one direction, either north or south. If the wave motion did not tunnel through, that is, were limited to only the basin of origin, Kelvin's theorem would be violated. Hence the wave must tunnel through. In doing so, southward motion on one side of the ridge is balanced by a similar southward motion on the other side of the ridge segment so that the average clockwise circulation around the segment is zero as the theorem demands. On the other hand, for the second figure wave the vortical motions are stacked in counter-rotating pairs so that the average tangential velocity along the eastern side of the ridge is already exactly zero. Kelvin's theorem is then satisfied without the wave tunneling through and, in fact, calculations of the forced motion, as shown, demonstrate that the wave is blocked.

We have done both analytical and numerical calculations of this phenomenon in idealized cases to verify these ideas. What remains is a greater challenge: With the collaboration of our colleagues, we hope to study the process in both the laboratory and the natural ocean to see whether this strange and dramatic tunneling phenomenon is robust enough to be a major factor in our understanding of ocean circulation.

Research Reveals Interdecadal N. Atlantic Atmosphere-Ocean Oscillation

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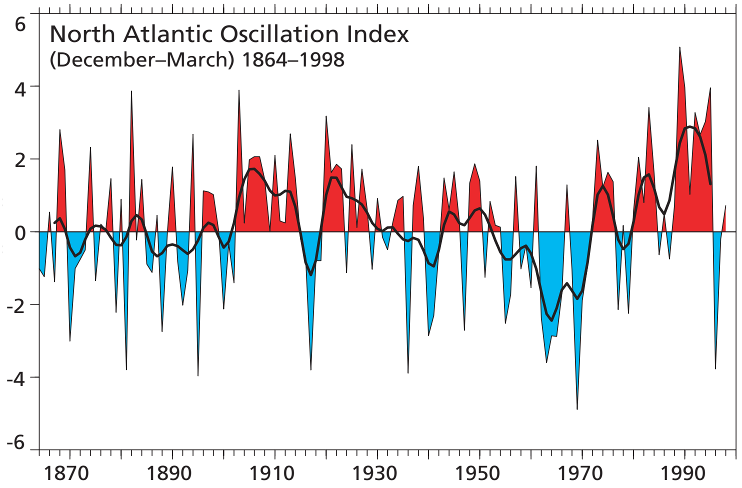
What is the ocean's role in Earth's climate system? When we, living in the atmosphere, perceive a shift in climate—most of the winters for a decade tending to be colder or wetter than those of the preceding decade, for example—are there concurrent changes in the oceanic component of the climate system? If so, are they merely a response to the changeable atmospheric climate, or do the oceanic changes feed back to alter the atmospheric climate?

Some of our work focuses on defining the role of the North Atlantic Ocean in interannual/interdecadal fluctuations of climate. Atmospheric variability in the North Atlantic sector is dominated by the North Atlantic Oscillation (NAO): simultaneous strengthening or weakening of the Icelandic low pressure center and the Azores high pressure ridge along with lateral movements of their locations. The intensity of westerly winds reflects the pressure difference between these sites; thus NAO's principle signature is in the variable intensity of the westerlies and the latitude of their maximum winds.



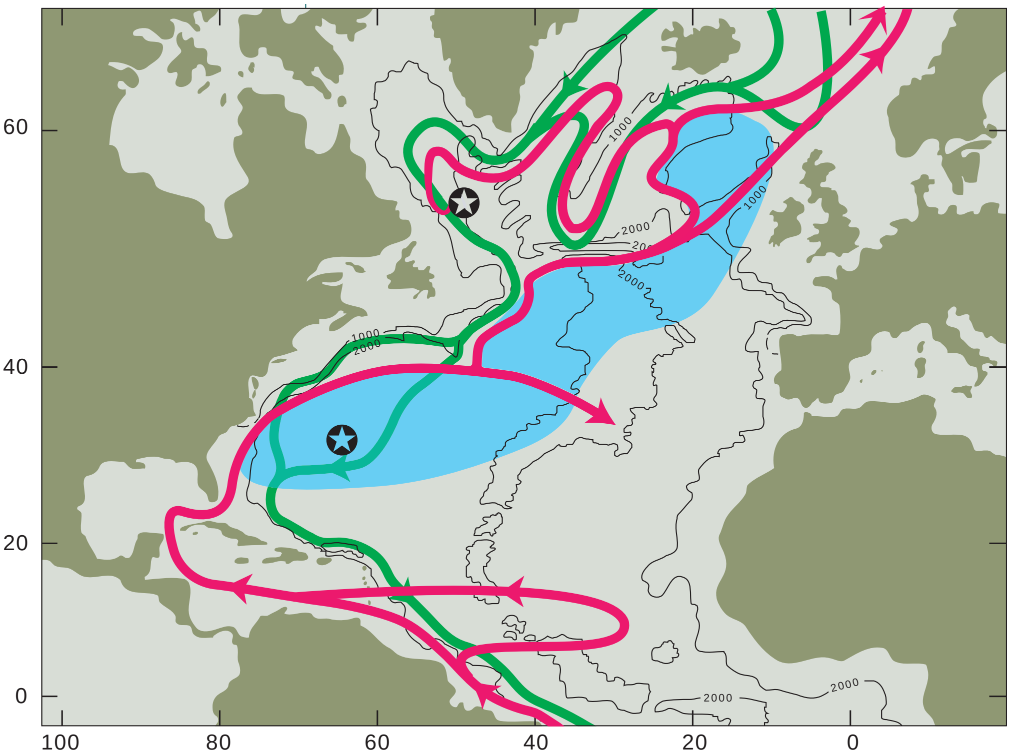
A 134 year record of the North Atlantic Oscillation (NAO) index using sustained sea level pressure measurements in Iceland and Portugal, constructed by Jim Hurrell of the National Center for Atmospheric Research. The index uses average sea level pressure for the cold season months (December to March) in Iceland, reflecting the strength of the Icelandic low pressure center, and in Portugal reflecting the strength of the subtropical "Azores" high pressure ridge. When the sea level pressure difference is large, "high NAO" conditions prevail (positive index), with westerly winds stronger than average, and centered on the 45°N to 60°N belt. When the difference is small, "low NAO" conditions prevail (negative index), with westerly winds weaker than average, and distinctly shifted southwards of the average latitude.

Climatologists affirm that in Europe, Iceland, Greenland, and eastern North America fluctuations in climate—air temperature, humidity, rainfall, and storm frequencies and intensities—correlate with the NAO. But what of the North Atlantic Ocean beneath that NAO-fluctuating atmosphere?

The history of NAO fluctuations (see figure at right) reveals that the climate system in the North Atlantic has been running a 50-year experiment for us, with atmospheric forcing modulated interdecadally. The NAO index decreased from the 1950s through 1971, resulting in a 1960s record of weakened westerlies displaced southwards from their average location. Subsequently, the NAO index increased from 1972 through the mid-1990s, and the strengthened westerlies shifted northwards from their average location. What are the consequences of this fluctuation of atmospheric forcing of the ocean?

The most extensive oceanic sustained measurement archive available to us is sea surface temperature (SST). NAO-correlated air-sea heat exchange anomalies produce distinct patterns of SST anomalies—evidence that the upper ocean integrates the atmospheric forcing anomalies. In 1996 articles in the "Oceans and Climate" issue of *Oceanus* (Volume 39, Number 2), we discussed evidence that the observed winter SST anomalies are the surface expression of substantial upper ocean heat content anomalies. These reflect altered conditions along the pathway of upper ocean transformation of warm water to cold in the thermohaline overturning circulation of the North Atlantic (top figure opposite). We also showed that the altered products of this transformation could be detected returning southward through the subtropics beneath the thermocline.

We now have another contribution to the growing evidence for this North Atlantic Atmosphere-Ocean Oscillation. We used two sustained measurement time series available in the subsurface North Atlantic, one near Bermuda and one in the central Labrador Sea (marked by stars on the map), to construct an ocean transport index analogous to the atmospheric NAO index. The two stations fall near the



Jack Cook

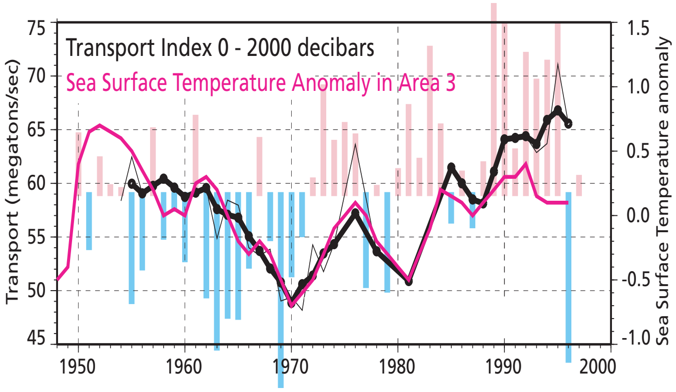
The primary pathways involved in the North Atlantic warm-to-cold water transformation. The basin scale gyre recirculations of the tropical, subtropical, and subpolar circulations are suppressed here to emphasize the warm water transformation pipeline of the upper ocean (red pathways) and the compensating cold return flows at depth (green pathways). The blue area indicates the belt where winter sea surface temperature anomalies slowly propagate from the western subtropical gyre into the eastern subpolar gyre with a typical transit time of a decade. These winter sea surface temperature signals are upper ocean heat content anomalies that reflect fluctuations of the balance between the large annual heating of the atmosphere by the release of heat from the ocean in that belt, and the supply of that heat to and through the belt by the flow of water along the red pathway. The two stars indicate the two sustained measurement time series, near Bermuda and in the central Labrador Sea, used to construct the index of the oceanic flow along the belt.

centers of subtropical and subpolar circulation gyres, and the difference of pressure between these two locations is a measure of the flow along the thermohaline transformation pathway, much as the atmospheric NAO index reflects the intensity of the westerly winds.

Comparison of the ocean transport index with the NAO index (figure below right) shows that in the last half of this century the thermohaline transformation pathway has responded, sluggishly, to the NAO correlated changes in buoyancy- and wind-forcing. Weakening of ocean transport to a minimum in 1971 occurred during the period of declining NAO index. This was followed by strengthening transport to a maximum in 1995 during the period of rising NAO index. We have included in the figure the time history of SST along the transformation pathway south of Nova Scotia. It demonstrates that the oceanic transport index and SST vary together: that the weaker phase of pathway transport involved colder waters while the stronger phase of pathway transport involved warmer waters. This indicates that the interdecadal North Atlantic Atmosphere-Ocean Oscillation of the past half century has involved fluctuation in heat transport along the transformation pathway, and ultimately of oceanic heat released to the overlying atmosphere.

The most important, and most controversial, physical process question raised by these observations is whether or not the fluctuations of oceanic heat content and transport at mid latitudes feed back to force changes in the atmosphere. If so, the seeds for future climate prediction may lie with the slow and majestic fluctuation of the ocean. Indeed, those seeds may already be germinating, for as this report goes to press we have received word that three independent numerical models of the atmosphere have simulated the observed time history of the NAO since 1950 by applying as a boundary condition the observed SST history. With a global observing system to monitor upper ocean heat content and circulation, and a physically sound ocean circulation model to forecast the evolution of the ocean and its coupling to the atmosphere, climate forecasting will follow.

We continue to address this crucial climate issue. This research is sponsored by grants from the National Science Foundation and the National Oceanic and Atmospheric Administration along with an award from the Andrew W. Mellon Foundation Endowed Fund for Innovative Research.



The blue and red bars show the annual values of the cold season NAO index. The black curve is the estimated transport of water along the conveyor belt pathway connecting the western subtropical gyre to the eastern subpolar gyre, the pathway delivering warm subtropical waters to higher latitudes. It indicates an interdecadal fluctuation of about 30 percent of the mean flow rate. The red curve represents the history of sea surface temperature anomalies in the blue belt of the accompanying map at a location southeast of Newfoundland. The red and black curves link the weak transport phase with cooler temperatures, and the stronger transport phase with higher temperatures.