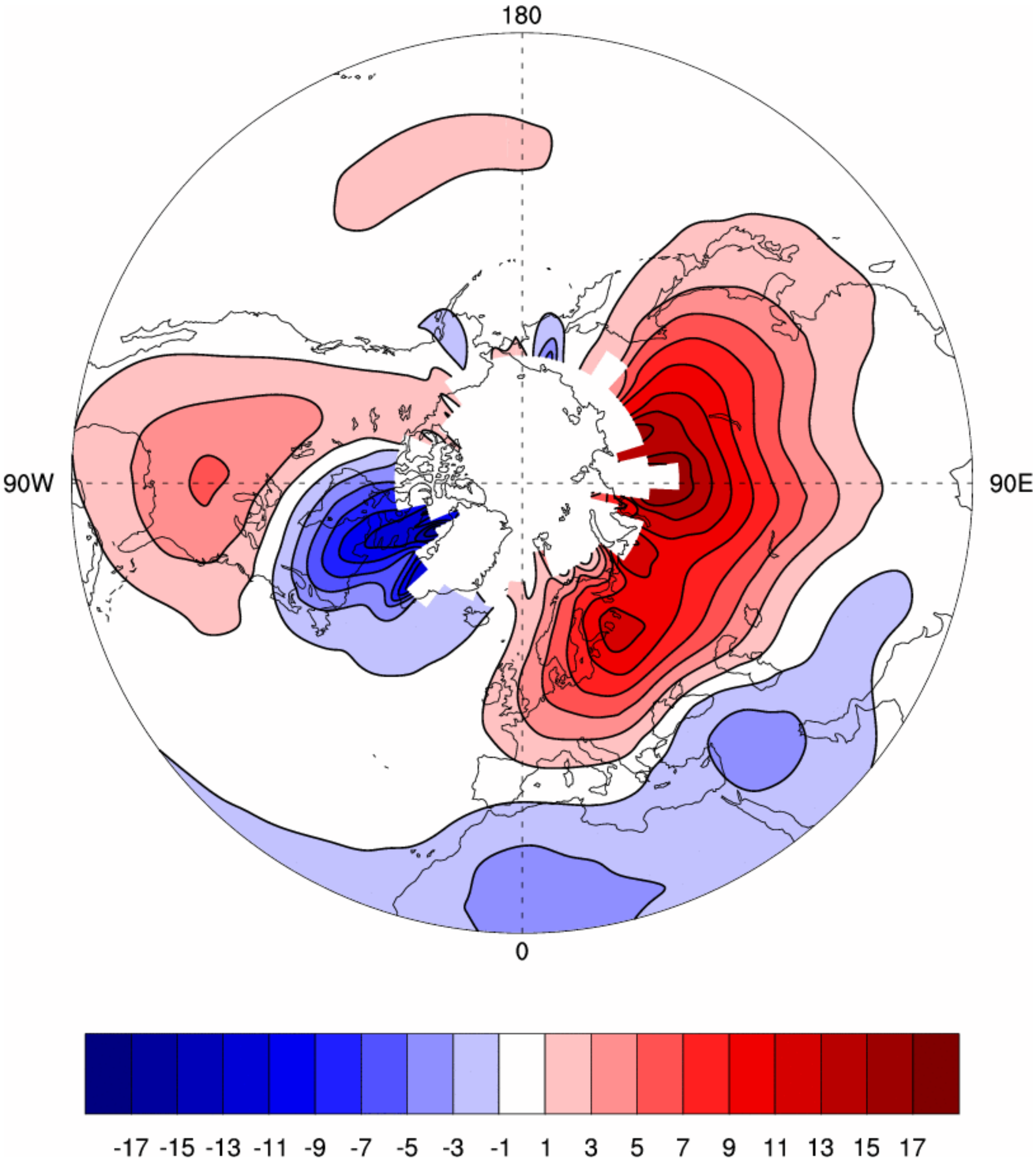

Figure 3. *Change in winter (December-March) surface temperature corresponding to a unit deviation of the NAO index over 1900 to 2005. The contour increment is 0.2°C. Regions of insufficient data (e.g., over much of the Arctic) are not contoured.*

This pattern of temperature change is important. Because the heat storage capacity of the ocean is much greater than that of land, changes in continental surface temperatures are much larger than those over the oceans, so they tend to dominate average NH (and global) temperature variability. Given especially the large and coherent NAO signal across the Eurasian continent from the Atlantic to the Pacific, it is not surprising that

NAO variability accounts for about one-third of the year-to-year changes in average NH winter surface temperature. Moreover, the long-term changes in atmospheric circulation associated with the NAO index have contributed substantially to the winter warming of the NH in recent decades.

Changes in the mean circulation patterns over the North Atlantic associated with the NAO are also accompanied by changes in the intensity and paths of storms (atmospheric disturbances operating on time scales of about a week or less). During boreal winter, a well-defined storm track connects the North Pacific and North Atlantic basins, with maximum storm activity over the oceans. Positive NAO index winters are associated with a northeastward shift in the Atlantic storm activity, with enhanced action from southern Greenland across Iceland into northern Europe and a modest decrease in activity from the Azores across the Iberian Peninsula and the Mediterranean. Positive NAO winters are also typified by more intense and frequent storms in the vicinity of Iceland and the Norwegian Sea.

The ocean realizes the effects of storms in the form of surface waves, so that it exhibits a marked response to long lasting shifts in the storm climate. The change toward more positive NAO index winters in recent decades (**Figure 1**) has been associated with increased wave heights over the northeast Atlantic and decreased wave heights south of 40°N. Such changes have consequences for the operation and safety of shipping, offshore industries, and coastal development.

Changes in the mean flow and storminess associated with swings in the NAO are also reflected in pronounced changes in the transport and convergence of atmospheric moisture. Winters tend to be drier than average over much of Greenland, the Canadian Arctic, much of central and southern Europe, the Mediterranean and parts of the Middle East during positive NAO index winters, whereas more precipitation than normal falls from Iceland through Scandinavia (**Figure 4**). This pattern, together with change toward more positive NAO index winters since the late 1960s, is consistent with recent observed changes in precipitation over much of the Atlantic basin.

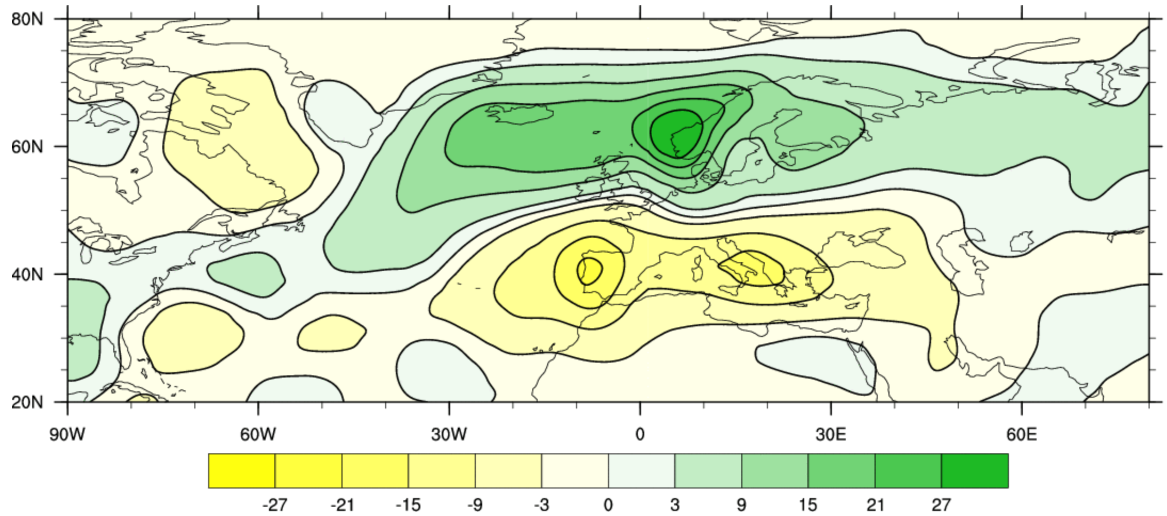

Figure 4. *Change in winter (December-March) precipitation corresponding to a unit deviation of the NAO index over 1979-2003. The contour increment is 0.3 mm day^{-1}.*

In addition to these impacts, significant changes in ocean surface temperature and heat content, ocean currents and their related heat transport, and sea ice cover in the Arctic and sub-Arctic regions are also induced by changes in the NAO. For example, the oceanic response includes changes in the distribution and intensity of winter convective activity in the North Atlantic. The convective renewal of intermediate and deep waters in the Labrador Sea and the Greenland-Iceland-Norwegian Seas contribute significantly to the production and export of North Atlantic Deep Water and, thus, helps to drive the global thermohaline circulation. The intensity of winter convection at these sites is not only characterized by large interannual variability, but also interdecadal variations that are synchronized with variations in the NAO. Likewise, the strongest interannual variability of Arctic sea ice occurs in the North Atlantic sector and is primarily driven by changes in the NAO. A seesaw in ice extent between the Labrador and Greenland Seas characterizes the ice variations.

Mechanisms

Considering the significant impact the NAO exerts on the climate, the economy and ecosystems of the NH, understanding the mechanisms that determine its structure and variability in time is of central importance. There is ample evidence that most of the atmospheric circulation variability in the form of the NAO arises from the internal, nonlinear dynamics of the extratropical atmosphere. Interactions between the time-mean flow and synoptic-timescale transient eddies are the central governing dynamical mechanism. As such, the month-to-month and even year-to-year changes in the phase and amplitude of the NAO are largely unpredictable. But that external forces might nudge the atmosphere to assume a high or low NAO index value over a particular month or season is important: even a small amount of predictability could be useful considering the significant impact the NAO exerts on the climate and ecosystems of the NH, and a better understanding of how the NAO responds to external forcing is crucial to the current debate on climate variability and change.

A number of different mechanisms that could influence the detailed state of the NAO have been proposed. Within the atmosphere itself, changes in the rate and location of tropical heating have been shown to be one way to influence the atmospheric circulation over the North Atlantic and, in particular, the NAO. Tropical convection, in turn, is sensitive to the underlying SST distribution, which exhibits much more persistence than SST variability in middle latitudes. Moreover, recent warming of the tropical oceans is inconsistent with natural climate variability. This might lead, therefore, to some predictability of the NAO phenomenon resulting from human-induced climate change. Indeed, while the details vary from model to model, most climate models simulate an increasing trend in the NAO index through the end of the 21st Century, with associated shifts in storm tracks and associated weather and climate extremes.

Interactions with the lower stratosphere are also possibly important, and this mechanism could be another way changes in atmospheric composition influence the NAO. For example, changes in ozone, greenhouse gas concentrations and/or levels of solar output affect the radiative balance of the stratosphere that, in turn, modulates the strength of the winter polar vortex. Given the relatively long time scales of stratospheric circulation variability (anomalies persist for weeks) dynamic coupling between the stratosphere and the troposphere via wave mean flow interactions could yield a useful level of predictive skill for the wintertime NAO.

One of the most urgent challenges is to advance our understanding of the interaction between anthropogenic forcing and the NAO. It now appears as though there may well be a deterministic relationship, which might allow for moderate low frequency predictability and thus needs to be studied carefully. Also, 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. At the same time, the response of marine and terrestrial ecosystems to a shift in the NAO index might enhance or reduce the atmospheric carbon dioxide levels and thus provide a positive or negative feedback.