NORTH ATLANTIC OSCILLATION (NAO)

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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, a dozen or so distinct teleconnection patterns can be identified during boreal winter. One of the most prominent is the North Atlantic Oscillation (NAO). The NAO dictates climate variability from the eastern seaboard of the USA to Siberia and from the Arctic to the subtropical Atlantic. This widespread influence indicates that the NAO is more than just a North Atlantic phenomenon. In fact, it has been suggested that the NAO is the regional manifestation of a larger scale (hemispheric) mode of variability known as the Arctic Oscillation (see below). Regardless of terminology, meteorologists for more than two centuries have noted the pronounced influence of the NAO on the climate of the Atlantic basin.

Variations in the NAO are important to society and the environment. Through its control over regional temperature and precipitation variability, the NAO directly impacts agricultural yields, water management activities, and fish inventories among other things. The NAO accounts for much of the interannual and longer-term variability evident in northern hemisphere surface temperature, which has exhibited a warming trend over the past several decades to values that are perhaps unprecedented over the past 1000 years.

Understanding the processes that govern variability of the NAO is therefore of high priority, especially in the context of global climate change. This article defines the NAO and describes its relationship to variations in surface temperature and precipitation, as well as its impact on variability in the North Atlantic Ocean and on the regional ecology. It concludes with a discussion of the mechanisms that might influence the amplitude and timescales of the NAO, including the possible roles of the stratosphere and the ocean.

What is the NAO?

Like all atmospheric teleconnection patterns, the NAO is most clearly identified when time averaged data (monthly or seasonal) are examined, since time averaging reduces the 'noise' of small-scale and transient meteorological phenomena not related to large-scale climate variability. Its spatial signature and temporal variability are most often defined through the regional sea level pressure field, for which some of the longest instrumental records exist.

The NAO refers to a north–south oscillation in atmospheric mass with centers of action near Iceland and over the subtropical Atlantic from the Azores across the Iberian Peninsula. Although it is the only teleconnection pattern evident throughout the year in the northern hemisphere, its amplitude is largest during boreal winter when the atmosphere is dynamically the most active. During the months December through March, for instance, the NAO accounts for more than one-third of the total variance in sea level pressure over the North Atlantic.

A time series (or index) of more than 100 years of wintertime NAO variability and the spatial signature of the oscillation are shown in **Figures 1** and **2**[1]. Differences of $>15\,\mathrm{hPa}$ occur across the North Atlantic between the two phases of the NAO. In the so-called positive 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

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[1] More sophisticated and objective statistical techniques, such as eigenvector analysis, yield time series and spatial patterns of average winter sea level pressure variability very similar to those shown in **Figures 1** and **2**.

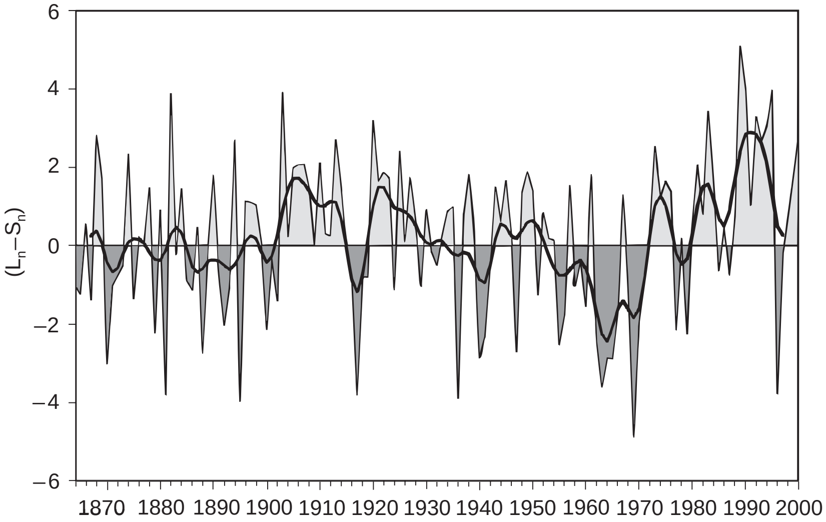

Figure 1 Winter (December–March) index of the NAO based on the difference of normalized sea level pressure between Lisbon, Portugal, and Stykkisholmur/Reykjavik, Iceland from 1864 to 2000. The average winter sea level pressure data at each station were normalized by division of each seasonal pressure by the long-term mean (1864–1983) standard deviation. The heavy solid line represents the index smoothed to remove fluctuations with periods <4 years.

the northern hemisphere, 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 USA and anomalous northerly flow across western Greenland, the Canadian Arctic, and the Mediterranean.

The NAO is also readily apparent in meteorological data throughout the depth of the troposphere, and its variability is significantly correlated with

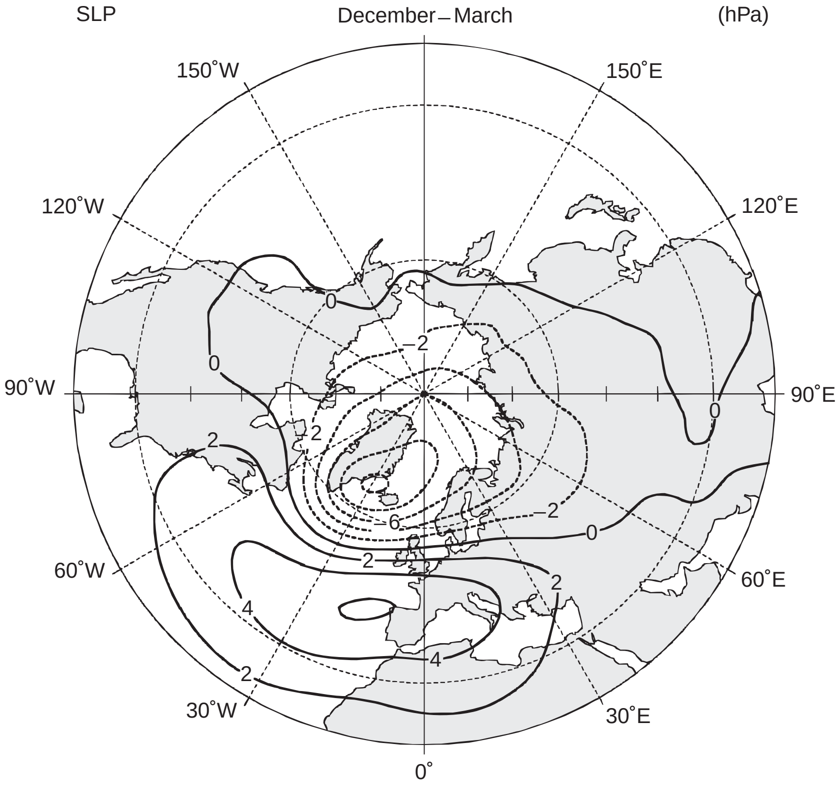

Figure 2 Difference in sea level pressure between years with an NAO index value >1.0 and those with an index value <-1.0 (high minus low index winters) since 1899. The contour increment is 2 hPa and negative values are dashed.

changes in the strength of the winter polar vortex in the stratosphere of the northern hemisphere. Within the lower stratosphere, the leading pattern of geopotential height variability is also characterized by a seesaw in mass between the polar cap and the middle latitudes, but with a much more zonally symmetric (or annular) structure than in the troposphere. When heights over the polar region are lower than normal, heights at nearly all longitudes in middle latitudes are higher than normal. In this phase, the stratospheric westerly winds that encircle the pole are enhanced and the polar vortex is 'strong' and anomalously cold. It is this annular mode of variability that has been termed the Arctic Oscillation.

However, the signature of the stratospheric Arctic Oscillation in winter sea level pressure data looks very much like the anomalies associated with the NAO, with centers of action over the Arctic and the Atlantic (**Figure 2**). The 'annular' character of the Arctic Oscillation in the troposphere, therefore, reflects the vertically coherent fluctuations throughout the Arctic more than any coordinated behavior in the middle latitudes outside of the Atlantic basin. That the NAO and Arctic Oscillation reflect essentially the same mode of tropospheric variability is emphasized by the fact that their time series are nearly identical, with differences depending mostly on the details of the analysis procedure.

There is little evidence for the NAO to vary on any preferred timescale (**Figure 1**). Large changes can occur from one winter to the next, and there is also a considerable amount of variability within a given winter season. This is consistent with the notion that much of the atmospheric circulation variability in the form of the NAO arises from processes internal to the atmosphere, in which various scales of motion interact with one another to produce random (and thus unpredictable) variations. On the other hand, there are also periods when anomalous NAO-like circulation patterns persist over many consecutive winters. In the Icelandic region, for instance, sea level pressure tended to be anomalously low during winter from the turn of the century until about 1930 (positive NAO index), while the 1960s were characterized by unusually high surface pressure and severe winters from Greenland across northern Europe (negative NAO index). A sharp reversal has occurred over the past 30 years, with strongly positive NAO index values since 1980 and sea level pressure anomalies across the North Atlantic and Arctic that resemble those in **Figure 2**. In fact, the magnitude of the recent upward trend is unprecedented in the observational record and, based on reconstructions using paleoclimate and model data, perhaps over the past several centuries as well. Whether such low frequency (interdecadal) NAO variability arises from interactions of the North Atlantic atmosphere with other, more slowly varying components of the climate system (such as the ocean), whether the recent upward trend reflects a human influence on climate, or whether the longer timescale variations in the relatively short instrumental record simply reflect finite sampling of a purely random process, are topics of considerable current interest.

Impacts of the NAO

Temperature

The NAO exerts a dominant influence on wintertime temperatures across much of the northern hemisphere. Surface air temperature and sea surface temperature (SST) across wide regions of the North Atlantic Ocean, North America, the Arctic, Eurasia, and the Mediterranean are significantly correlated with NAO variability.[2] Such changes in surface temperature (and related changes in rainfall and storminess) can have significant impacts on a wide range of human activities, as well as on marine and terrestrial ecosystems.

When the NAO index is positive, enhanced westerly flow across the North Atlantic during winter moves relatively warm (and moist) maritime air over much of Europe and far downstream across Asia, while stronger northerlies over Greenland and north-eastern Canada carry cold air southward and decrease land temperatures and SST 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.

The pattern of temperature change associated with the NAO 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 northern hemisphere (and global) temperature variability. Especially given the large and coherent NAO signal across the Eurasian continent from the Atlantic to the Pacific (**Figure 3**), it is not surprising that NAO variability explains

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[2] Sea surface temperatures (SSTs) are used to monitor surface air temperature over the oceans because intermittent sampling is a major problem and SSTs have much greater persistence.

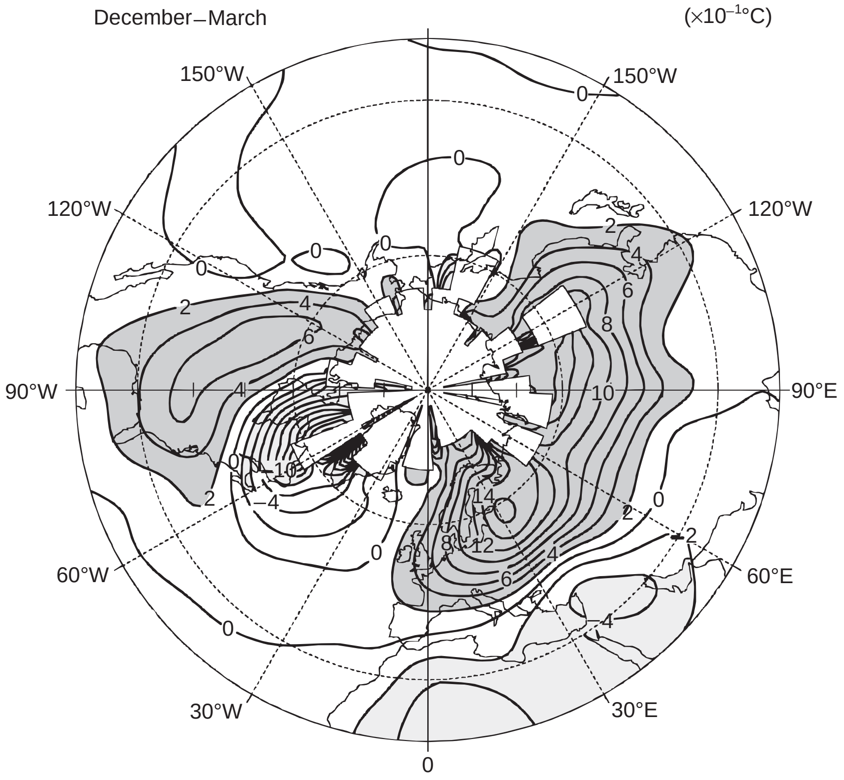

Figure 3 Changes in land surface and sea surface temperatures ($\times 10^{-1}$°C) corresponding to unit deviations of the NAO index for the winter months (December–March) from 1935 to 1999. The contour increment is 0.2°C. Temperature changes >0.2°C are indicated by dark shading, and those <-0.2°C are indicated by light shading. Regions with insufficient data are not contoured.

about one-third of the northern hemisphere interannual surface temperature variance during winter.

The strength of the link between the NAO and northern hemisphere temperature variability has also added to the debate over our ability to detect and distinguish between natural and anthropogenic climate change. Since the early 1980s, winter temperatures over much of North America and Eurasia have been considerably warmer than average, while temperatures over the northern oceans have been slightly colder than average. This pattern, which has contributed substantially to the well-documented warming trend in northern hemisphere and global temperatures over recent decades, is quite similar to winter surface temperature changes projected by computer models forced with increasing concentrations of greenhouse gases and aerosols. Yet, it is clear from the above discussion that a significant fraction of this temperature change signal is associated with the recent upward trend in the NAO (**Figures 1** and **3**). How anthropogenic climate change might influence modes of natural climate variability such as the NAO, and the nature of the relationships between increased radiative forcing and interdecadal variability of these modes, remain central research questions.

Precipitation and Storms

Changes in the mean circulation patterns over the North Atlantic are accompanied by changes in the intensity and number of storms, their paths, and their associated weather. Here, the term ‘storms’ refers to atmospheric disturbances operating on timescales of about a week or less. During winter, a well-defined storm track connects the North Pacific and North Atlantic basins, with maximum storm activity over the oceans. The details of changes in storminess differ depending on the analysis method and whether the focus is on surface or upper-air features. Generally, however, positive NAO index winters are associated with a northward shift in the Atlantic storm activity, with enhanced activity from southern Greenland across Iceland into northern Europe and a modest decrease in activity to the south. The latter is most noticeable 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 integrates 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.

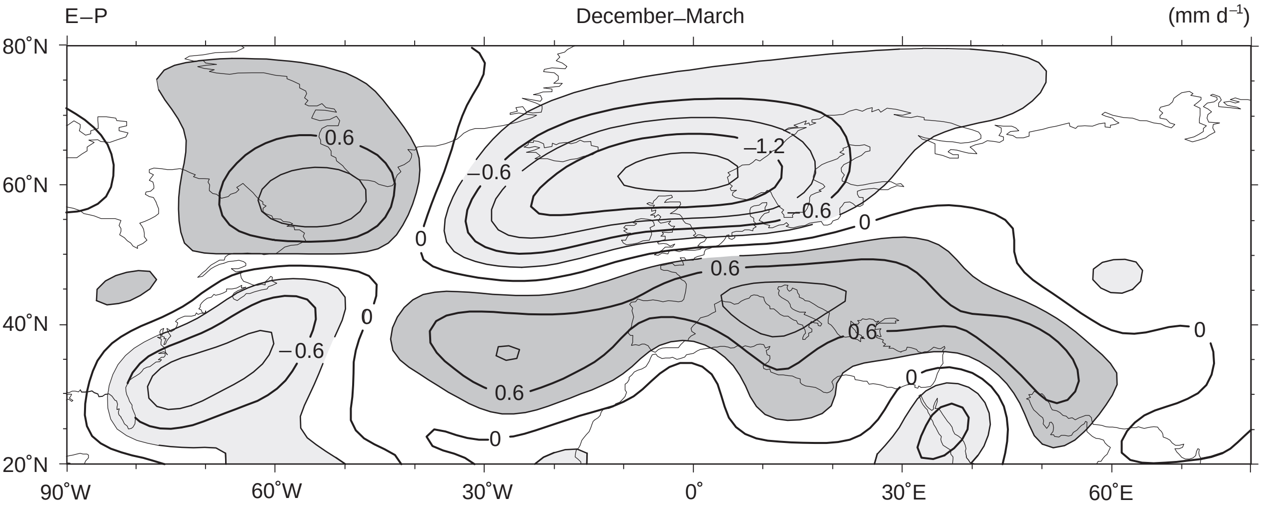

Figure 4 Difference in evaporation (E) minus precipitation (P) between years with an NAO index value > 1.0 and those with an index value < -1.0 (high minus low index winters) since 1958. The contour increment is $0.3\,\mathrm{mm\,d^{-1}}$. Differences $> 0.3\,\mathrm{mm\,d^{-1}}$ are indicated by dark shading, and those $< 0.3\,\mathrm{mm\,d^{-1}}$ are indicated by light shading.

The recent upward trend toward more positive NAO index winters has been associated with increased wave heights over the north-east 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 and, thus, the distribution of evaporation and precipitation. Evaporation (E) exceeds precipitation (P) over much of Greenland and the Canadian Arctic during high NAO index winters (**Figure 4**), where changes between high and low NAO index states are on the order of $1\,\mathrm{mm\,d^{-1}}$. Drier conditions of the same magnitude also occur over much of central and southern Europe, the Mediterranean, and parts of the Middle East, whereas more precipitation than normal falls from Iceland through Scandinavia.

This pattern, together with the upward trend in the NAO index since the late 1960s (**Figure 1**), is consistent with recent observed changes in precipitation over much of the Atlantic basin. One of the few regions of the world where glaciers have not exhibited a retreat over the past several decades is in Scandinavia, where more than average amounts of precipitation have been typical of many winters since the early 1980s. In contrast, over the Alps, snow depth and duration in recent winters have been among the lowest recorded this century, and the retreat of Alpine glaciers has been widespread. Severe drought has persisted throughout parts of Spain and Portugal as well. As far east as Turkey, river runoff is significantly correlated with NAO variability. There is also some observational and modeling evidence of a declining precipitation rate over much of the Greenland Ice Sheet over the past two decades, although measurement uncertainties are large.

Ocean Variability

It has long been recognized that fluctuations in SST and the strength of the NAO are related, and there are clear indications that the North Atlantic Ocean varies significantly with the overlying atmosphere. The leading pattern of SST variability during winter consists of a tripolar structure marked, in one phase, by a cold anomaly in the subpolar North Atlantic, a warm anomaly in the middle latitudes centered off Cape Hatteras, and a cold subtropical anomaly between the equator and 30°N. This structure suggests that the SST anomalies are driven by changes in the surface wind and air–sea heat exchanges associated with NAO variations. The relationship is strongest when the NAO index leads an index of the SST variability by several weeks, which highlights the well-known result that extratropical SST responds to atmospheric forcing on monthly and seasonal timescales. Over longer periods, persistent SST anomalies also appear to be related to persistent anomalous patterns of SLP (including the NAO), although the mechanisms which produce SST changes on decadal and longer time-scales remain unclear. Such fluctuations could primarily be the local oceanic response to atmospheric decadal variability. On the other hand, nonlocal dynamical processes in the ocean could also be contributing to the SST variations.

Subsurface ocean observations more clearly depict long-term climate variability, because the effect of the annual cycle and month-to-month variability in the atmospheric circulation decays rapidly with depth. These measurements are much more limited than surface observations, but over the North Atlantic they too indicate fluctuations that are coherent with the winter NAO index to depths of 400 m.

The ocean's response to NAO variability also appears to be evident in 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, help 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 appear to be synchronized with variations in the NAO (**Figure 1**). Deep convection over the Labrador Sea, for instance, was at its weakest and shallowest in the postwar instrumental record during the late 1960s. Since then, Labrador Sea Water has become progressively colder and fresher, with intense convective activity to unprecedented ocean depths (> 2300 m) in the early 1990s. In contrast, warmer and saltier deep waters in recent years are the result of suppressed convection in the Greeland/Iceland/Norwegian Seas, whereas intense convection was observed there during the late 1960s.

There has also been considerable interest in the occurrence of low salinity anomalies that propagate around the subpolar gyre of the North Atlantic. The most famous example is the Great Salinity Anomaly (GSA). The GSA formed during the extreme negative phase of the NAO in the late 1960s, when clockwise flow around anomalously high pressure over Greenland fed record amounts of fresh water through the Denmark Strait into the subpolar North Atlantic ocean gyre. There have been other similar instances as well, and statistical analyses have revealed that these propagating salinity modes are closely connected to a pattern of atmospheric variability strongly resembling the NAO.

Sea Ice

The strongest interannual variability of Arctic sea ice occurs in the North Atlantic sector. The sea ice fluctuations display an oscillation in ice extent between the Labrador and Greenland Seas. Strong interannual variability is evident in the sea ice changes over the North Atlantic, as are longer-term fluctuations, including a trend over the past 30 years of diminishing (increasing) ice concentration during boreal winter east (west) of Greenland. Associated with the sea ice fluctuations are large-scale changes in sea level pressure that closely resemble the NAO.

When the NAO is in its positive phase, the Labrador Sea ice boundary extends farther south, while the Greenland Sea ice boundary is north of its climatological extent. Given the implied surface wind changes (**Figure 2**), this is qualitatively consistent with the notion that sea ice anomalies are directly forced by the atmosphere, either dynamically via wind-driven ice drift anomalies, or thermodynamically through surface air temperature anomalies (**Figure 3**). The relationship between the NAO index (**Figure 1**) and an index of the North Atlantic ice variations is indeed strong, although it does not hold for all individual winters. This last point illustrates the importance of the regional atmospheric circulation in forcing the extent of sea ice.

Ecology

Changes in the NAO have a wide range of effects on North Atlantic ecosystems. Temperature is one of the primary factors, along with food availability and spawning grounds, in determining the large-scale distribution pattern of fish and shellfish. Changes in SST and winds associated with changes in the NAO have been linked to variations in the production of zooplankton, as well as to fluctuations in several of the most important fish stocks across the North Atlantic. This includes not only longer-term changes associated with interdecadal NAO variability, but also interannual signals as well.

Over land, fluctuations in the strength of the NAO have been linked to variations in plant phenology. In Norway, for example, most plant species have been blooming from 2–4 weeks earlier in recent years because of increasingly warm and wet winters, and many species have been blooming longer. Winter climate directly impacts the growth, reproduction, and demography of many animals, as well. European amphibians and birds have been breeding earlier over the past two to three decades, and these trends have been attributed to earlier growing seasons and increased forage availability. Variations in the NAO index are also significantly correlated with the growth, development, fertility, and demographic trends of large mammals from North America to northern Europe, such as northern ungulates and Canadian lynx.

What are the Mechanisms that Govern NAO Variability?

Although the NAO is an internal mode of variability of the atmosphere, surface, stratospheric or anthropogenic processes may influence its phase and amplitude. At present there is no consensus on the process or processes that most influence the NAO, especially on long (interdecadal) timescales. It is quite possible that NAO variability is affected by one or more of the mechanisms described below.

Atmospheric Processes

Atmospheric general circulation model (AGCMs)[3] provide strong evidence that the basic structure of the NAO results from the internal, nonlinear dynamics of the atmosphere. The observed spatial pattern and amplitude of the NAO are well simulated in AGCMs forced with fixed climatological annual cycles of solar insolation and SST, as well as fixed atmospheric trace gas composition. The governing dynamical mechanisms are interactions between the time-mean flow and the departures from that flow. Such intrinsic atmospheric variability exhibits little temporal coherence and, indeed, the timescales of observed NAO variability (**Figure 1**) do not differ significantly from this reference.

A possible exception is the interdecadal NAO variability, especially the strong trend toward the positive index polarity of the oscillation over the past 30 years. This trend exhibits a high degree of statistical significance relative to the background interannual variability in the observed record; moreover, multi-century AGCM experiments like those described above do not reproduce interdecadal changes of comparable magnitude. A possible source of the trend could be through a connection to processes that have affected the strength of the atmospheric circulation in the lower stratosphere.

During winters when the stratospheric westerlies are enhanced, the NAO tends to be in its positive phase. There is a considerable body of evidence to support the notion that variability in the troposphere can drive variability in the stratosphere, but it also appears that some stratospheric control of the troposphere may also occur.

The atmospheric response to strong tropical volcanic eruptions provides some evidence for a stratospheric influence on the Earth's surface climate. Volcanic aerosols act to enhance north–south temperature gradients in the lower stratosphere by absorbing solar radiation in lower latitudes. In the troposphere, the aerosols exert only a very small direct influence. Yet, the observed response following eruptions is not only lower geopotential heights over the pole with stronger stratospheric westerlies, but also a positive NAO-like signal in the tropospheric circulation.

Reductions in stratospheric ozone and increases in greenhouse gas concentrations also appear to enhance the meridional temperature gradient in the lower stratosphere, leading to a stronger polar vortex. It is possible, therefore, that the upward trend in the NAO index in recent decades (**Figure 1**) is associated with trends in either or both of these quantities. Indeed, a decline in the amount of ozone poleward of 40°N has been observed during the last two decades, and the stratospheric polar vortex has become colder and stronger.

Ocean Forcing of the Atmosphere

In the extratropics, it is clear that the atmospheric circulation is the dominant driver of upper ocean thermal anomalies. A long-standing issue, however, has been the extent to which anomalous extratropical SST feeds back to affect the atmosphere. Most evidence suggests that this effect is quite small compared with internal atmospheric variability. Nevertheless, the interaction between the ocean and atmosphere could be important for understanding the details of the observed amplitude of the NAO, its interdecadal variability, and the prospects for meaningful predictability.

While intrinsic atmospheric variability is random in time, theoretical and modeling evidence suggest that the ocean can respond to it with marked persistence or even oscillatory behavior. On seasonal and interannual timescales, for example, the large heat capacity of the upper ocean can lead to slower changes in SST relative to the faster, stochastic atmospheric forcing. On longer timescales, SST observations display a myriad of variations. Middle and high latitude SSTs over the North Atlantic, for example, were colder than average during the 1970s and 1980s, but warmer than average from the 1930s through the 1950s. Within these periods, shorter-term variations in SST are also apparent, such as a dipole pattern that fluctuates on approximately decadal time scales with anomalies of one sign east of Newfoundland, and anomalies of opposite polarity off the south-east coast of the USA.

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[3] Atmospheric general circulation models consist of a system of equations that describe the large-scale atmospheric balances of momentum, heat, and moisture, with schemes that approximate small-scale processes such as cloud formation, precipitation, and heat exchange with the sea surface and land.

A key to whether or not changes in the state of the NAO reflect these variations in the state of the ocean surface is the sensitivity of the atmosphere to middle and high latitude SST and upper ocean heat content anomalies. Most AGCM studies show weak responses to extratropical SST anomalies, with sometimes contradictory results. Yet, some AGCMs, when forced with the time history of observed, global SSTs and sea ice concentrations over the past 50 years or so, show modest skill in reproducing aspects of the observed NAO behavior, especially its interdecadal fluctuations (**Figure 1**).

Such results do not necessarily imply, however, that the extratropical ocean is behaving in anything other than a passive manner. It could be, for instance, that long-term changes in tropical SSTs force a remote atmospheric response over the North Atlantic, which in turn drives changes in extratropical SSTs and sea ice. Some model studies indicate a sensitivity of the North Atlantic atmosphere to tropical SST variations, including variations over the tropical Atlantic which are substantial on both interannual and interdecadal timescales.

The response of the extratropical North Atlantic atmosphere to changes in tropical and extratropical SST distributions, and the role of land processes and sea ice in producing atmospheric variability, are problems which are currently being addressed. Until these are better understood, it is difficult to evaluate the realism of more complicated scenarios that rely on truly coupled interactions between the atmosphere, ocean, land, and sea ice to produce North Atlantic climate variability. It is also difficult to evaluate the extent to which interannual and longer-term variations of the NAO might be predictable.

Glossary

Great salinity anomaly A widespread freshening of the upper 500–800 m layer of the far northern North Atlantic Ocean, traceable around the subpolar gyre from its origins north of Iceland in the mid-to-late 1960s until its return to the Greenland Sea in the early 1980s.

See also

Abrupt Climate Change. Arctic Basin Circulation. Current Systems in the Atlantic Ocean. Elemental Distribution: Overview. Evaporation and Humidity. Fisheries and Climate. Heat and Momentum Fluxes at the Sea Surface. North Sea Circulation. Ocean Circulation. Open Ocean Convection. Plankton and Climate. Sea Ice: Overview; Variations in Extent and Thickness. Thermohaline Circulation. Wave Generation by Wind. Wind Driven Circulation.

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