PERSPECTIVES: CLIMATE

The North Atlantic Oscillation

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Surface temperatures over the Northern Hemisphere (NH) are likely to be warmer now than at any other time over the past millennium. The rate of warming has been especially high in the past 40 years or so. A substantial fraction of this most recent warming is accounted for by a remarkable upward trend in the North Atlantic Oscillation (NAO) (see the first figure). The NAO dictates climate variability from the eastern seaboard of the United States to Siberia and from the Arctic to the subtropical Atlantic, especially during winter. Agricultural yields, water management, and fish inventories, among many other things, are directly affected by the NAO. Yet despite this pronounced influence, scientists remain puzzled about which climate processes govern NAO variability (especially its recent trend), how the phenomenon has varied in the past or will vary in the future, and whether it is at all predictable.

These questions were at the heart of a recent American Geophysical Union Chapman Conference in Ourense, Spain (*1*). For the first time, atmospheric scientists, oceanographers, paleoclimatologists, biologists, and those interested in the socioeconomic impacts of climate variability came together to focus exclusively on the NAO. Theory, observations, and model simulations of climate variability related to the NAO were discussed by approximately 180 scientists and students from Europe, North America, and Japan.

The NAO is characterized by an oscillation of atmospheric mass between the Arctic and the subtropical Atlantic. It is usually defined through changes in surface pressure (see the first figure). When the NAO is in its "positive" phase, the wintertime meridional pressure gradient over the North Atlantic is large because the Icelandic low-pressure center and the high-pressure center at the Azores are both enhanced. Both centers are weakened during its "negative" phase. The changes in pressure gradient from one phase to another produce large changes in the mean wind speed and direction over the North Atlantic. Heat and moisture transport between the Atlantic and the surrounding continents also vary markedly, as do the intensity and number of winter storms, their paths, and the weather associated with them.

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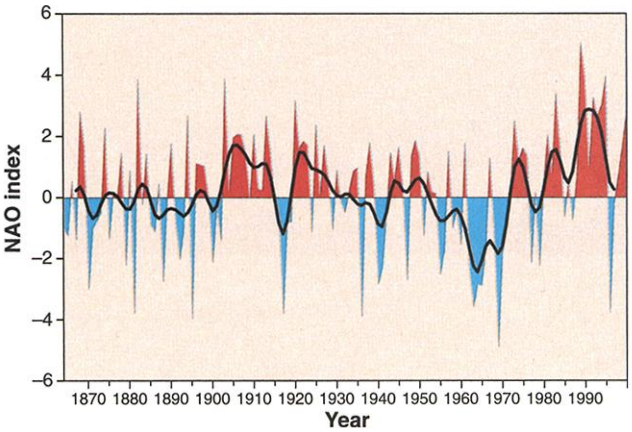
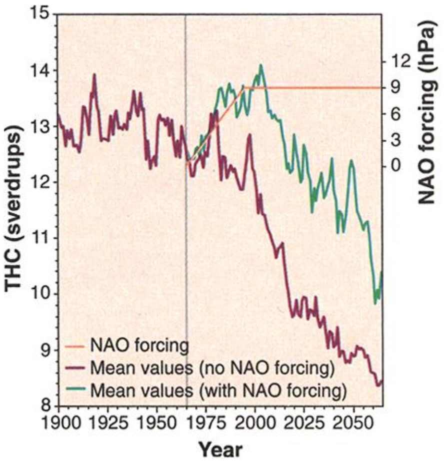


An upward trend. Winter (December to March) index of the NAO based on the difference of normalized pressures between Lisbon, Portugal, and Stykkishólmur/Reykjavik, Iceland from 1864 through 2000. The heavy solid line represents the meridional pressure gradient smoothed to remove fluctuations with periods less than 4 years.

Until a few years ago, relatively little attention was paid to the NAO because changes in its phase and amplitude from one winter to the next were considered unpredictable. The prevailing understanding was that atmospheric circulation variability in the form of the NAO arises from processes internal to the atmosphere, in which various scales of atmospheric motion interact with one another to produce chaotic, large-scale perturbations. Recently there has been renewed interest in the NAO, primarily for three reasons. First, the NAO strongly affects the Atlantic Ocean by inducing substantial changes in surface wind patterns, thereby altering the heat and freshwater exchange at the ocean surface. These changes in turn affect the strength and character of the Atlantic thermohaline circulation (THC) and the horizontal flow of the upper ocean and could temporarily reverse the slowing of the THC predicted by some climate models in response to anthropogenic climate change (see the second figure) (*2*). Second, changes in the NAO have a wide range of effects on marine and terrestrial ecosystems, including the large-scale distribution and population of fish and shellfish, the production of zooplankton, the flowering dates of plants, and the growth, reproduction, and demography of many land animals. Third, a small but useful percentage of NAO variance might be predictable after all. Predictability could arise from the influence of slow changes in the ocean or from external factors, in particular rising levels of greenhouse gases (GHG), as perhaps suggested by the recent, prolonged upward NAO trend (see the first figure). It is this trend that is most at odds with the notion that only chaotic atmospheric processes are at work over the North Atlantic.



How the ocean may respond. Time series of the North Atlantic THC from two sets of simulations with a coupled ocean-atmosphere model (*2*). The green line denotes mean THC values from model runs forced with increasing GHGs and sulfate aerosols. The red line denotes mean THC values from the same model runs, but with NAO-induced wintertime trends in surface fluxes of heat, water, and momentum imposed after 1965. The amplitude of the imposed NAO forcing (kept constant after 1995) is given by the orange line.

Recent research (*3*) and presentations at the meeting have shown that the strength of the NAO can be traced in meteorological data not only at the surface but also throughout the troposphere and stratosphere. The changes in wintertime circulation of the lower stratosphere span most of the NH and show a trend toward much stronger westerly winds encircling the North Pole. It is well established that variability in the troposphere can drive variability in the stratosphere, but new observational and modeling evidence suggests that some stratospheric control of the troposphere may also be occurring (H.-F. Graf, Max-Planck-Institute for Meteorology; J. Perlwitz, Columbia University/NASA-GISS). The observed trend in Atlantic surface climate may therefore be linked to processes affecting the stratospheric circulation on long time scales.

Reductions in stratospheric ozone and increases in GHG concentrations, which radiatively cool the low and middle stratosphere during the polar night, are obvious candidates (N. P. Gillett, University of Oxford). On shorter, seasonal time scales, an apparent delay in the wintertime tropospheric response to changes in the stratospheric circulation could lead to useful intermediate-range predictability (M. P. Baldwin, Northwest Research Associates).

The ocean may also have an appreciable influence on the atmosphere. New evidence presented at the meeting (C. Deser, National Center for Atmospheric Research) shows that the tendency of the ocean to preserve its thermal state from one winter to the next may impress some persistence on the atmosphere. A new statistical analysis revealed patterns in Atlantic sea surface temperatures (SSTs) that precede specific phases of the NAO by up to 6 months (A. Czaja, Massachusetts Institute of Technology; M. J. Rodwell, Hadley Center, UK Meteorological Office). Moreover, it has recently been shown (*4*, *5*) that atmospheric general circulation models, forced with the known global evolution of SST and sea ice cover, reproduce the observed (see the first figure) multiannual and longer term changes in the NAO. This indicates that low-frequency North Atlantic climate variability is not merely stochastic atmospheric noise but rather contains a response to changes in ocean surface temperatures and/or sea ice. Furthermore, new results (M. P. Hoerling, NOAA-CIRES Climate Diagnostics Center) link the recent NAO trend to a progressive warming of tropical SSTs, in particular, the observed warming of the tropical Indian and Pacific Ocean waters. The latter is also predicted to occur as a result of increases in GHGs.

The Chapman Conference resulted in a new, invigorated look at seasonal-to-interannual prediction beyond El Niño and a deeper understanding of anthropogenic climate change. Much remains to be learned about the NAO, but it seems increasingly less likely that natural variability is the cause of the recent NAO trend, regardless of whether the forcing is from the stratosphere, the ocean, or other processes yet to be identified.

References and Notes

1. The North Atlantic Oscillation, Ourense, Spain, 28 November to 1 December 2000. Abstracts and other information available at www.ldeo.columbia.edu/NAO/conference/chapman_conf.html. The speakers mentioned in the text are merely representative of the more than 170 papers presented at the meeting.
2. T. L. Delworth, K. W. Dixon, *J. Clim.* **13**, 3721 (2000).
3. D. W. J. Thompson *et al.*, *J. Clim.* **13**, 1018 (2000).
4. M. J. Rodwell *et al.*, *Nature* **398**, 320 (1999).
5. V. M. Mehta *et al.*, *Gephys. Res. Lett.* **27**, 121 (2000).

PERSPECTIVES: FLUID DYNAMICS

Droplets Speeding on Surfaces

Darsh T. Wasan, Alex D. Nikolov, Howard Brenner

Numerous processes from offset printing to painting depend on the rapid spreading of water droplets on solid surfaces. On page 633 of this issue, Daniel *et al.* (*1*) report on the remarkably fast movement of liquid drops on a surface with a radial temperature gradient that generates a surface tension–driven fluid motion, also known as Marangoni flow. They achieve this high-speed droplet movement through a clever manipulation of the forces acting on the droplet. The concept may be of interest for numerous industrial processes, such as coating, soldering, printing, cooling, photolithography, and microfluidic device fabrication.

Examples of flow driven by surface tension gradients abound. Consider the calming effect of oil on troubled water, the "dance" of a camphor ball on a water surface, the ripples that form in the skin of chocolate pudding near the cup center, and the tears of wine in a wine glass. Thomson (*2*) and Marangoni (*3*) were the first to investigate and begin to explain this type of flow in the mid-19th century. Variations in temperature or liquid composition cause a spatial variation in surface tension at a liquid-gas and/or solid-liquid surface, creating a tangential stress at that surface. This stress or surface traction acts on the adjoining fluid, causing interfacial fluid motion, which is in turn transmitted to the bulk fluid (*4*).

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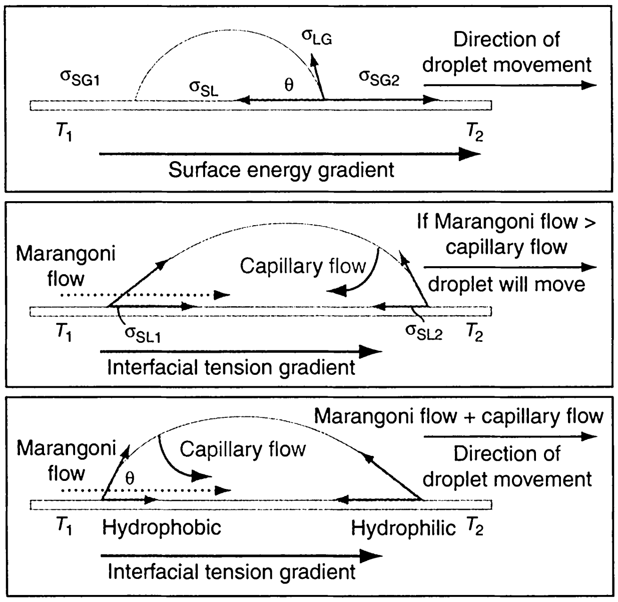
In their experiments, Daniel *et al.* (*1*) combined the Marangoni flow caused by a temperature gradient with the directional flow generated by a deliberately altered wettability of the solid surface. The wettability gradient was created by depositing hydrophobic molecules on the central part of a hydrophilic surface and then forming water drops by condensing saturated steam on the hydrophobic region. To create a temperature gradient along the solid surface, they circulated cold fluid beneath it. As the drops moved toward the cooler area of the solid surface, which was also more hydrophilic (that is, more easily wet by water), they grew by coalescing with smaller surrounding drops. High-speed video observations show that the water drops moved as fast as 1.5 m/s.



Different mechanisms of droplet flows. (Top) Droplet movement due to a surface energy gradient. Young's equation (*8*) defines the force balance between the respective interfacial tensions existing at the solid-liquid (σ_{SL}), solid-gas (σ_{SG}), and liquid-gas (σ_{LG}) interfaces and the contact angle (θ). **(Middle)** Flow patterns inside the droplet and on the liquid-solid interface due to a surface or/and interface gradient and capillary pressure. The droplet will only move if the capillary flow is exceeded by the Marangoni flow. **(Bottom)** Flow patterns inside the droplet and on the liquid-solid interface due to a surface or/and interface gradient and capillary pressure; the solid surface wettability increases in the direction of drop movement. Capillary flow drives the droplet in the same direction as Marangoni flow, leading to fast droplet movement (*1*).

To put these observations in context, let us consider three different situations in which a water drop on a solid surface with an imposed temperature gradient may find itself (see the figure). In the simplest case, it is only the surface energy of the solid surface, σ_{SG}, that drives the flow; a droplet placed on a solid surface will move in the direction of higher surface energy (to the right if $\sigma_{SG2} > \sigma_{SG1}$) (see the top panel). Things become more complex if the surface tension is not uniform throughout the droplet. The difference in surface tension (σ) along the length of the drop (*L*), generated by a temperature gradient, creates a Marangoni flow because the solid-liquid