The North Atlantic Atmosphere-Ocean Oscillation

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The following contribution is an example of the ocean and atmosphere interaction and its impact on climate that is a natural topic of study for the Climate Variability and Predictability Programme. In addition, observations being collected as part of the Atlantic Circulation and Climate Experiment (pages 43-46) should prove useful in better observing and understanding the North Atlantic Atmosphere-Ocean Oscillation described below.

The North Atlantic Oscillation (NAO) denotes a mode of variability of the standing waves of the northern hemisphere tropospheric circulation. It is manifested by simultaneous strengthening/weakening of the intensities of the Icelandic low pressure center and the Azores high pressure ridge as well as lateral movements of their locations, and it is most fully developed in winter data. Along with this tropospheric pressure variability, the NAO has characteristic patterns of surface air warming/ cooling, sea surface temperature (SST) warming/ cooling, enhanced/diminished rainfall, shifts in numbers and pathways of storms, shifts of polar stratospheric circulation, altered patterns of eddy meridional heat transport by the atmosphere, and changes in air-sea heat and water vapor exchanges. The NAO is a "natural" mode of atmospheric variability in the sense that these patterns of variability occur in simulations by atmosphere-only climate models. This means is that a variety of forcings can easily elicit or be projected onto this mode of response in the tropospheric circulation. Thus, the existence of NAO behavior at some frequency can be difficult to definitively attribute to any particular forcing candidate.

Of particular interest is the prevalence of decadal/

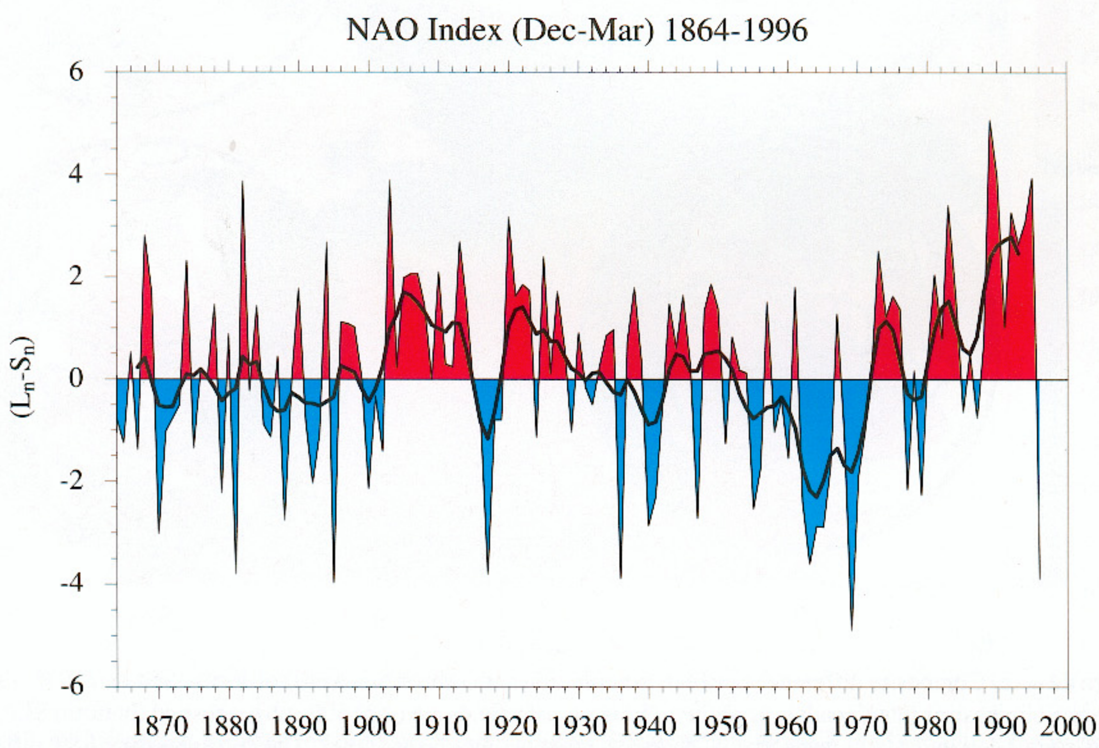

Figure 43 — An update (Hurrell, personal communication, 1996) of a winter NAO index using normalized sea level pressure differences between Lisbon, Portugal and Stykkisholmur, Iceland. Reds and blues shade the individual high and low years, while the heavy curve is a smoothed rendition.

interdecadal variability in the NAO, both in the modern instrumental record of about 130 years (Hurrell, 1995; Figure 43); the record recently extended to 170+ years (Jones et al., 1997); and in longer proxy records such as a 280-year tree ring record (Cook et al., 1997) and a 715-year Greenland ice core record (White et al., 1996). Besides intermonthly variability and strong seasonality of the character, the NAO index can "stick" in a high or low state for long periods or trend off over a decade or two from high to low (or vice versa). Figure 44a (Kushnir and Held, 1996) shows an example of differences in SST and 500 mb height and SST and sea level pressure (SLP) between two 15-year periods. The earlier period is of declining NAO, leading into the very low NAO of the winters of the 1960s; the later is a period of rising NAO preceding the unprecedented very high NAO of the early 1990s. Kushnir (personal communication, 1996) points out that this "pattern displays a basin-wide SST pattern, and a baroclinic atmospheric pattern that decays with height, as if forced by the change in surface thermal conditions. Most of the SST change is not associated with a local change in the westerlies." Figure 44b shows similar composites constructed for individual high and low NAO years rather than the long consecutive composites of Figure 44a. The pattern in Figure 44b is such that warm SST is associated with weaker than

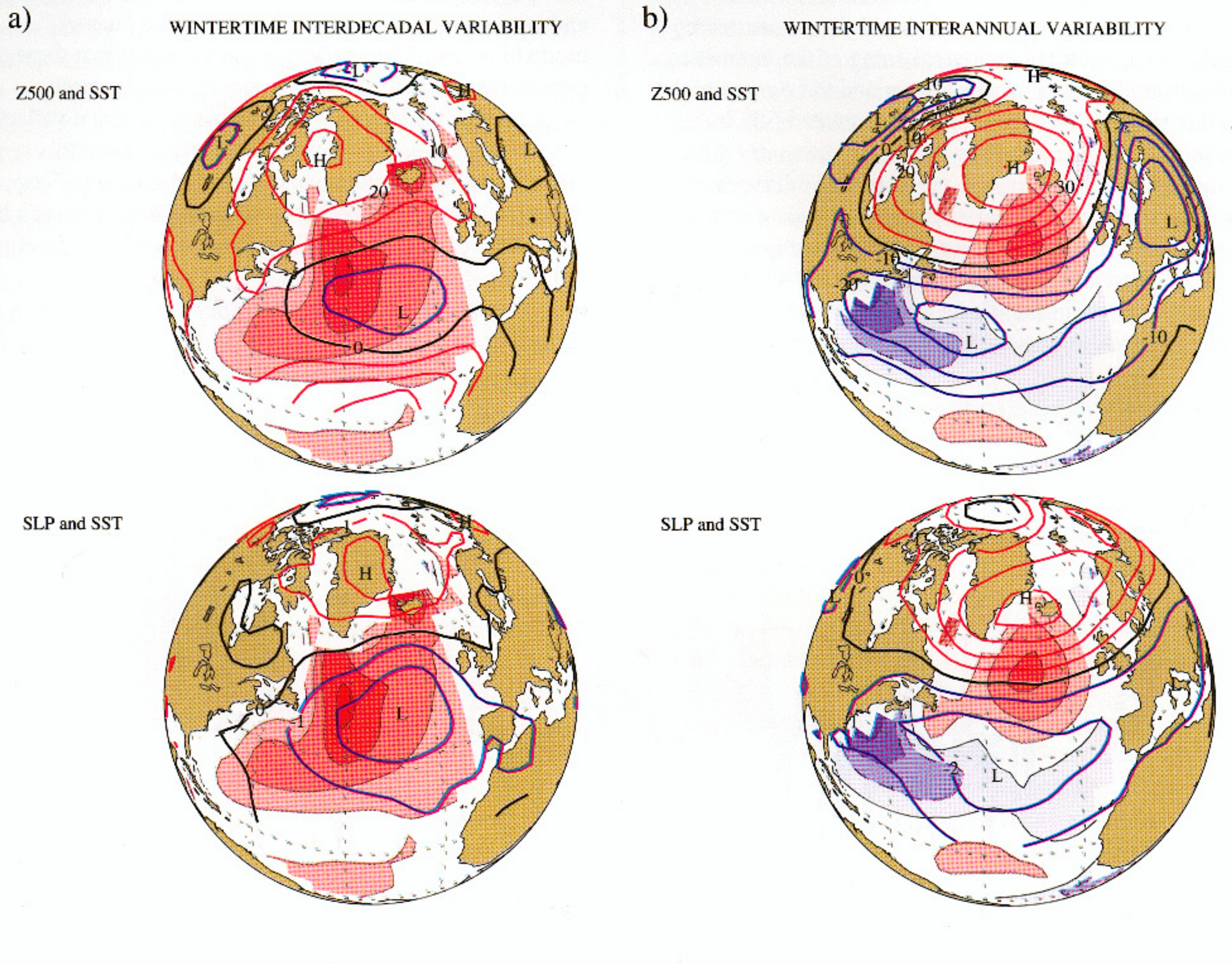

Figure 44 — a) Composite difference between the cold seasons (December-April) of 1950-1964 and 1970-1984. This difference emphasizes interdecadal variability. The contoured fields are (top) 500-mb height and (bottom) SLP; contour intervals are 10 m and 1 mb, respectively. Negative contours are dashed lines. The corresponding SST difference is shown in the shaded areas at intervals of 0.2°C; zero contours are omitted. The darker the shading, the larger the anomaly magnitude. b) As in a) but for the difference between the winters (December-January) with moderate to large positive and negative North Atlantic SST anomalies from 50°-60°N. This difference emphasizes interannual variability.

normal westerlies and vice versa. The atmospheric perturbation displays an equivalent barotropic structure, as is typical to modes of extratropical low-frequency variability. Kushnir and Held (1996) remark that this figure's simplest interpretation is as an interannual atmosphere-ocean interaction where "atmospheric anomalies that exist independent of extratropical SST variability force the ocean with little feedback." On the other hand, they note that the pattern is not inconsistent with some global circulation model results where SST anomalies force or modify similar equivalent barotropic structures. While the compositing criterion for Figure 44b is applied one year at a time, Kushnir notes a tendency for high/low NAO winters to cluster into groups of two to five consecutive winters, a persistence requiring explanation. The beginning of an explanation is emerging, as is outlined below.

While the covariances of various climate elements with the NAO index are inherently interesting, the involvement of NAO in global warming is particularly controversial. There is evidence of progressively increasing amplitude of decadal energy in the NAO record over the last 130 years (Hurrell and van Loon, 1997) consistent with the idea of an intensifying decadal/interdecadal NAO amplitude this century. Images of global temperature changes (Hurrell, 1996) show patterns of warming and cooling for the most recent 15 years compared to the preceding 15 years, which include a significant NAO fingerprint. Hurrell (1996) has removed the part of northern hemisphere extra-tropical surface temperature variance that he estimates as attributable to the NAO and to a weaker contribution from Pacific modes of variability. Hurrell finds that much of the recent global warming disappears, leaving little trend between 1935-1995. Thus, the low frequency behavior of the NAO and other mid-northern hemisphere atmospheric modes makes a strong imprint on the global surface warming distribution as compiled in the 1995 Intergovernmental Panel on

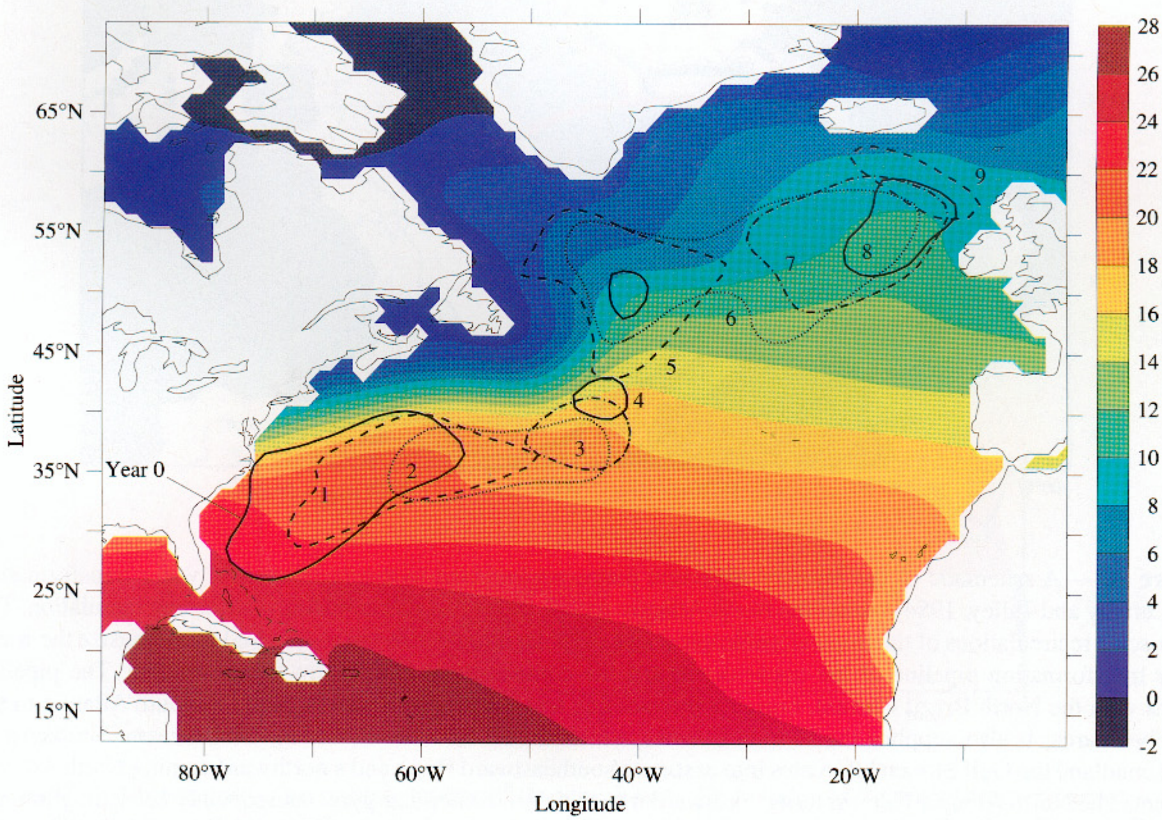

Figure 45 — Correlation between low frequency fluctuations in local wintertime SST as a function of lag in years and the low frequency fluctuations in wintertime SST averaged over the region east of Cape Hatteras (year 0 labeled contour). Contours delimit area where lag correlation exceeds 0.8 (except for year 9 where >0.75 is used). The background field is the average winter SST for 1945-1989 (Sutton and Allen, 1997).

Climate Change climate assessment (IPCC, 1996), a fact underlying the Wallace et al. (1995, 1996) documentation of the Cold Ocean/Warm Land pattern.

This link between global warming and natural variability is very provocative with a variety of alternate interpretations. One end of the spectrum is that global warming is a fiction, with the indications of warming merely representing a phase in the natural modes of atmospheric variability. The other end of the spectrum is that global warming is modulating the amplitude of NAO, for example through alteration of the stratosphere, a particularly sensitive part of the atmosphere in greenhouse warming models. The stratosphere functions as a sort of lid for the troposphere, where the waxing/waning of standing waves (i.e., the NAO) takes place, and the strength of the winter stratospheric cyclonic vortex has a demonstrated strong correlation with a baroclinic tropospheric mode of variability quite similar to the NAO mode (Perlwitz and Graf, 1995).

How does the low frequency behavior of the NAO come about? To be resolved is the classic mid-latitude climate variability dilemma. Is the decadal NAO variability just a reflection of low frequency chaotic behavior of the atmosphere? Or, does some aspect of the ocean's

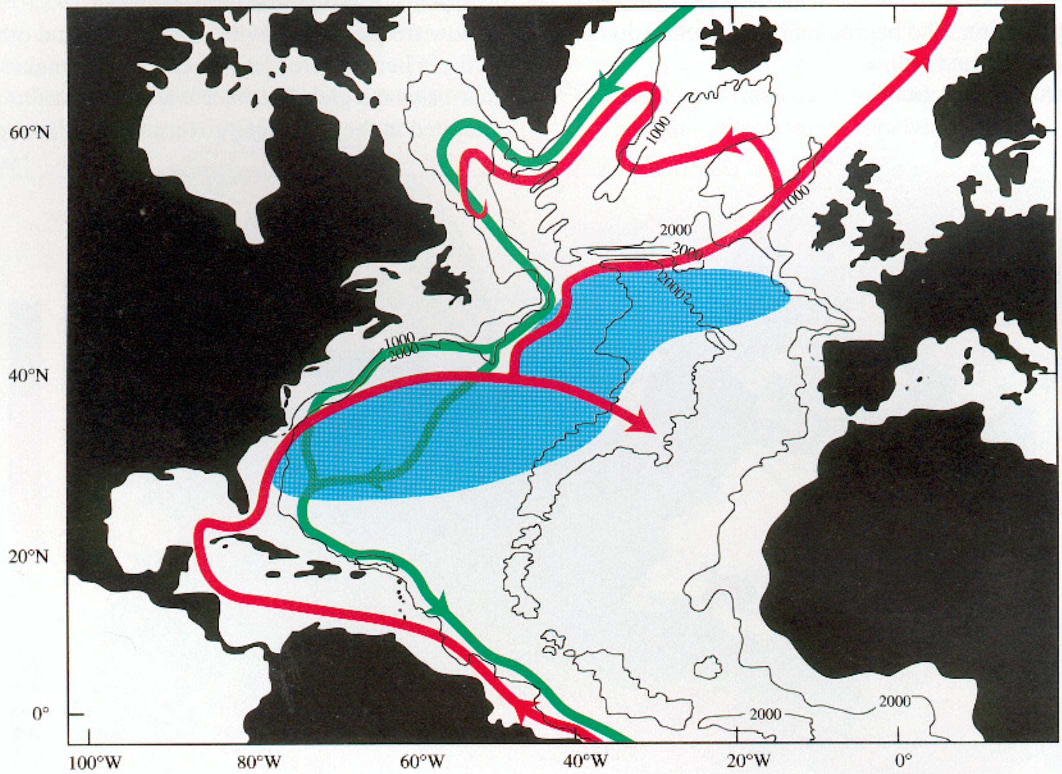

Figure 46 — A schematic of the primary advection pathways involved in the warm-to-cold water transformation (McCartney and Talley, 1984) within the North Atlantic part of the global thermohaline overturning circulation. The basin-scale recirculations of the tropical, subtropical and subpolar circulations are suppressed to emphasize the warm water transformation pipeline of the upper ocean and the compensating cold return flows at depth. The pipeline begins with the North Brazil Current, bringing thermocline and intermediate waters from the South Atlantic to the Caribbean area; it also supplies the Florida Current, which transitions into the strong Gulf Stream. Southeast of Newfoundland the Gulf Stream bifurcates into eastward/southeastward flows and a northward-turning North Atlantic Current. The North Atlantic Current turns northward into the eastern subpolar gyre, subsequently branching into the Norwegian Current. The westward flow moves across the northern Subpolar gyre and culminates the warm water transformation with the production of Labrador Sea Water. The blue area shows where the following two phenomena coexist. First, it is the domain of mode waters (McCartney and Talley, 1982)—annually persistent thermostads formed by winter convection. It also is an area of subtropical recirculation where a significant fraction of the eastward flow of the Gulf Stream and North Atlantic Current along its northern edge is expelled into the subtropical gyre to return more slowly westward.

large heat capacity serve as "memory" of the previous winter's conditions and, through some coupling mechanism, return the atmosphere to something like the same sort of winter state year after year? Several critical new developments have occurred over the past two years. There is an emerging story of the ocean's participation in the NAO—a covariance of ocean and atmosphere fluctuations at decadal/interdecadal periods indicating that the NAO is a North Atlantic Atmosphere-Ocean Oscillation (NAAOO). Some of the oceanic signals of the NAAOO are described in a recent issue of *Oceanus* (1996, Vol. 39, No. 2). Is the North Atlantic Ocean merely responding to a low frequency atmosphere, or is the ocean driving the low frequency atmosphere?

Hansen and Bezdek (1996) have shown that slowly propagating SST anomalies account for the overall regional decadal warm/cold SST in composites like Figure 44a. This propagation is the first clear evidence of a role of oceanic advection in setting winter SST. The pathway is nicely revealed by Sutton and Allen (1997) by a lag correlation of winter SST anomalies (Figure 45). Over a period of nine years, SST anomalies reappear in winter, displaced progressively northeastward. In the process they trace out the pathway of the Gulf Stream, North Atlantic Current, and the adjacent band of mode waters (McCartney and Talley, 1982) that outcrop in winter to the south of these strong currents (Figure 46). The downstream-cooling mode waters reflect this "transformation pipeline," functioning as the primary warm-to-cold conversion process in the North Atlantic part of the global thermohaline overturning circulation (McCartney and Talley, 1984). The recurrent winter SST anomalies are expressions of local relative warmth or coldness of these modes waters, and the northeastward propagation of winter SST anomalies (at an average speed of about 2 cm/sec) reflects both the average throughput of mode water along the transformation pipeline and its carrying of heat content anomalies from

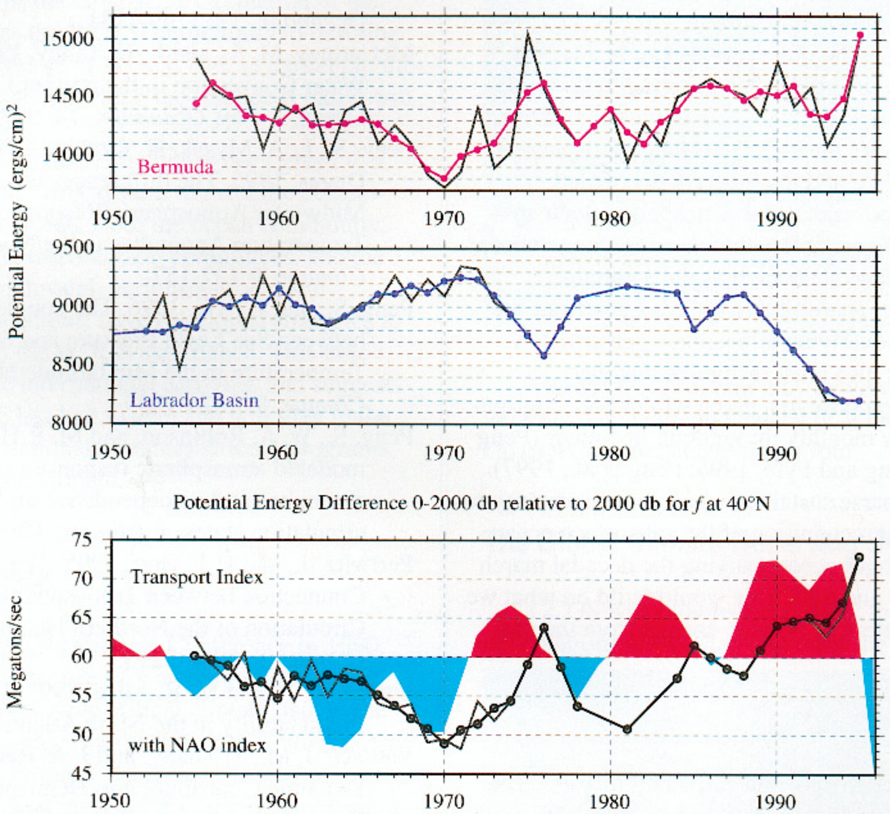

Figure 47 — Time history of an oceanic analog of the atmospheric NAO index of Figure 43 (shown here as a shaded curve). The upper two curves are the anomaly of potential energy (0-2000 db) in the central Sargasso Sea near Bermuda (representing the subtropical gyre central high) and in the central Labrador Basin (representing the subpolar gyre central low). The lower panel shows their difference multiplied by the average coriolis parameter to yield the baroclinic transport (0-2000 db) across the line between those two locations — thus a transport index along the northeastward flow of the transformation pipeline (Figure 46). This also shows the intensity of flow associated with the SST anomalies delineated in Figure 45.

the western subtropical gyre (a warm pool) to the eastern subpolar gyre (a cold pool).

There is evidence (Figure 47) that the intensity of flow in the warm-to-cold water transformation pipeline varies in concert with the decadal march of the NAO index. The decline of the NAO index through the 1950s and 1960s was a period dominated by a strong, warm, propagating winter SST anomaly and declining oceanic baroclinic transport. However, the rise of NAO index from 1970 to 1995 was dominated by a strong, cold, propagating winter SST anomaly and increasing oceanic baroclinic transport.

The next steps needed in this study may include the following:

1. To understand how the nine-year, trans-Atlantic propagation and subsequent circulation around the subpolar gyre of winter SST anomalies (representing local anomalies of upper ocean heat content) occur in the warm-to-cold transforming pool of mode water adjacent to the Gulf Stream and North Atlantic Current.
2. To look for systematic responses of winter atmospheric conditions to the recurrent winter SST anomalies both in the observations and in coupled atmosphere-ocean simulations. Alternative scenarios still to be examined include the passive ocean driven by the atmosphere, the coupled ocean-atmosphere driving each other, and the inherent decoupled variability of both ocean and atmosphere. Such an exploration must recognize that there are many winter SST configurations that occur as the anomalies gradually move. Therefore, many configurations are possible for an overlying atmosphere perturbed by SST. This work also must recognize that the atmosphere's response to a given winter SST configuration may vary monthly throughout the winter (Peng et al., 1995; Peng and Fyfe, 1996; Peng et al., 1997).
3. To develop a sparse sustained measurement strategy to allow continued recognition of the subsurface ocean circulation changes accompanying the decadal march of winter NAO and SST. This would build on what we know of the pattern of oceanic change from the past 50 years.

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