From the Academy

The North Atlantic Oscillation: Past, present, and future

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The climate of the Atlantic sector exhibits considerable variability on a wide range of time scales. A substantial portion is associated with the North Atlantic Oscillation (NAO), a hemispheric meridional oscillation in atmospheric mass with centers of action near Iceland and over the subtropical Atlantic. NAO-related impacts on winter climate extend from Florida to Greenland and from northwestern Africa over Europe far into northern Asia. Over the last 3 decades, the phase of the NAO has been shifting from mostly negative to mostly positive index values. Much remains to be learned about the mechanisms that produce such low frequency changes in the North Atlantic climate, but it seems increasingly likely that human activities are playing a significant role.

When the North Atlantic Oscillation (NAO) is in its positive phase, low-pressure anomalies over the Icelandic region and throughout the Arctic combine with high-pressure anomalies across the subtropical Atlantic to produce stronger-than-average westerlies across the midlatitudes. During a positive NAO, conditions are colder and drier than average over the northwestern Atlantic and Mediterranean regions, whereas conditions are warmer and wetter than average in northern Europe, the eastern United States, and parts of Scandinavia (Fig. 1 top). Walker and Bliss (1) were among the first to recognize and study this pattern of climate anomalies, which is most pronounced during boreal winter (December through March).

A remarkable feature of the NAO is its trend toward a more positive phase over the past 30 years, with a magnitude that seems to be unprecedented in the observational record (2). Some of the most pronounced anomalies have occurred since the winter of 1989, when record positive values of the NAO index have been documented (Fig. 1 *Lower*). Moreover, the trend in the NAO accounts for a myriad of remarkable changes in the climate over the middle and high latitudes of the Northern Hemisphere, as well as in marine and terrestrial ecosystems. Among these changes are:

Milder winters in Europe downstream and across Asia, juxtaposed against more severe winters over eastern Canada and the northwest Atlantic (2);

Pronounced regional changes in precipitation patterns, resulting in the advance of some northern European glaciers and the retreat of Alpine glaciers (3, 4);

Changes in sea-ice cover in both the Labrador and Greenland Seas as well as over the Arctic (5);

Pronounced decreases in mean sea level pressure (SLP) over the Arctic and changes in the physical properties of Arctic sea water (6, 7);

Changes in the intensity of convection in the Labrador and the Greenland–Iceland Seas, which in turn influence the strength and character of the Atlantic meridional overturning circulation (8);

Stratospheric cooling over the polar cap and total column ozone losses poleward of 40°N (9);

Changes in the production of zooplankton and the distribution of fish (e.g., ref. 10), and changes in the length of the growing season over Europe (11).

All of these changes seem to be strongly related to the recent trend in the NAO index. Also, regions seemingly far removed from the Atlantic, such as the Middle East, experience significant NAO-related impacts.

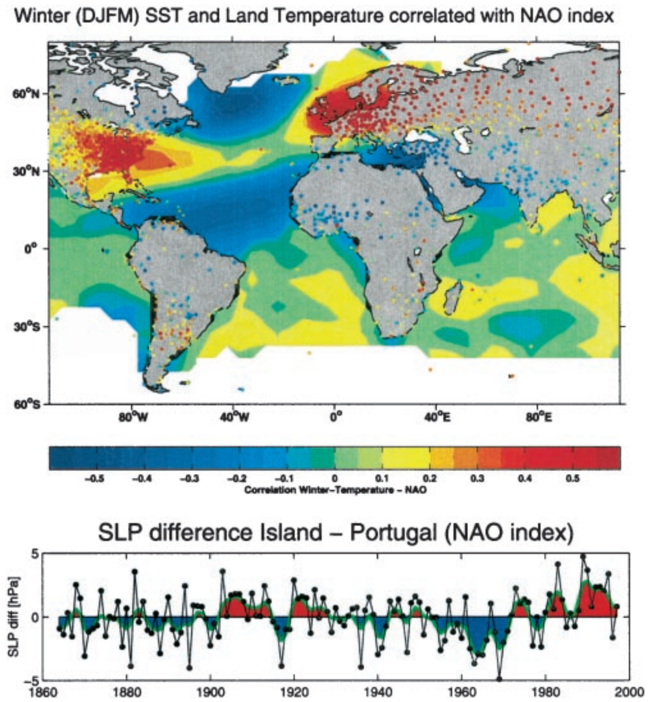

Fig. 1. Spatial correlation map of mean winter (DJFM) station temperature and sea surface temperature (SST) correlated against the NAO index (*Lower*). The NAO index is defined by Hurrell (2) as the difference between the normalized DJFM sea level pressure (SLP) anomaly at Lisbon, Portugal and Stykkisholmur, Iceland. During a positive NAO, colder conditions prevail over western Greenland and the Mediterranean region, whereas warmer conditions prevail in northern Europe, the northeast United States, and parts of Scandinavia. SST reflects a tripole pattern with a cold anomaly in the subpolar region, a warm anomaly in the mid-latitudes centered off Cape Hatteras, and a cold subtropical anomaly between the equator and 30°N.

With regional population increasing by 3.5% each year and irrigation practices consuming roughly 80% of available water supply, sustainable water resource management is central to the public health and political stability of the Middle East. Instru-

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mental records of temperature, precipitation, and stream flow in the Tigris-Euphrates headwater region have shown significant interannual to decadal variability associated with the NAO. During a positive phase of the NAO, Turkish winter temperature and precipitation records will reflect a cooler and drier climate (12). In the past, NAO-related interdecadal-centennial scale variability may have played a principal role in regulating Middle Eastern climate, thereby strongly affecting the complex, agriculturally based societies that emerged along the Tigris and Euphrates rivers (13).

The remarkable behavior of the NAO in recent decades and, more generally, its pronounced low-frequency behavior over the longer record have added to the debate over our ability to detect and distinguish between natural and anthropogenic climate change. Hurrell (14) has shown that the recent upward trend in the NAO accounts for much of the observed regional surface warming over Europe and Asia. Because global average temperatures are dominated by temperature variability over the northern land masses, a significant fraction of the recent warming trend in global surface temperatures can be explained as a response to observed changes in atmospheric circulation. Because the NAO is a natural mode of the atmosphere, one could argue that much of the recent warming is not related to the build-up of greenhouse gases in the atmosphere over the past century. This viewpoint, however, ignores the possibility that anthropogenic climate change might influence modes of natural variability, perhaps making it more likely that one phase of the NAO is preferred over the other.

There is ample evidence that shows that much of the atmospheric circulation variability in the form of the NAO arises from internal atmospheric processes. Atmospheric general circulation models (AGCMs) forced with climatological annual cycles of solar insolation, sea surface temperature (SST), and fixed atmospheric trace-gas composition display NAO-like fluctuations. The governing dynamical mechanisms are eddy–mean flow interaction at the exit region of the Atlantic storm track and eddy–eddy interaction between baroclinic transients and low-frequency variability. Such intrinsic atmospheric variability exhibits little temporal coherence, so that the low-frequency variations evident in the ≈150-year observational record of the NAO could be interpreted as sampling variability.

Recently, Thompson and Wallace (15) suggested that the NAO might more appropriately be thought of as an annular (zonally symmetric) hemispheric mode of variability characterized by a seesaw of atmospheric mass between the polar cap and the middle latitudes in both the Atlantic and Pacific Ocean basins. A very similar structure also is evident in the Southern Hemisphere. They named this mode the Arctic Oscillation (AO) and showed that, during winter, its vertical structure extends deep into the stratosphere (e.g., ref. 16). During winters when the stratospheric vortex is strong, the NAO (or AO) tends to be in a positive phase. Baldwin and Dunkerton (17) suggest that the signal propagates from the stratosphere downward to the surface, so that the recent trend in the tropospheric circulation over the North Atlantic could be related to processes that affect the strength of the stratospheric polar vortex. However, the proposed mechanism of planetary wave reflection is controversial and needs more study.

On the other hand, it has long been recognized that fluctuations in SST and the strength of the NAO are related (18), and there are clear indications that the North Atlantic Ocean varies significantly with the overlying atmosphere. The leading mode of SST variability over the North Atlantic during winter consists of a tripole pattern with a cold anomaly in the subpolar region, a warm anomaly in the middle latitudes centered off Cape Hatteras, and a cold subtropical anomaly between the equator and 30°N (Fig. 1 *Upper*; refs. 19 and 20). SST observations also display a myriad of long-term (interannual and decadal) responses (21, 22), which allows for the possibility that decadal and longer-term variations in the state of the ocean surface imprint themselves back on the atmosphere.

A key question is the sensitivity of the middle latitude atmosphere to changes in surface boundary conditions, including SSTs, sea-ice, and/or land. Although most AGCM experiments have led to rather confusing and inconsistent conclusions (23), Robertson *et al.* (24) report that changing the SST distribution in the North Atlantic affects the frequency of occurrence of different regional low-frequency modes and substantially increases the interannual variability of the NAO simulated by their AGCM. Other recent AGCM experiments (25, 26) have pointed to SST in the North Atlantic as having a marked effect on NAO variability as well, and it also has been suggested that tropical SSTs are the primary driver of low frequency variations in the North Atlantic climate (27). The response of the atmosphere to changes in tropical, middle and high latitude SST distributions within the Atlantic Basin remains a problem that needs to be addressed.

Although the NAO is a natural mode of atmospheric variability, surface (ocean and land), stratospheric, or even anthropogenic processes may influence its phase and amplitude. At present, there is no consensus on the process or processes that are responsible for observed low-frequency variations in the NAO. The absence of a demonstrated skillful predictive model leaves us with significant uncertainty about NAO variability in the future. The proposed response to increased greenhouse gas concentrations through forcing from warmer tropical SSTs (27) or a strengthened stratospheric vortex (28) implies, however, that the positive index phase might continue.

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