

# Atlantic Climate Variability Experiment Prospectus

## Summary

Energetic, large-scale variability is observed in the atmosphere and ocean of the Atlantic Sector on interannual and decadal time scales. It is manifested as coherent fluctuations in temperature, rainfall, surface pressure and temperature reaching eastward to central Europe and northern Asia, southward to subtropical West Africa and westward to North and South America with a myriad of well documented impacts on society and the environment. The coordinated changes in the position of mid-latitude atmospheric pressure centers and winter storm tracks over the Atlantic, as well as the strength of the trade winds, are commonly referred to as the North Atlantic Oscillation (NAO). In the tropical Atlantic, surface temperature variability and associated changes in the inter-tropical convergence zone and the Hadley circulation occurs on interannual to decadal time scales, phenomena we collectively call Tropical Atlantic Variability (TAV). The NAO and TAV are reflected in marked changes in wind stress on the ocean, as well as air-sea heat and fresh water fluxes. These in turn induce substantial changes in the wind- and buoyancy-driven ocean circulations, water mass transformation and possibly poleward heat transport. Indeed many ocean properties show strong links to overlying atmospheric variability, suggesting that much of the observed ocean variability is driven by the atmosphere. Whilst it is known that the Atlantic ocean plays a central role, through its thermohaline circulation, in the mean climate, its role in modulating atmospheric variability on interannual to decadal time scales is less clear.

We propose an Atlantic Climate Variability Experiment (ACVE) to address the overarching question: In what ways does coupled atmosphere-ocean dynamics in the Atlantic sector play an active role in climate variability? Its primary goal is to quantitatively test and improve our under-

standing of mechanisms and models of atmospheric and ocean processes that lead to climate variability in the Atlantic and its global consequences. We must determine whether observed and simulated variability is fundamentally coupled, whether one component drives variability in the other, whether modeled variability bears any relation to observed variability, and whether modes of variability once identified are predictable. Improvement of atmospheric and oceanic circulation models, especially boundary layer formulations, is a central part of ACVE.

The specific objectives of the Atlantic Climate Variability Experiment are to:

- Describe and model coupled atmosphere-ocean interactions in the Atlantic sector, quantify their influences on the regional and larger scale climate system, and investigate their predictability.
- Assemble a quantitative historical and real time data set that may be used to test, improve and initialize models of coupled Atlantic climate variability.
- Investigate the sensitivity of the meridional overturning circulation of the ocean to changes in surface forcing and assess the likelihood of abrupt climate change.

Some of the processes involved in climatic modulation of the North Atlantic will require broad-scale study of entire gyres or basins; other topics can be examined in focused process experiments. Some investigations must extend over a decade so as to observe a full cycle of the variability of interest. But clever treatment of existing historical observations will provide an important long-time-scale perspective. Understanding the causes of interannual to decadal climate variability demands a new type of research program. The current global network of sustained observations is too thin to support detailed quantitative study of specific climate modes. Moreover,

typical process studies do not last long enough to resolve decadal-time-scale variability.

What is needed is an integrated program of sustained observations, process studies and modeling conducted jointly by meteorologists and oceanographers that last a decade or longer. The proposed Atlantic Climate Variability Experiment needs to develop time-dependent, basin-scale analyses of the Atlantic ocean and atmosphere, based on an economically efficient observing system having significantly greater coverage and density than that provided by routine observations available today. The phenomenological focus will be the NAO and TAV modes of climate variability. The ACVE will encompass model-data synthesis in which mechanisms, key processes, and global teleconnections will be addressed quantitatively inside an improving coupled climate model framework. A prerequisite is to develop an active dialogue between observers, modelers and theoreticians.

This document provides the scientific objectives and framework for achieving an international Atlantic CLIVAR program. It represents a consensus document of U.S. and European scientists reflecting the findings of two U.S. workshops: in Lamont (September, 1997) and Dallas (February 1998); and a joint U.S.-European meeting held in Florence (May 1998). A list of scientist who attended these meetings is attached in section 8.

After a brief introduction in section 1, the scientific background is set out in section 2. Section 3 discusses some of the societal impacts of Atlantic-sector climate variability. The scientific questions are set out in section 4, and a proposed strategy for addressing them is given in section 5. Programmatic context is discussed in section 6, along with an outline of the next steps necessary to advance the planning and begin the implementation for this project.

## 1. Introduction

The climate of the Atlantic Sector has exhibited considerable variability on a wide range of time scales. Improved understanding of this variability is essential for a) assessing the likely range

of future climate fluctuations and the extent to which they may be predictable, and b) understanding the potential impact of climate change due to changing levels of greenhouse gases.

A substantial proportion of the climate variability in the Atlantic region is associated with a phenomenon known as the North Atlantic Oscillation (NAO). Although the spatial pattern of the NAO appears to be a natural mode of atmospheric variability, its phase may be influenced by surface, stratospheric, or even anthropogenic processes. The NAO has undergone major low frequency variation this century. The rising NAO state over the past twenty years has been accompanied by a strengthening of the Pacific-North America (PNA) pattern of atmospheric variability, and together they have resulted in a global pattern of cooling of the mid-latitude oceans, and warming over northern hemisphere land masses.

Several mechanisms have been proposed to account for the observed low-frequency variability in the NAO including atmospheric response to changes in sea surface temperatures, variability of deep atmospheric convection in the tropics, and the effects of changing external forces such as solar insolation, volcanic eruptions, and anthropogenic emissions of climatically important trace gases. Alternatively, the NAO may simply be a natural internal mode of the atmosphere. Distinguishing between these hypothesized mechanisms is a high priority. Low frequency variation of the Atlantic Ocean is also poorly understood. SST anomalies have been observed to propagate slowly through the upper-ocean gyre circulations, formed in response to, or possibly inducing changes in the NAO. The phase of the NAO also appears to be correlated to the formation of deep water in the Greenland, Iceland, Norwegian and Labrador Seas, which in turn influence the strength and character of the Atlantic meridional overturning circulation (MOC). Although changes in the MOC can occur naturally, there is also the possibility that they could be triggered by anthropogenic emissions. A breakdown of the MOC could lead to drastic changes in global climate. A program investigating Atlantic variability should therefore also explore those atmo-

spheric, oceanic and ice processes which are critical to the MOC.

Substantial variability is observed in the tropical Atlantic region on interannual and decadal time scales. Sea surface temperature (SST) anomalies have been observed both north and south of the equator, along with regional changes in winds and precipitation. Following the success of ENSO modeling in the Pacific, study of low-latitude Atlantic variability has highlighted the tropical Atlantic's response to variable atmospheric forcing, and the atmospheric response to tropical SST gradients. Key questions in both the Atlantic and Pacific include the nature and consequences of tropical-subtropical interactions between the free atmosphere and the ocean, as well as inter-ocean interactions via teleconnections within the tropics or involving the higher-latitude PNA and NAO patterns.

Most important, the predictability of climate fluctuations in the Atlantic region needs to be established. Great progress has been made in the last 20 years developing understanding of the evolution of ENSO in the Pacific and its influence on future weather patterns. It is timely to begin comparable studies of Atlantic modes of climate variability. Even if it turns out that the predictability of such modes is limited, improved understanding of climate variability in the Atlantic region is essential to better assess the potential impact of climate change due to changing levels of greenhouse gases, and the possibility of rapid climate change associated with changes in the MOC.

## 2. Modes of Atlantic Climate Variability

To motivate the science plan described below, we give here a brief review of what is known about Atlantic climate variability<sup>1</sup>.

### 2.1 — The North Atlantic Oscillation

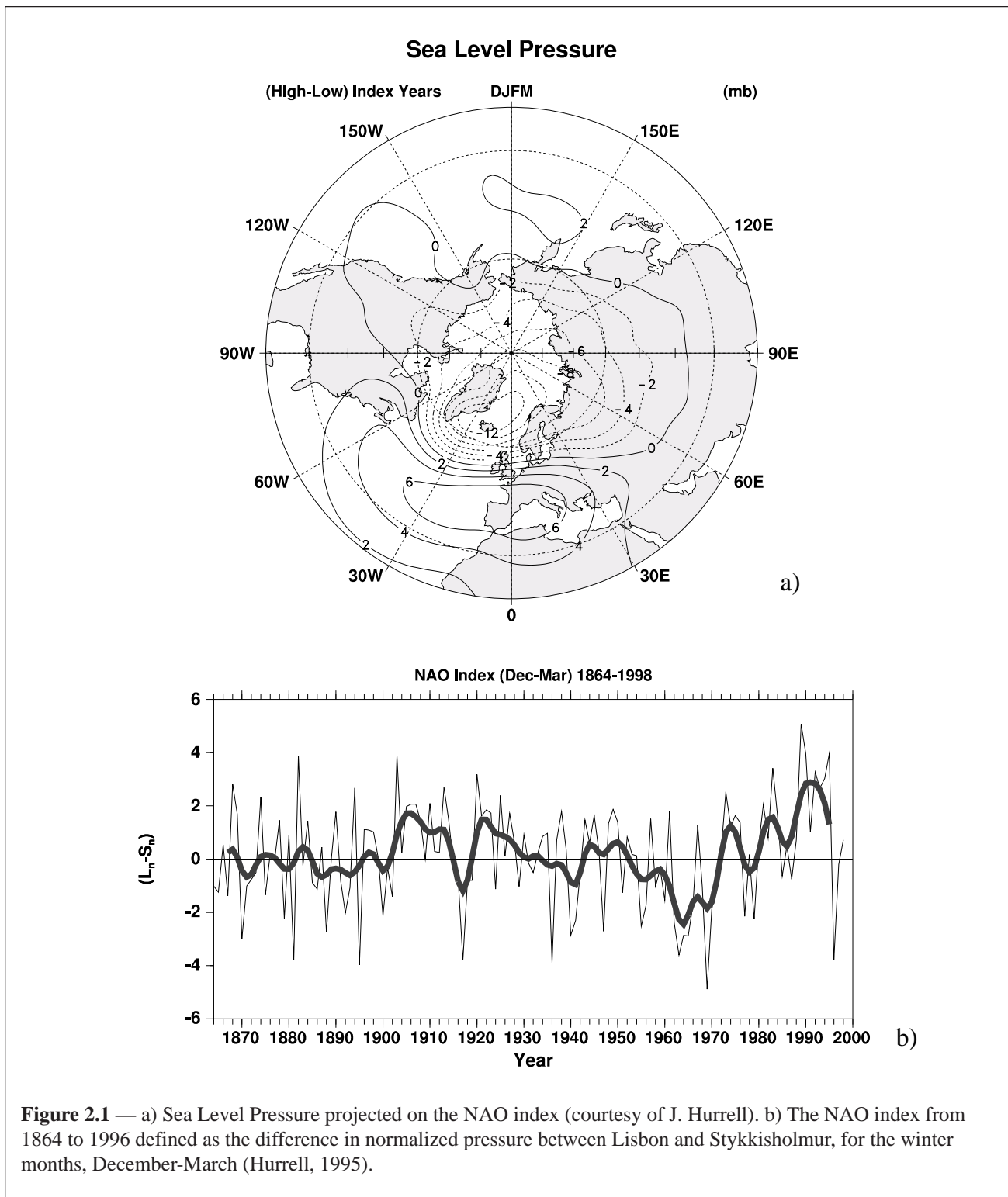
Earlier this century, meteorologists noticed that year-to-year fluctuations in winter air temperatures on either side of Iceland were often out of phase. When temperatures were below normal over Greenland they were above normal in Scandinavia, and vice versa. Concomitant fluctuations in rainfall, and sea level pressure (SLP) were also documented, reaching eastward to central Europe, southward to subtropical West Africa and westward to North America. Walker and Bliss (1932) noted a tendency for pressure to be anomalously low near Iceland in winter when it is anomalously high near the Azores and southwest Europe. This mode of climate variability has come to be known as the North Atlantic Oscillation (NAO), a name first used by Walker in 1924 (see Rogers, 1990). The horizontal structure of the NAO is plotted in the Figure 2.1a. In contrast to the mean flow, the NAO has a pronounced “equivalent barotropic” structure (vertical phase lines, Wallace and Gutzler, 1981, Kushnir and Wallace, 1989) and increases in amplitude with height in rough proportion to the strength of the mean zonal wind. This result is consistent with the notion that the NAO has a structure that is close to that of a stationary external Rossby mode (Held, private communication) and maybe inseparable from true dynamics of the zonally symmetric circulation. It appears to be a “resonant structure” (a “neutral mode” of the climatology; Marshall and Molteni; 1993), which can be excited in a number of different ways.

The vertical structure of the NAO gives us strong clues as to its likely mechanism. Eddy-mean-flow interaction (i.e., dynamics internal to the atmosphere) is thought to be the primary forcing mechanism on short time-scales. Eddy-potential vorticity flux forcing readily projects on to the vertical structure of the NAO.

The NAO index, defined as the normalized

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<sup>1</sup> Detailed discussions of climate variability phenomena in and over the Atlantic Ocean are given in a “White Paper” on the Atlantic Climate Variability (<http://geoid.mit.edu/accp/avehtml.html>) and elsewhere (e.g., <http://www.clivar.ucar.edu/hp.html>). Some of that material may be also viewed at the ACVE web page (<http://www.ldeo.columbia.edu/~visbeck/acve/>). See also (<http://www.cgd.ucar.edu/cas>) and the international CLIVAR documents (<http://www.clivar.ucar.edu/hp.html>) D1-D3.



SLP difference between Iceland and the Azores, from 1864 to the present day is plotted in Figure 2.1b. Positive values indicate stronger-than-average middle-latitude westerly winds. Such a simple index is chosen because of the availability of data - it clearly cannot accurately capture

the seasonal variations in the NAO (Barnston and Livezey; 1987), or the possibility that the centers of the actual pattern may not overlap these locations.

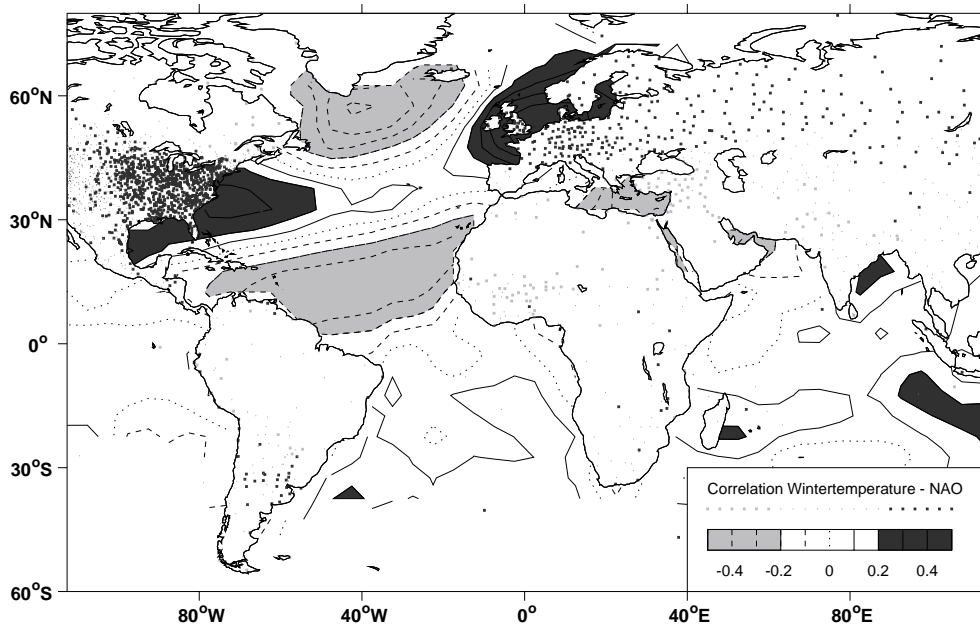
Paleo indicators of the NAO suggest that it has been coherent over long periods of the 700-

year stable isotope record from the GISP-2 ice core from central Greenland (White et al., 1996). Similar evidence emerges from the tree-ring data (Cook et al; 1998). H. Wanner (personal communication, 1998), however, reconstructs the NAO from proxy and documentary sources and hypothesizes that decadal-scale cold phases during the Late Maunder Minimum (1675-1715) were related to successive negative NAO events. If the main forcing mechanism of the NAO were due to its interaction with synoptic-scale eddies, then one might expect its frequency spectrum to be white. The spectrum of the wintertime NAO index is slightly red (power increases with period) with an indication of enhanced power in some frequency bands (though not large enough to be considered statistically significant; Wunsch, 1998). However, frequency domain analyses (Mann and Park, 1996; Tourre et al., 1998), suggests that these relatively weak spectral peaks relate to basin-wide coherent phenomena and so perhaps are real. Thompson and Wallace (1998) have drawn attention to the fact that the NAO may be the regional manifestation of a hemispheric mode of variability centered over the Arc-

tic Ocean. This “Arctic Oscillation” - the AO - is an equivalent barotropic, zonally symmetric structure which couples the troposphere with the stratosphere (Perlwitz and Graf; 1995) and modulates the strength of the polar vortex, as in the zonal index of Rossby et al (1939). Because the energy density of the mode remains high well into the stratosphere, it has been suggested that the NAO could be modulated through its interaction with the polar vortex and hence be sensitive to anthropogenic influences in the stratosphere. Cause-and-effect within the stratosphere are not yet sorted out; one extreme view is the “Charney-Drazin” picture of upward propagating energy from the energetic winter troposphere, with the stratosphere both conditioning the waveguide, and turning the energy into a breaking planetary wave. Another is that an increasingly strong polar stratospheric vortex could actively excite the tropospheric NAO.

### 2.1a — Covarying patterns in the ocean

There are clear indications that the North Atlantic Ocean varies significantly with the overlying atmosphere. Expectation of an im-



**Figure 2.2** — Regression between winter SST and land surface temperatures and the NAO index (courtesy of M. Visbeck and H. Cullen)

print of the changing atmosphere on the ocean, and perhaps a coupling between climate change signals in the two fluids, follows from several related points:

First, changes in the NAO, are reflected in marked changes in surface wind stress, air-sea heat exchange, and the evaporation-precipitation balance (Cayan, 1992a) and sea-ice. Heat flux anomalies directly drive month-to-month SST tendencies in the North Atlantic (Cayan, 1992b). Figure 2.2 shows the regression of SST on the NAO index during winter. It reveals a tri-polar pattern - a cold subpolar region, warmth in middle latitudes and a cold region between the equator and 30°N. This is also the leading pattern of SST variability during winter. Its emergence is consistent with the spatial form of the anomalous surface fluxes associated with the NAO pattern, as pointed out by Cayan (1992a, b). It appears that the strength of the correlation increases when the NAO index leads SST indicating that SST is responding to atmospheric forcing on monthly time scales (Frankignoul 1985; Battisti et al 1995; Delworth; 1997). Changes in sea-ice cover in both the Labrador and Greenland Seas are well correlated with the NAO, with a particularly strong atmospheric feedback.

Second, the NAO has its largest amplitude in winter. The interior ocean has a selective memory for winter conditions, both in the subduction of winter conditions in to the thermocline (Stommel, 1979; Marshall et al, 1993; Williams, et al., 1995), and in the seasonal sequestering of winter conditions from below the seasonal thermocline. Third, the ocean acts as an integrator of the high-frequency forcing acting on it. If an SST anomaly is 'tied' to a deep thermal anomaly, which is re-exposed each winter (Alexander and Deser, 1995), then the SST anomaly can re-emerge year after year and so might have a greater ability to alter, through anomalous fluxes, the overlying atmosphere. Sea surface temperature observations display a myriad of long-term (interannual and decadal) responses. The pattern of SST variability is indicative of the ability of the ocean to store heat locally and move it around (Deser and Blackmon, 1993; Hansen and Bezdek, 1996). The

spreading of SST anomalies along the path of the Gulf Stream and North Atlantic Current is of particular interest (Sutton and Allen, 1997). Here winter SST anomalies born in the western subtropical gyre are found to propagate eastward with a transit time of a decade or so. Subsurface ocean observations provide an even clearer depiction of long-term climate variability because the effect of the annual cycle and month-to-month variability in the atmospheric circulation decays rapidly with depth. A large freshening event (dubbed the Great Salinity Anomaly, GSA) occurred in the sub-polar gyre in the early 1970s (Dickson et al., 1988). Observations suggest it may have been linked to coherent changes in the overlying atmospheric circulation and an extreme manifestation of the quasi-decadal fluctuations (Reverdin et al., 1997; Belkin et al; 1998). The GSA event followed the deep reaching changes in temperature and salinity in the North Atlantic, from the late 1950s to the early 1970s (Levitus, 1989). These changes coincide with a multi-decadal fluctuation of SST and atmospheric conditions (Kushnir, 1994; Hansen and Bezdek, 1996). Variability in the temperature of the upper subtropical ocean has also been linked with fluctuations in the NAO index (Molinari et al., 1997). On decadal time scales, the intensity of convection tends to see saw between the Labrador Sea and the Greenland-Iceland Seas (Dickson et al., 1996) orchestrated by fluctuations in the NAO. The link between propagating SST anomalies and the properties of water (McCartney et al., 1996) mixed at the end of winter, shows that the end-product of the transformation process, Labrador Sea Water (LSW), underwent extended warming and cooling trends consistent with the phase of the NAO.

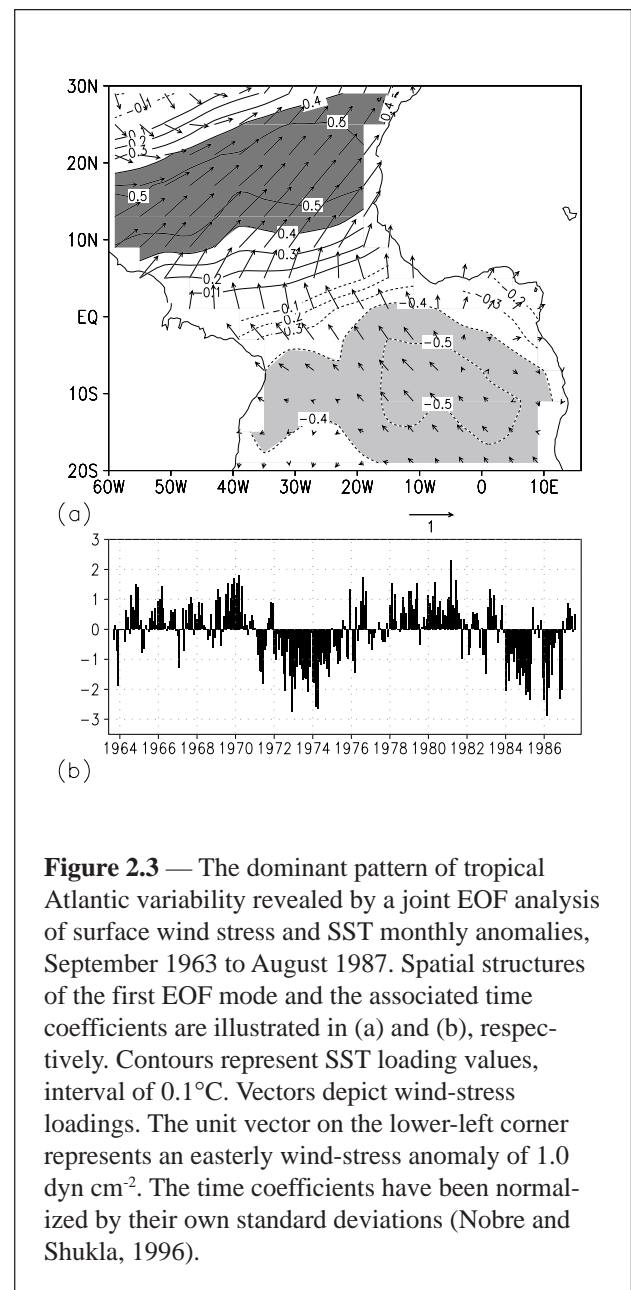
## 2.2 — Tropical Atlantic Variability

The dominant low-frequency climate phenomenon in the tropical Atlantic is the covarying fluctuation of tropical SST and trade winds (Nobre and Shukla, 1996, and Figure 2.3a). The time series of the joint SST and wind pattern (Figure 2.3b) clearly contains long-term components and a noticeable imprint of decadal variability. These fluctuations exhibit a pattern of basin-wide

SST anomalies straddling the mean position of the ITCZ, with concomitant changes in trade wind intensity. The Northern Hemisphere trades, and the associated cross equatorial flow, seem to depend sensitively on SST. Very little wind variability is found south of the equator. Weaker than normal trades are associated with positive local SST anomalies, and vice versa (Nobre and Shukla, 1996; Enfield and Mayer, 1997). The northern trades are also affected by SST changes south of the equator, such that colder than normal SST in the South Atlantic correspond to weaker than normal trades in the North Atlantic and vice versa. Early statistical analysis of SST data revealed a dipolar structure (particularly when referenced to meteorological anomalies, Moura and Shukla, 1981) and led investigators to dub the pattern the “tropical Atlantic SST dipole.” However, SST variability north and south of the equator are not correlated (Houghton and Tourre, 1992; Enfield and Mayer, 1997, Mehta, 1998), suggesting that it is the change in the cross-ITCZ SST contrast to which the trades respond. While it is becoming apparent that SST variability on both sides of the Atlantic ITCZ is not well described as a temporally coherent seesaw fluctuation, it does seem that climate variability in the tropical Atlantic is sensitive to the cross equatorial SST differences (Hastenrath and Heller, 1977; Servain, 1991; Ward and Folland, 1991; Folland et al., 1991). The build-up of the North Atlantic SST anomaly lags behind the local change in the wind circulation by a month or two (Nobre and Shukla, 1996), much like the lag between the atmosphere and ocean in mid-latitudes (Frankignoul, 1985). However, as the SST anomaly builds up, the Northern Hemisphere trades adjust, so that on seasonal time scales the atmosphere feels the SST anomaly buildup and responds to it (Nobre and Shukla, 1996). A mode of tropical Atlantic atmosphere-ocean variability has been identified that is akin to ENSO in the Pacific (Covey and Hastenrath, 1978; Philander, 1986; Zebiak, 1993) and involves variations in SST along the equator. These perturbations in equatorial winds and SST are not as dominant as their Pacific counterpart, apparently because the Atlantic basin is much narrower

than the Pacific, and do not appear to be consistently sustained (Zebiak, 1993). However, they do exert some influence over the adjacent land masses.

The Atlantic sector clearly responds to the Pacific El Niño although the relative importance of this remote forcing in tropical Atlantic variability is still unresolved. (Hastenrath et al., 1987; Hameed et al., 1993; Nobre and Shukla, 1996; Enfield and Mayer, 1997). The ENSO influence is transferred through the atmosphere, via changes in both the Walker circulation and Northern Hemisphere extratropical teleconnections (i.e., the Pa-



**Figure 2.3** — The dominant pattern of tropical Atlantic variability revealed by a joint EOF analysis of surface wind stress and SST monthly anomalies, September 1963 to August 1987. Spatial structures of the first EOF mode and the associated time coefficients are illustrated in (a) and (b), respectively. Contours represent SST loading values, interval of 0.1°C. Vectors depict wind-stress loadings. The unit vector on the lower-left corner represents an easterly wind-stress anomaly of 1.0 dyn cm<sup>-2</sup>. The time coefficients have been normalized by their own standard deviations (Nobre and Shukla, 1996).

cific North American Pattern, PNA). ENSO is thought to particularly effect the western flank of the Northern Hemisphere subtropics, during the winter and spring following the onset of ENSO. It appears that ENSO effects further east in the Gulf of Guinea is rather small (Enfield and Mayer, 1997).

Finally, there exists a link between tropical climate variability and the NAO (see Figure 2.2). Variability of the NAO can change the intensity of the trades in the eastern subtropical North Atlantic and thence SST. Moreover, the NAO itself may be sensitive to subtropical SST anomalies (S. Jewson, personal communication, 1998, show that there is a significant model response with and without the tripole SST pattern of Figure 2.2, and argues that it is the subtropical SST anomalies which are the most important). It has even been suggested (Tourre et al; 1998, Rajagopalan, personal communication; Robertson et al, personal communication) that there is a link between the NAO and tropical SST in the South Atlantic. It remains to be seen whether the induced changes in tropical SST can feed back on the extratropical circulation through mechanisms akin to those acting in the Pacific.

### **2.3 — Thermohaline circulation and abrupt climate change**

The mean circulation of the ocean plays a key role in meridionally transporting water properties such as heat and freshwater, carbon and nutrients. In concert with meridional atmospheric fluxes, ocean transports balance the earth's global heat and hydrologic budgets. At 25°N, the Atlantic's subtropical gyre circulation carries some 1.2 PW of heat northward: approximately 60 percent of the net poleward ocean flux and 30 percent of the total flux by ocean and atmosphere at this latitude (Hall and Bryden, 1982). This poleward heat flux is of course intimately associated with the watermass transformations that take place as thermocline waters move north and are ultimately converted by air-sea interaction into cold North Atlantic Deep Water (NADW). Thermocline waters of the South Atlantic, representing some mix of Indian Ocean and Pacific water

masses, move north within the S. Atlantic subtropical circulation and enter the tropical regime largely at the western boundary. There, significant water mass transformation occurs within the energetic equatorial circulations, with much warmer waters emerging northward. The warm-water link between tropical and northern subtropical circulations is complex, involving both strongly varying Ekman transport in the interior and highly time-dependent western boundary current flows. Upon entering the subtropical gyre, the northward thermocline water flow is incorporated into the Florida Current/Gulf Stream system and related interior circulation. The role of the Atlantic in a world of increasing CO<sub>2</sub> emissions has received increased attention of late. About 60 percent of the global oceanic CO<sub>2</sub> uptake may take place in the Atlantic sector, a consequence of its intense meridional overturning circulation. However, some model projections suggest that in only a few decades, Atlantic climate might radically shift into a different equilibrium with much reduced MOC. Evidence for rapid climate shifts in the past has been found in several paleo records and is attributed to changes in the strength of the MOC. A weaker MOC will result in a reduced poleward oceanic heat transport and might dramatically reduce oceanic CO<sub>2</sub> uptake and more importantly, rapidly cool Europe and the northeastern American continent. One might rightfully question the accuracy of such projections. However, the dramatic impact on the western world of such a scenario, even if highly unlikely, justifies a concerted effort to monitor the evolving climate in the Atlantic sector and improve fundamental understanding of the coupled climate system.

## **3. Impacts of Atlantic Climate Variability**

### **3.1 — The North Atlantic Oscillation**

#### **• Temperature and global warming**

The NAO exerts a dominant influence on the wintertime temperatures of the Northern Hemisphere. Surface air temperature and SST

in wide regions across the North Atlantic basin, in eastern North America, the Arctic, Eurasia and the Mediterranean, are significantly correlated with NAO variability. Changes in temperature over land (and related changes in rainfall and storminess, see below) are of serious consequence to a wide range of human activities.

Changes of more than 1°C in surface temperature can be associated with a one standard deviation change in the NAO index occur over the northwest Atlantic and extend from northern Europe across much of Eurasia (Hurrell, 1995; Hurrell and van Loon, 1997, see Figure 3.1). Temperature changes over northern Africa, the Middle East and the southeast U.S. are also notable. Of particular interest is the contribution of the NAO variability to the recent trend in Global/hemi-

spheric mean wintertime temperature. Hurrell (1996) demonstrated that both NAO and ENSO are linearly related to this climate trend with NAO dominating a larger land area than ENSO. Thompson and Wallace (1998) argue that an index of the AO is more strongly correlated to the temperature trend over Eurasia than the NAO. Perlwitz and Graf (1995) suggest that the trend in the NAO and the associated trend in wintertime temperature over Eurasia (and other details of the trend pattern) are a manifestation of the anthropogenic greenhouse effect. They hypothesize that stratospheric increases in CO<sub>2</sub> result in enhanced radiative cooling of the polar stratosphere in winter, leading to a strengthening of the polar vortex. They then invoke stratosphere-troposphere interaction to explain the recent positive trend in the NAO index



**Figure 3.1** — Observed surface temperature change associated with a one standard deviation of the NAO index. The regression coefficient was computed for the winters of 1935-1996 (from Hurrell and van Loon, 1997). Contours are in 0.1°C. Dark (light) shading indicate positive (negative) changes.

through enhancement of tropospheric stationary waves.

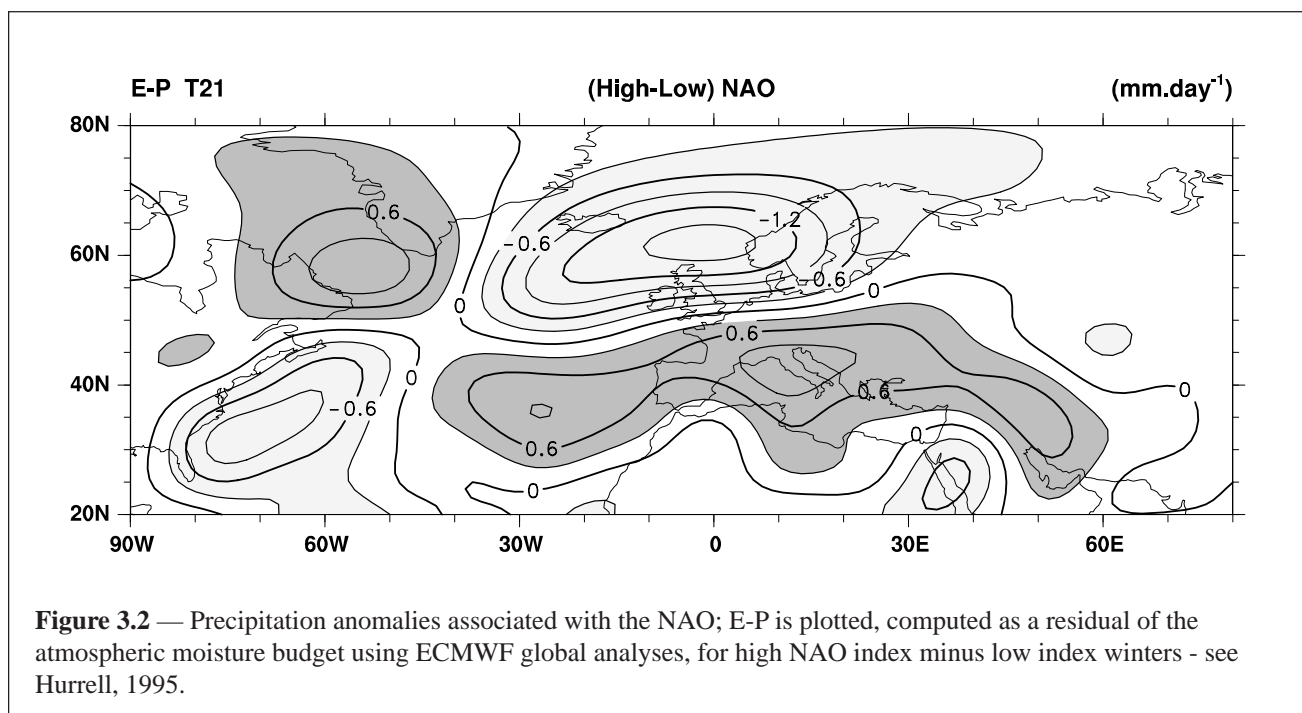
- **Precipitation and Storms**

Changes in mean circulation patterns over the North Atlantic are accompanied by pronounced shifts in the storm tracks and associated synoptic eddy activity. These effect the transport and convergence of atmospheric moisture and can be directly tied to changes in regional wintertime precipitation (Figure 3.2, see also van Loon and Rodgers, 1978; Lamb and Pepler, 1987; Hurrell, 1995). Drier than normal conditions occur during high NAO index winters over much of central and southern Europe, the northern Mediterranean countries, and west North Africa. At the same time, wetter than normal conditions occur from Iceland through Scandinavia. Over North America the effect of NAO on precipitation is not strong. However an out of phase relationship between the NAO index and snowfall over New England was found. The NAO-related changes in precipitation patterns have directly affected different European economies, in particular because of the long stretch of consecutive winters in which the NAO continued to intensify. Over the Alps, for instance, snow depth and duration over

the past several winters have been among the lowest recorded this century, causing economic hardship to those industries dependent on winter snowfall (Beniston, 1997). Severe drought also prevailed throughout Spain and Portugal affecting olive harvests. In contrast, increases in wintertime precipitation over Scandinavia was related to recent positive mass balances in the maritime glaciers of southwest Norway, one of the few regions of the globe where glaciers have not been retreating.

Storminess in the midlatitudes is associated with the path of synoptic disturbances and their frontal systems. Indeed, this is the source of the above- indicated changes in midlatitude rainfall patterns. It is well known that changes in low-frequency patterns are associated with changes in storm activity and shifts in the storm tracks (Lau, 1988; Rogers, 1990). The NAO is clearly linked to systematic changes in storm tracks over the Northern Hemisphere from North America to Eurasia and the Mediterranean (Rogers, 1997).

There is a connection between the seasonally-averaged NAO and low frequency variability within a season (e.g., blocking) over



the Atlantic (see Nakamura, 1996). There is weaker intra-seasonal variability near Greenland and the Labrador Sea and stronger intra-seasonal variability over Europe, when the NAO index is positive (and visa-versa).

The ocean integrates the effects of storms in the form of surface waves, to exhibit a marked response to long lasting shifts in the storm climate, as is the case with variability related to the NAO. The recent rising trend in the intensity of the NAO has had a profound effect on the surface wave climate of the North Atlantic. The trend in measured wave heights has been supported by many anecdotal reports about increasing wave heights encountered by mariners and North Sea oil rig operators. Recent studies by Bacon and Carter (1993) and Kushnir et al. (1997) have tied, in a more quantitative manner, the increase in wave heights to the increase in wintertime storminess and mean wind speeds in the North Atlantic during the last 30 years or so.

- **Fisheries and ecosystems**

Changes in the NAO have been associated with a wide range of effects on the marine ecosystem too. This includes changes in the production of zooplankton and the distribution of fish (e.g., Fromentin and Planque 1996; Friedland et al., 1993, Drinkwater, 1994). The NAO has been linked to blooms of the “brown tide” unicellular algae in coastal waters of Eastern Long Island, which devastate the local commercial scallop fishery (LaRoche et al., 1997).

Evidence has also recently emerged that, in Scandinavia, the NAO influences temporal and spatial variability in timing of plant growth: the length of the plant growth season varied by 20 days between extremes of the NAO index (Post et al., 1997). Through effects on vegetation and climatic conditions, the NAO was furthermore observed to influence several aspects of life history and ecology of terrestrial, large mammalian herbivores, including: phenotypic variation, fecundity, demographic trends, and population dy-

namical processes (Post et al., 1997). Influences of the NAO are evident among five species of ungulates in populations in Greenland, Canada, the U.S., Great Britain, Norway and Finland.

### 3.2 — Tropical Atlantic Variability

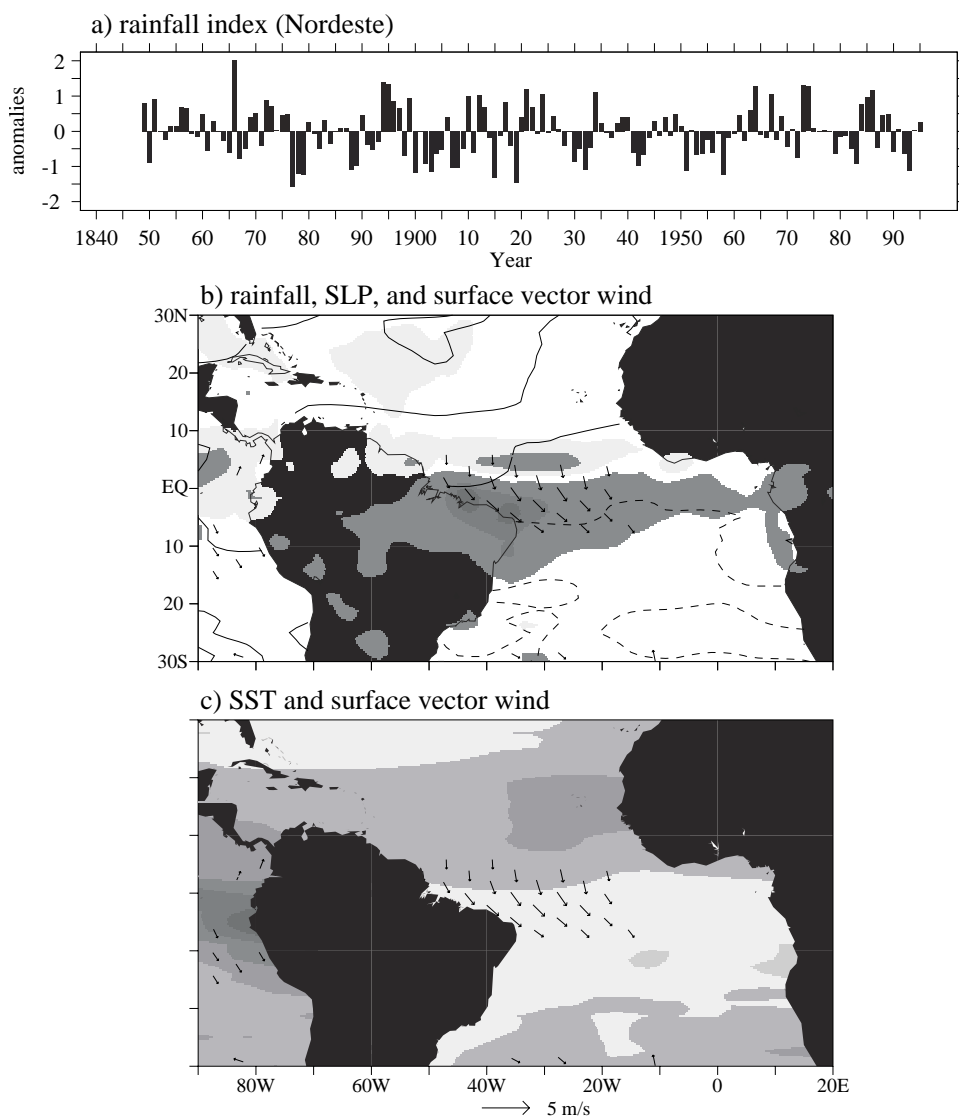
- **Rainfall and droughts**

Although sea surface temperature anomalies in the tropical Atlantic are weaker than those associated with the Pacific El Niño, they can cause disastrous climate hazards over the Americas and Africa. In the tropical Atlantic, rainfall is governed by the annual migration of the subtropical high pressure cells on both sides of the equator and the changes in their strength, as well as the north-south swings of the Intertropical Convergence Zone. Many of the continental regions bordering the tropical Atlantic experience a sharp seasonal contrast in rainfall where half the year is wet and the other half dry. Some of these regions are blessed with abundant rainfall, while others are semiarid. It is in these semiarid regions that a delay in seasonal rainfall or a significant drop in its total amount can bring serious hardship to their inhabitants. Such is the situation in sub Saharan Africa (the Sahel, 15°W-15°E, 15-20°N) with its boreal summer rainfall, and the northeast corner of Brazil (Nordeste, 35 45°W, 2-10°S) where it rains in the boreal winter. Many meteorologists have for quite some time been concerned with the dynamics of climate anomalies in these two regions. Hastenrath and collaborators (Hastenrath and Heller, 1977; Hastenrath, 1978; Hastenrath et al., 1984; Hastenrath and Greischar, 1993, Moura and Shukla, 1981; Ward and Folland, 1991; Nobre and Shukla, 1996) found that tropical Atlantic SST distribution and the associated anomalies in sea level pressure and wind are leading factors in determining the anomalies in seasonal Nordeste rainfall. These same climatic factors were also found to be strongly linked with rainfall anomalies over the Sahel and western tropical Africa (Lamb, 1978; Hastenrath,

1984; Folland et al., 1986; Folland et al., 1991).

Rainfall anomalies in the Nordeste display a wide range of time scales with clear decadal components (Figure 3.3a). Such long time scales are also present in the Sahel rainfall time series (not shown). The correlation between seasonal rainfall in the Nordeste and tropical Atlantic rainfall indicates an out of phase relationship between SST anomalies in the ocean regions underlying the Northern and Southern Hemisphere trade wind region, respectively (Hastenrath and Heller, 1977;

Markham and McLain, 1977; Moura and Shukla, 1981). Dry Nordeste years tend to occur when SSTs north of the equator are warmer than normal and SSTs south of the equator are colder than Normal. Rainfall in subtropical west Africa is more complex but also displays considerable dependence on a similar out of phase variation of SST in the tropical Atlantic (Lamb, 1978; Lough, 1986; Lamb and Pepler, 1987). It rains more when Northern Hemisphere subtropical SST are warm, and Southern Hemisphere SST are cold. Recent attempts to understand the dy-



**Figure 3.3** — a) Seasonal rainfall anomalies over the Nordeste region of Brazil. b) Correlation of Nordeste rainfall index with rainfall anomaly (shaded), wind vector and sea surface pressure (contours). c) Correlation of Nordeste rainfall index with SST (shaded) and wind vector (courtesy of Mitchell).

namics of this asymmetric SST distribution are described in Carton et al., 1996, Nobre and Shukla, 1996 and Chang et al., 1997.

- **Hurricanes**

Interannual variability of the seasonal frequency of Atlantic hurricanes is related to, amongst other factors, the sign and amplitude of the SST anomaly in the subtropics (Gray, 1990; Shaeffer, 1996). Moreover, Gray (1990) also suggests that tropical cyclone intensity is correlated with the multi-decadal fluctuation of North Atlantic SST (Kushnir, 1994). In fact, Gray anticipates a return to a stormier tropical climate, similar to that of the 1950s, when the North Atlantic finally recovers from its recent cold phase. Such an increase would threaten the densely populated coastal regions in the Gulf of Mexico and the North American Atlantic seaboard which have developed markedly during the relatively benign 1970s and 1980s.

### **3.3 — Abrupt Climate Change**

The possibility of a major change in the oceanic meridional overturning circulation under greenhouse forcing has been proposed by Manabe, Stouffer, Broecker, and Rahmstorf, in separate works based on a variety of coupled GCMs, and ocean-only GCMs. “Abrupt climate change” has received a particular burst of attention in the literature and the popular press through the suggestion that the increasing freshwater transports and warmer atmospheric temperatures in a greenhouse world will blanket the high-latitude oceans with a buoyant layer, and cause instability or even collapse of the MOC. Model formulation of the air-sea fluxes of heat and moisture, the sites of deep convection in simulations, and many other dynamical aspects of the models are in question. Yet one cannot ignore the possibility that increased fresh-water input and atmospheric high-latitude temperature could suppress the MOC. The impact, particularly on Eurasian climate is potentially severe. The fairly low probability is thus multiplied by a large potential impact, and thus demands attention.

## **4. The scientific challenges**

Given the societal, economic and ecological impact of interannual to decadal time scale climate variability, it is of paramount importance to improve our dynamical understanding of climate fluctuations in and over the Atlantic Ocean, to study the predictability of these fluctuations, and to quantify their impact on regional weather patterns and short time-scale climate variability. Several potentially important mechanisms of basin-scale atmosphere-ocean interaction and coupling have been proposed. These physical processes need to be explored and dynamical hypotheses advanced and tested within the Atlantic Climate Variability Experiment. In particular, data analysis and the collection of new observations must be guided by theoretical and modeling work that explore mechanisms underlying the coupled system.

We will first review the basic hypothesis for coupled Atlantic Climate Variability and then identify a set of related key issues that need to be addressed during ACVE. We then focus on the component parts of the atmosphere-ocean system to reveal their inherent nature in isolation, and finally proceed to a consideration of the coupled behavior both regionally and on large scale.

### **4.1 — Hypotheses for Coupled Atlantic Climate Variability**

On interannual to decadal time scales there are preferred modes of variability of the coupled atmosphere-ocean system. The basic hypothesis which needs to be explored during ACVE is: The preferred modes of climate variability are significantly influenced by ocean-atmosphere interactions local to the Atlantic and distinct from the modes of either the ocean and atmosphere in isolation. For this hypothesis to hold, SST anomalies must exert a significant influence on atmospheric flows. In particular, the atmospheric response to SST anomalies must significantly influence the flux of heat, moisture and momentum at the ocean surface.

In contrast, the null hypothesis is: The atmosphere has internal modes of variability with a somewhat red spectrum. The ocean integrates this

essentially stochastic forcing, responding more robustly to the lower frequencies and thereby red- dening the response spectrum. Interdecadal variability then is either a result of decade to decade changes in atmospheric boundary conditions due to anthropogenic, solar, or volcanic effects, or, more likely, represents the low frequency tail of a red spectrum.

The major challenge of ACVE is to determine the validity of these two hypotheses by means of observations, numerical simulations and theoretical studies. Because the source of climate variability can be internal (natural) and external due to anthropogenic forcing, attempts to test the hypotheses must take these factors into the consid- eration.

The strength of active ocean-atmosphere cou- pling is likely to vary spatially. In middle/high latitudes, the diabatic heating is confined within the lower boundary of the atmosphere, making it difficult to thermally force the NAO directly at the ocean surface. Therefore, weak air-sea feed- backs are anticipated. The ocean, then, is prima-

rily driven by the surface fluxes associated with internal variability of the atmosphere that reflects the spatial pattern of the NAO. The NAO not only provides a dominant forcing to middle/high lati- tude SST variability and meridional overturning cell (MOC) in the Atlantic ocean, but also may play a significant role in exciting variability in the tropics (Figure 4.1). In contrast to heating in higher latitudes, convective heating in the tropics extends much deeper into the atmosphere, making the tropical atmosphere more responsive to SST forcing. Thus, active ocean-atmosphere coupling is more likely to occur in the lower lati- tudes.

A coupled mechanism has been proposed for the tropical Atlantic whereby the cross-equatorial SST gradient plays a crucial role for the position of the ITCZ. This in turn will influence the strength of the trade winds and feedback to tropi- cal SST anomalies (Figure 4.2). Moreover, the variability of the ITCZ may have an important remote impact on the NAO, possibly through re- arranging the Hadley circulation (Figure 4.1). It

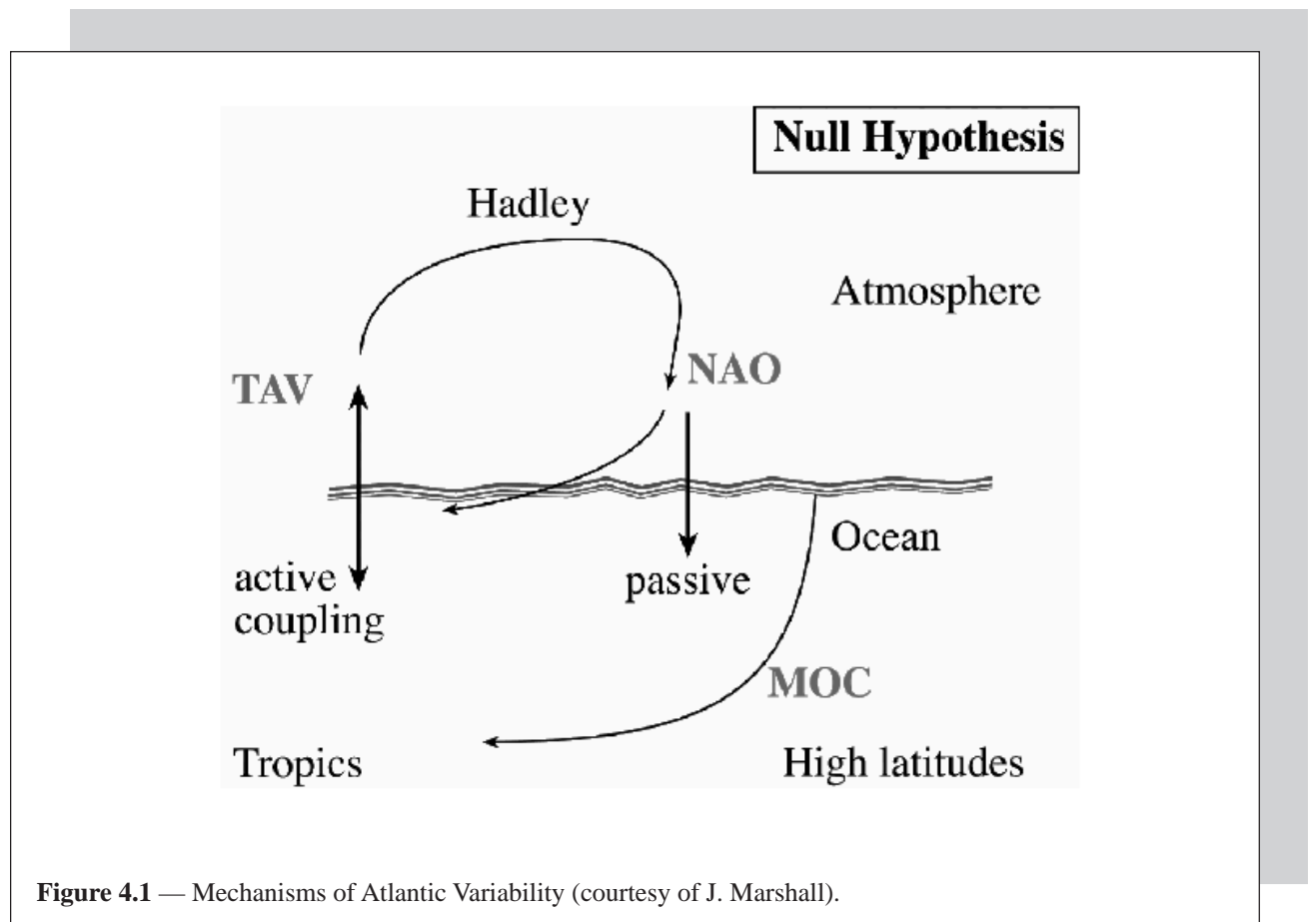
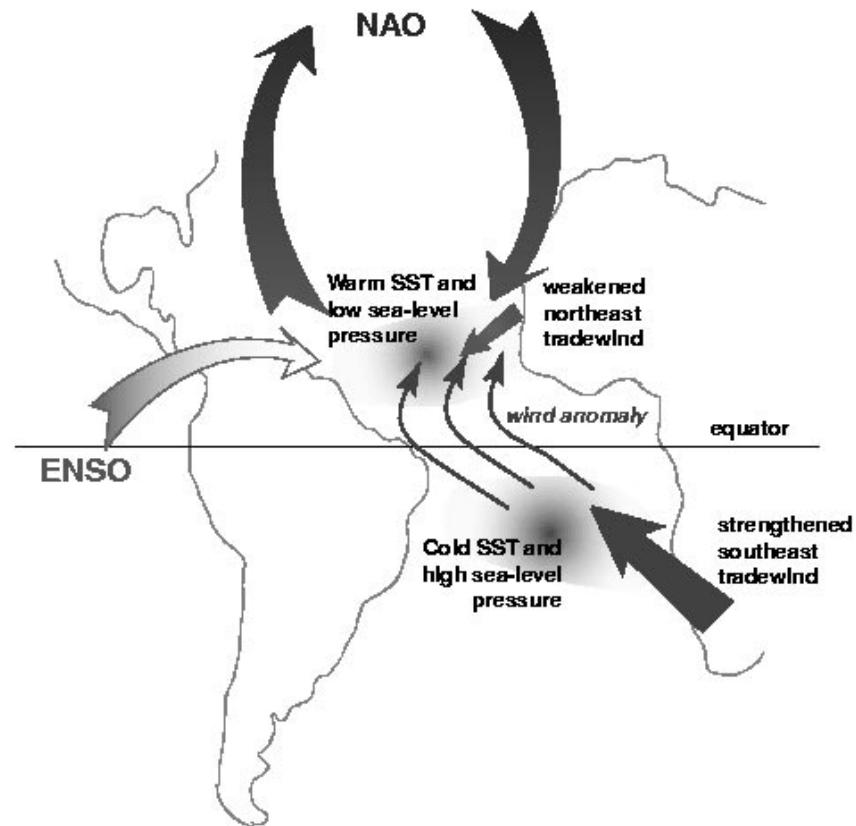


Figure 4.1 — Mechanisms of Atlantic Variability (courtesy of J. Marshall).

## Mechanisms of Tropical Atlantic Variability



**Figure 4.2** — Mechanisms of Tropical Atlantic Variability (courtesy of P. Chang).

is, therefore, plausible that the NAO and TAV are interrelated. Exploring interrelationships between the NAO and TAV will be one of the major focus of ACVE.

Additionally, TAV is subject to remote influence of the ENSO related variability in the tropical Pacific (Figure 4.2). The remote influence may take place either through an anomalous walker circulation due to an eastward shift of the atmospheric convection, or through North Hemispheric atmosphere teleconnections (i.e., PNA). How these two processes are related is currently not clear.

## 4.2 — Modes of Variability

### THE UNCOUPLED SYSTEM

#### The Atmosphere

It is well known that atmospheric GCMs, with prescribed SST, display NAO-like fluctuations. Although no single theoretical explanation for the NAO is widely accepted, it seems that its fundamental dynamics arise from atmospheric processes. There is probably no single cause; rather the NAO appears to be a preferred mode of the atmosphere that can be excited in a number of different ways, its position and spatial structure

linked to the basic characteristics of the large-scale atmospheric circulation. However, it is important to determine whether atmospheric processes alone can lead to long-term, decadal climate variability in the Atlantic Basin with observed amplitudes, phases and scales. Distinguishing between coupled and uncoupled modes of variability is observationally difficult. Research specifically designed to explore the dynamics of NAO-type variability is required. These investigations should address the following questions regarding various aspects of planetary wave dynamics governing tropospheric quasi-stationary anomalies over the Atlantic:

- What is the relative importance of topographic and thermal forcing of the extra-tropical planetary wave field over the Atlantic?
- Does the Atlantic-sector atmosphere display sensitivity to atmospheric deep convective activity within the basin, particularly in the tropics?
- What is the role of land surface processes and topography on both sides of the basin in exciting and regulating NAO variability and its variants?
- What is the relevance of instability mechanisms (barotropic/baroclinic) and synoptic-scale excitation and feedback on Atlantic extra-tropical low-frequency atmospheric variability?
- How do the properties of horizontal and vertical propagation (stratospheric connections), as well as non-linear atmospheric interactions, affect NAO and other teleconnections?

Could they lead to multi-year variability as an internal atmospheric phenomenon?

The response of the atmosphere to sea-surface temperature anomalies has been the subject of many observational and modeling studies going back to the very first atmospheric GCMs. A broad consensus between observations, theory, and models exists with regard to the response of the atmosphere to tropical SST anomalies, in particular over the Pacific Basin. However, there is no clear theoretical understanding of, or consensus about, the response of the atmosphere to SST anomalies in mid-latitudes. Indeed, GCM mod-

eling experiments yield perplexing results which seem to depend on model properties, model integration methodology, and the geographical and seasonal distribution of the SST anomalies. Resolving this issue is crucial to the understanding of decadal variability in the North Atlantic (and elsewhere) and to making progress in our studies of the coupled interaction. The atmospheric response to the evolving pattern of low-latitude SST in different basins of the oceans remains an important research topic, in particular the atmospheric linkages between the tropical Atlantic and other ocean basins. Key subjects include the atmospheric response to dipole-like SST perturbations. Atmospheric studies should also be designed to understand the remote influences of the Pacific ENSO on the tropical Atlantic variability.

Questions that need to be answered regarding midlatitude ocean-atmosphere coupling are:

- What is the sensitivity of the atmosphere to the location and amplitude of SST anomalies and subsurface thermal anomalies?
- What are the spatial patterns of the atmosphere's response to mid-latitude SST anomalies. What are the atmospheric dynamical mechanisms responsible for setting it up these patterns? Is the atmospheric response linear, or do the patterns depend on the polarity of the SST anomaly?
- How does the response of the atmosphere evolve in time? Does the response depend on the season, and on the time scale of the oceanic thermal anomalies?
- Is the observed near-surface circulation pattern over the tropical Atlantic Ocean reproducible by forcing an AGCM with a dipole-like SST perturbation? If so, what are the underlying dynamics determining the circulation pattern? How does the modified circulation pattern affect the surface heat flux?
- How important are continental heat sources to the tropical Atlantic circulation?
- What are the atmospheric connections between tropical and extra-tropical climate variability in the Atlantic? What influence do tropical Atlantic SST anomalies have on extra-tropical atmospheric variability?

- Through what physical mechanisms does the Pacific Ocean exert influence on the tropical Atlantic?
- Why does the ENSO influence appear to be stronger in the northern tropical Atlantic than in the southern tropical Atlantic?

### The Ocean

It has been shown through theory and models that because of its large thermal heat capacity, the ocean can respond locally to high-frequency stochastic atmospheric forcing on seasonal and inter-annual time-scales (Hasselmann, 1976; Frankignoul, 1985). Decadal variability in the ocean surely involves non-local processes as well, such as the vertical and horizontal exchange of water masses. It is thus important to explore the following issues:

- What are the preferred patterns of oceanic variability and their characteristic time scales? What dynamical mechanisms govern them?
- How do anomalies propagate through the ocean? What is the oceanic teleconnectivity?
- What changes in horizontal gyre transports and meridional overturning intensity result from random and sustained surface forcing, possibly orchestrated by slowly propagating internal Rossby waves or advection of stratification anomalies?
- Is the Atlantic much affected by conditions imposed at its northern and southern boundaries with the Arctic, and Southern Oceans respectively.
- What are the relationships between sub-surface ocean thermal anomalies and SST?

In most modeling studies of ocean variability, a simplified surface interaction is assumed where the heat and moisture exchange at the surface is either prescribed or derived from an atmosphere that adjusts to the changes in SST in prescribed ways. Such studies of the forced response must be complemented by investigations of internal (free) modes of ocean variability. This avenue is particularly relevant to the hypothesis that decadal variability originates in the ocean. Studies of both forced and free variability must be carried out with models of varying complex-

ity. It is important to resolve the spatial and temporal characteristics of such variability, their parameter sensitivity, and model dependence. Comparisons with observations are crucial in determining the degree of realism in the model simulations. As indicated above, processes that lead to SST variability should be a primary focus, but the model-observation comparisons should encompass other measures of the dynamical system to ensure a complete description of the variability.

Studies are required that enhance understanding of oceanic processes that influence SST in the tropics, including the role of gyre exchange processes. Specific questions that must be answered include:

- What is the role of ocean dynamics in on- and off-equatorial SST variability?
- What is the relative importance of horizontal heat transport and vertical mixing/subduction processes?
- How significant are cross-equatorial and tropical-subtropical gyre exchanges? What is the relative importance of western boundary current transports and interior Ekman transports?
- Do oceanic waves play an important role in creating or modulating SST fluctuations in the tropical and mid-latitude Atlantic Ocean?

### THE COUPLED SYSTEM

In studying the combined ocean-atmosphere system we need to identify what modes of variability owe their existence to active coupling between the two systems and could not otherwise be manifested. This is clearly a question that can only be addressed through a combination of modeling and observational studies: modeling/theory to offer and test plausible physical mechanisms, observations to examine evidence for their authenticity. In the tropical Atlantic system, coupled model experiments must also be performed to distinguish the relative importance of external forcing and local air-sea processes to variability there. External forcing must include the deterministic forcing associated with climate anomalies (e.g.,

ENSO) teleconnected into the Atlantic basin, and the stochastic forcing associated with dynamical instabilities internal to either the atmosphere or ocean. The following questions must be addressed:

- What are the coupled mechanisms that can lead to variability that exhibits characteristics of the observed variability in the North Atlantic?
- Is the coupling inherently regional or is it remote and/or basin-scale? If the coupling is regional, how does it depend on local properties?
- What is the role of remote atmospheric and ocean behavior in shaping the spatial and temporal characteristics of the variability?
- What is the “minimum physics” needed to capture realistic coupled behavior? To what degree is this physics adequate to describe and predict such phenomena?
- How do these simple mechanisms manifest themselves in more complex and more realistic models? Can particular coupled mechanisms be identified in these models? How do they interact or compete with one another?
- What new observation and analysis methods are required to test coupled variability found in simple or complex models?
- Is the dipole-like SST variability better described as a self-sustained oscillator due to unstable air-sea interactions, or as a stable dynamical system driven by stochastic processes?
- What is the relationship between the Atlantic dipole, NAO and equatorial modes?
- How do these patterns of climate variability interact with the seasonal cycle?

### 4.3 — Regional aspects

#### (a) Subpolar gyre and Northern Marginal Seas

Important interactions occur between cold-fresh and warm-salty water masses in the Labrador and the Greenland-Iceland-Norwegian Seas, where winter-season convection forms intermediate and deep water. Large, quasi-decadal and multi-decadal SST anomalies, coherent with SLP anomalies, are observed in these regions. Strong

evidence exists that SST and surface salinity (SSS) anomalies propagate cyclonically around the gyre and may be important in modulating the intensity of convection and the sea-saw between convective activity in the Labrador and GIN Seas. The following questions need to be addressed:

- What are the feedbacks and coupling mechanisms that maintain these anomalies?
- How is the formation of persistent sub-polar SLP-SST anomalies linked to local and remote (e.g., Arctic, subtropics) anomalies in surface properties (such as ice, heat fluxes and precipitation) and subsurface properties (such as mixed layer depth and intermediate/ deep water formation rates)?
- Do significant upwelling branches of the MOC exist which are local to, rather than remote from, the sinking branch, and how do they effect SST and SSS?
- What is the role of the annual cycle in quasi-decadal variability?
- What is the role of sea ice?
- How do the exchanges between the Arctic Ocean and the North Atlantic affect North Atlantic climate variability?

#### (b) Subtropical/Subpolar Gyre interactions

Prominent SST anomalies tend to form along the North Atlantic Current at the boundary between the subtropical and subpolar gyres. They are of particular interest because they have been linked to changes in climate over Western Europe. As reviewed above, it has been suggested that quasi-decadal anomalies in this region are the result of an inherently coupled phenomenon. Coupled model studies indicate that this region is a sensitive indicator of, and may be a driver of, multi-decadal variability of the thermohaline circulation. Moreover, coupled models also suggest that on decadal time scales, upper-ocean gyre dynamics play an important role. In this scenario, the life cycle of SST anomalies is determined by the interplay between the local response of the ocean to variations in surface heat flux and the advection of heat by the gyre circulation. The latter counteracts the former, but lagged in time. The atmosphere, reacting to the change in SST, is the

bridge connecting the local and non-local response of the ocean. In studying this mechanism, the following questions should be addressed:

- What are the essential dynamics of the ocean and atmosphere required to capture the interaction? Are the mechanisms that have been proposed robust? Can they be reproduced in models of various types?
- What is the role of the seasonal cycle in the interaction?
- How is the interaction affected by variability in the other parts of the Atlantic, and how does it affect variability elsewhere?

#### (c) Subtropical Gyre

In the northeastern part of the subtropical gyres much of the upper ocean thermocline ventilation takes place. Variability of the sea-surface properties in those subduction zones can subduct beneath the surface layer. Now shielded from the direct air-sea interaction they can propagate largely undisturbed within the gyre circulation throughout the subtropics/tropics unless exposed to surface entrainment zones in upwelling and the western boundary current regions. Specific issues are:

- Can subducted water mass anomalies survive many years subsurface to finally reemerge and modify sea surface conditions?
- How important are changes in the circulation relative to changes in the surface fluxes in the generation of to subducted temperature anomalies?

#### (d) Tropical/Subtropical Gyre Interaction

Decadal TAV may be driven remotely from the subtropics through variation of the shallow meridional Subtropical Cells (STCs) that carry subtropical thermocline water into the tropics. One hypothesized process involves zonal-wind anomalies about the tropical-subtropical boundary latitudes: the winds that set the strength of the STCs. STC modulation eventually alters the amount of cold water that flows into the eastern equatorial Atlantic. This in turn may modify the extent/intensity of the equatorial cold tongue, the air-sea heat flux and ultimately, the tropical at-

mospheric circulation. This process was likewise identified as a central element for the Pacific Basin Extended Climate Study.

Two possible corollaries of are worth noting. First, because there is a net poleward transport of upper-ocean water associated with the Atlantic's thermohaline circulation, nearly all of the thermocline water that feeds the equatorial undercurrent comes most directly from the southern hemisphere, a conclusion that is supported both by observations and models. Thus, it is more likely that variability of the southern STC leads to surface anomalies in the equatorial cold tongue. Second, because this process leads to a change in the equatorial upwelling, it initially causes an SST anomaly pattern that is essentially symmetric about the equator. It is not clear whether subsequent ocean-atmosphere interactions can generate asymmetric, dipole-like anomaly patterns and cause a shift in the position of the ITCZ. The most important questions are:

- Can subtropical thermocline water mass anomalies indeed transit to the tropics and influence surface conditions in the equatorial upwelling zones?
- Do feedback mechanisms exist between the equatorial surface ocean, atmosphere and the STCs to sustain decadal time scale oscillations?

#### (e) Tropical Ocean

Ocean-atmosphere interactions are generally expected to be important in the tropics because 1) the atmosphere is sensitive to changes in the SSTs and 2) the adjustment time scales of the tropical oceans are relatively short. The high correlation between the tropical Atlantic SSTs and rainfall variability in the neighboring continents reflects the atmosphere-ocean coupling in the region. Modeling studies further suggest that local air-sea interactions in the tropical Atlantic can lead to a decadal TAV and an ENSO-like interannual mode. For the decadal TAV mode, the dominant air-sea feedback appears to be between interhemispheric SST gradient and wind-induced latent heat flux in the tropical North and South Atlantic, al-

though two other related feedback mechanisms may also contribute to air-sea interactions in the tropical Atlantic:

- i) weakening of the trades in the warm SST region, which decreases entrainment into the surface mixed layer thereby causing even warmer SST; and
- ii) weakening of the trades along the North African coast, which reduces coastal upwelling thereby warming SST in the north-eastern tropical Atlantic.

For the ENSO-like mode a dynamic interaction between the equatorial trades and SST (the Bjerknes mechanism) is believed to be operating to a certain extent. Although the preliminary coupled model studies point to the potential importance of regional air-sea feedbacks in tropical Atlantic, many fundamental issues remain unsolved. For example, pertinent questions are:

- To what extent do local air-sea feedbacks contribute to the decadal hemispheric SST gradient variability and ENSO-like interannual variability in the tropical Atlantic?
- How much tropical Atlantic SST variability is attributable to “remote” influences of ENSO in the Pacific and NAO in the North Atlantic?
- What are the oceanic and atmospheric processes responsible for the coupling in the tropical Atlantic? In particular, what is the relationship between the off-equatorial SST anomaly and surface heat flux anomalies?

## 5. A Proposed Research Program

The structure of this chapter is as follows:

- 5.1 Elements of the basin scale ACVE
- 5.2 Analysis of Historical and Proxy Data
- 5.3 Sustained Observations on the Basin Scale
- 5.4 Observing the meridional overturning circulation
- 5.5 Modeling, Theory and Ocean State Estimation
- 5.6 Regional aspects of ACVE: Process Studies

The philosophy of the Atlantic Climate Variability Experiment is to take a basin-wide perspective in the study of coupled ocean-atmospheric variability in the Atlantic-sector on interannual to decadal time scales. Our proposed research program has been jointly developed between U.S. and European scientists. Its primary goal is to understand the mechanisms responsible for Atlantic Climate Variability and quantitatively test, and thereby improve, atmosphere-ocean models that describe them. We must determine whether variability simulated in models is fundamentally coupled, whether one component drives variability in the other, whether modeled variability bears any relation to observed variability, and whether modes of variability once identified are predictable. The improvement of atmospheric and oceanic circulation models, especially boundary layer formulations, is a central part of ACVE.

Our specific objectives are to:

- Describe and model coupled atmosphere-ocean interactions in the Atlantic Sector and quantify their influences on the regional and global climate system, and investigate their predictability.
- Understand and model the response of the atmosphere to air-sea exchanges in the Atlantic (in particular the anomalous exchanges associated with observed tropical and mid-latitude SST anomalies) as a function of horizontal pattern, scale, amplitude and frequency.
- Provide an improved description and understanding of the ocean’s response and potential feedback onto mid-latitude, NAO-like atmospheric forcing as a function of amplitude and frequency, and the associated time-varying fluxes of heat, fresh water, carbon dioxide and other gases, momentum and energy.
- Assemble a data set that may be used to test and improve models of coupled Atlantic climate variability.
- Investigate the sensitivity of the meridional overturning circulation to changes in surface forcing and assess the likelihood of abrupt climate change.

Some of the processes involved in climatic modulation of the North Atlantic will require a broad-scale study of the entire gyres or basins in the context of the global atmosphere; other topics can be examined in focused process experiments. Some investigations must extend over a decade, but clever treatment of existing historical observations can also provide an important long-time-scale perspective.

### **5.1 — Elements of the basin scale ACVE**

Key basin-scale elements of ACVE will be:

- analysis of historical and proxy data,
- basin scale observational networks,
- modeling, theory and state estimation (data assimilation),
- process studies embedded in the observational networks.

### **5.2 — Analysis of Historical and Proxy Data**

Continued analysis of historical instrumental and proxy data records is an essential component. Only through such study can the spatial and temporal properties of recurring interannual to decadal climate variability be characterized. In hand with modeling approaches, data analysis will be essential to evaluate emerging hypotheses concerning the mechanisms of Atlantic climate variability. Data analysis must also play a key role in optimizing the design and assessing the expected errors of future observing networks.

Proxy records of Atlantic climate variability are provided by tree ring and ice core stable isotope chronologies and marine and lake sediment records. The use of such records should continue to be actively pursued. Such data provide the only window on climate fluctuations before the instrumental period. They furthermore are particularly attractive for studying continental climate and its relation to oceanic conditions. Interpretation of proxy climate records is an area where models, suitably equipped with tracer or other specialized capabilities, will be of substantial utility. For example, atmospheric models with isotopic water-vapor/tracer capabilities can be used to synthetically generate ice core records, potentially leading to a better understanding of the relationship

between the observed ice-core records and climate variability.

Addressing the key scientific issues discussed in Section 4 requires an interdisciplinary research effort. Unfortunately such efforts are too often limited or hindered by the availability of, or easy access to, historical data. Investigators are frequently unaware of existing data sets, handicapped by data access difficulties, or unaware of documented problems with certain observations. New, updated or improved data sets are also difficult to identify and locate. We suggest that a major step forward would be to establish an Atlantic Climate Variability Data Center to improve data accessibility and documentation, and foster “data archeology”.

The primary purpose of the data center will be to catalog and provide easy access to basic observed historical data sets for interdisciplinary studies of Atlantic climate variability. The data center could be as simple as a world wide web page, pointing toward existing, publically available data, but maintained by a person or group of people with a basic understanding of the goals of the ACVE. To enhance productivity, the data center should utilize the knowledge of “expert users”, soliciting advice on the advantages and disadvantages of individual data sets from the researchers who process and/or use them. Such information could be included as meta data, organized by data set name and linked to the data sets themselves.

#### **Recommendations:**

- Creation of an Atlantic Climate Variability Data Center to improve data accessibility and documentation, and foster “data archeology”
- Close collaboration with activities of the paleoclimate community organized under PAGES

### **5.3 — Sustained Observations on the Basin Scale**

Two categories of measurements are needed to form the observational basis of ACVE: (i) sustained, Atlantic-wide observing systems in the atmosphere and ocean and (ii) shorter-term pilot network studies and process experiments. The

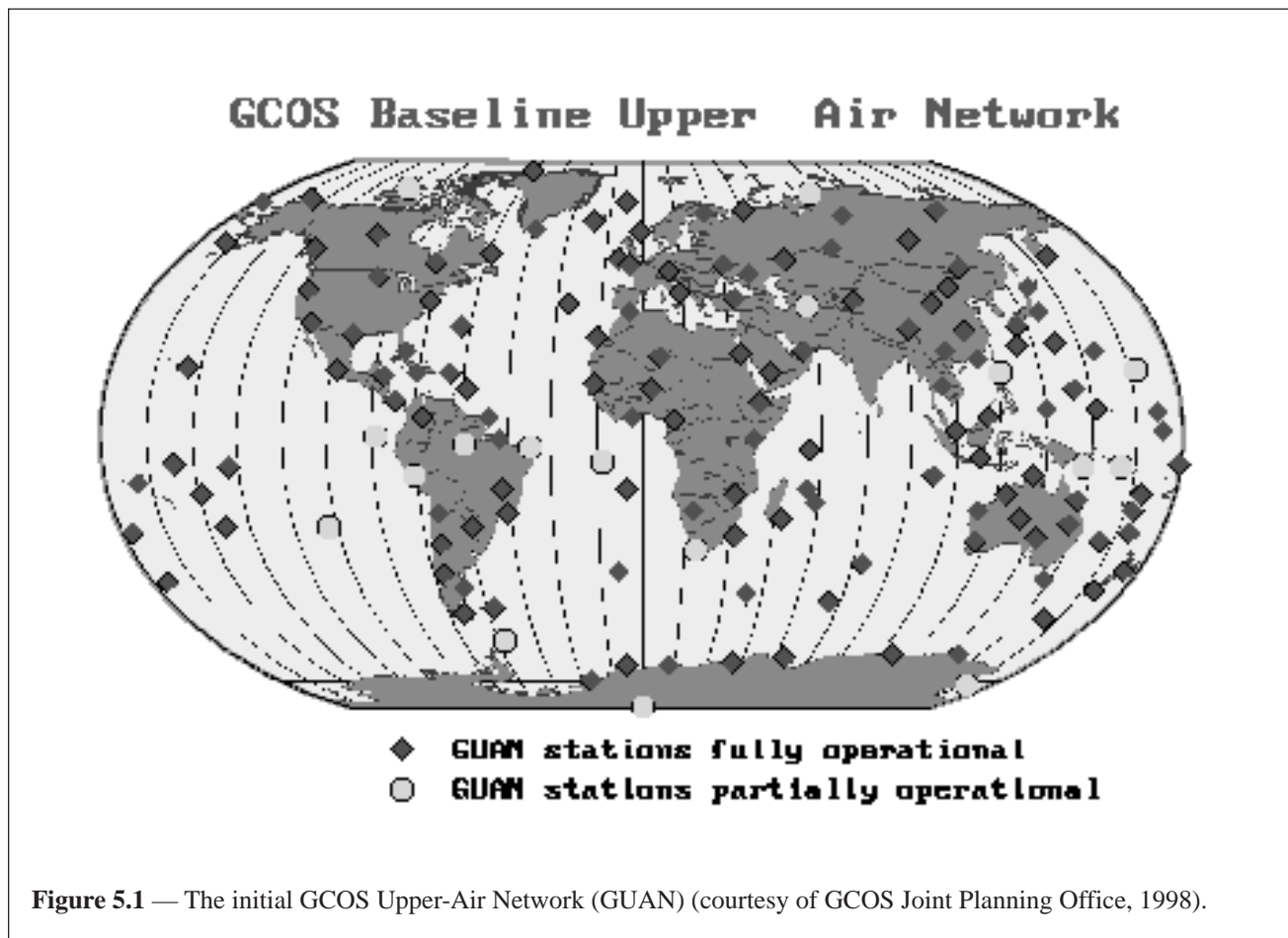
design of the pilot and sustained observing systems must be guided by examinations of the historical record, in combination with numerical model studies.

The goal of the sustained observing systems is to provide comprehensive descriptions of the oceanic and atmospheric circulations believed to be associated with Atlantic Climate Variability. This includes in particular the upper-ocean mixed layer, the atmospheric boundary layer, and the coupling between them. In the off-equatorial regions where SST exhibits prominent decadal variation, it is important to measure the time-varying air-sea heat flux, and establish the atmospheric and oceanic processes that determine it. It is also important to measure subsurface thermal structures, since ocean circulation and SST anomalies are typically associated with large changes in thermocline depth. In the following we outline explicitly which measurements will be the central elements for testing hypotheses of coupled climate variability in the Atlantic sector.

#### A. Atmospheric Observing Networks

Our general knowledge of seasonal-to-decadal atmospheric variability in the Atlantic region will be based primarily on analyses from the operational weather-prediction centers and on re-analyses of historical data. The backbone of such work is the World Weather Watch (WWW/GCOS) upper-air sounding network on the periphery of the Atlantic and those few island stations. Surface and upper-air observations from ships and commercial airliners provide additional data over the open ocean, largely concentrated along shipping lanes and air corridors.

Although since the 1970s satellite observations provide a significant constraint on the analyses, the Atlantic sector remains a data-void area. This is demonstrated in Figure 5.1 which shows the WMO's global upper-air network that is being proposed under the Global Climate Observing Systems (GCOS). Figure 5.2 shows the initial GCOS Surface Network (GSN). Regrettably, the WWW upper-air network has deteriorated



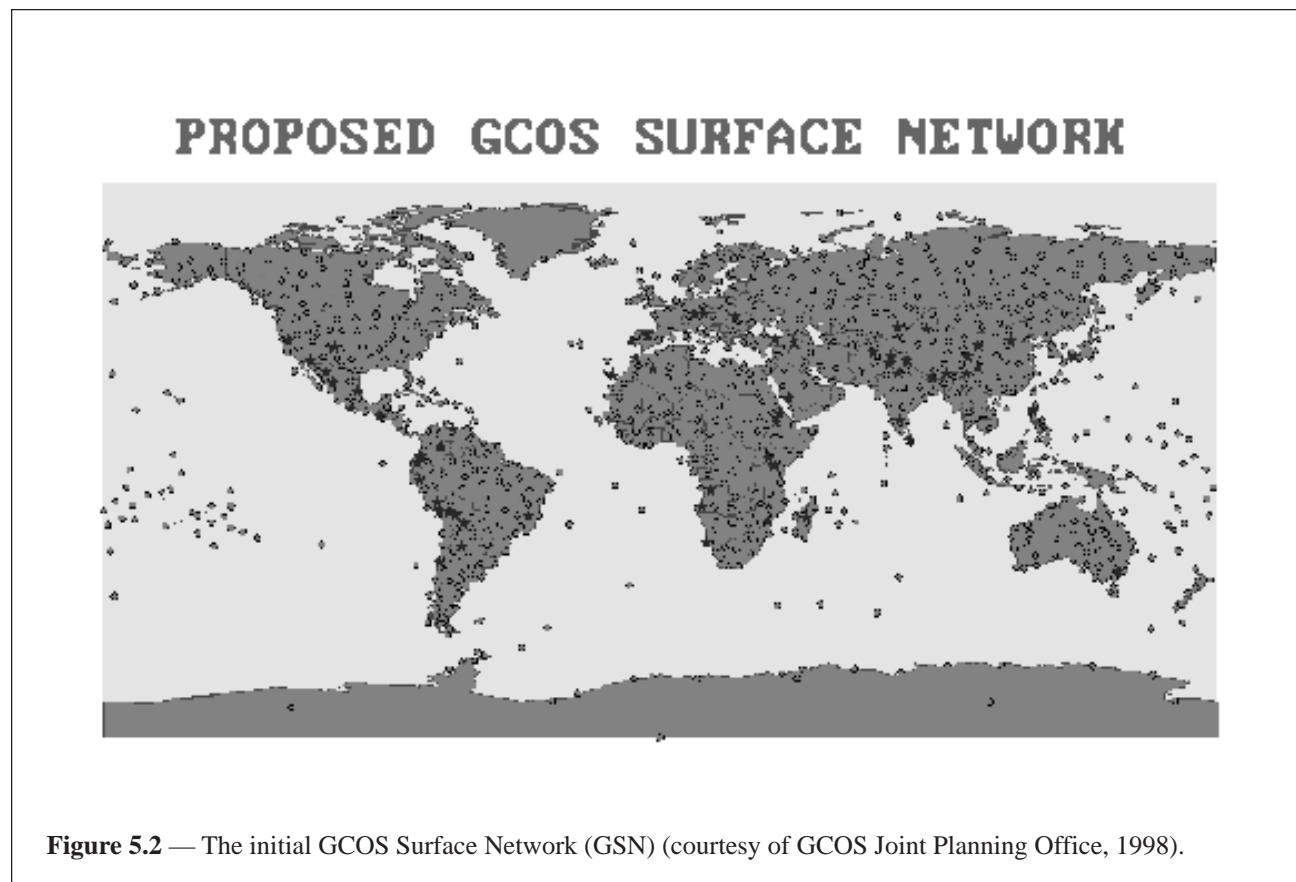
since the 1960s in terms of the number of stations and the frequency of observations. The Atlantic basin data-void areas will seriously impact ACVE process studies in which detailed knowledge of the atmosphere's vertical structure is required. The lack of in situ soundings over data-sparse regions also hinders efforts at the operational weather analysis and climate reanalysis centers to identify and remove regional biases in their data assimilation and analysis systems.

Attempts to calibrate satellite instruments in the field and to develop improved remote sensing retrieval algorithms benefit fundamentally from new high-quality in situ soundings. Satellite retrievals of the vertical temperature and humidity structure are unable to resolve the details of boundary layer structure, and the weighting functions of the radiative flux channels measured by the instruments place fundamental limits on the maximum resolution that can be expected. Wind information from space is obtained at only a few levels in the vertical.

Efforts to increase atmospheric upper-air sampling in remote marine environments at a reason-

able cost are underway. Atmospheric profilers and containerized radiosonde launchers are mature field instruments that can be operated from research and commercial ships of opportunity. More systematic measurements may become possible with autonomous aircraft and robotic balloon platforms, which under development and will probably become operational during ACVE.

It is important to realize that there is increasing evidence that atmospheric radiative transfer equations transmit too much energy through clouds. In the TOGA COARE region for example, models show as much as a  $30 \text{ W/m}^2$  bias in cloudy conditions compared to observations. Globally, the average bias in insolation may be about 10 percent, which, if not corrected, has serious consequences for ocean climate models. Technical developments are underway to acquire direct flux measurements autonomously from volunteer observing ships (VOS). In combination with the profiling instruments, these measurements will provide important new information crucial for enhancing our obviously limited understanding about the atmospheric radiation transfer and as-



sociated differential heating.

In addition to VOS, well-instrumented surface moorings are recommended at select sites. These will return accurate reference data to verify and/or calibrate surface meteorological fields from models, remote sensing platforms and other in-situ measurements. Work is in progress to upgrade the quality of the surface meteorology and air-sea fluxes on a global basis from the VOS fleet is dependent on such fixed reference sites. The reference sites will serve as primary standards for VOS data quality control and help define regional choices of air-sea flux formulae. The present drifting buoys provide a good example of how in situ observations are used to calibrate satellite data; in their case they provide the means to calibrate the AVHRR fields of SST. The reference site surface moorings will additionally provide surface wind, humidity, surface short wave and long wave radiation, and rainfall estimates. Possible sites include the mid-subpolar gyre near historical Ocean Weather Station “Juliet” or “Lima” and the area east of the Grand Banks, the New England Bight region that experiences polar air outbreaks, the center of the Azores-Bermuda high and the North Atlantic trade wind region to its south, the Gulf of Lyons in the Mediterranean Sea, and the area southwest of Cape Town in the eastern South Atlantic.

### **Recommendations**

The primary source of atmospheric observations for ACVE will be the GCOS, which is built on the observing system that supports operational numerical weather prediction. This implementation plan requires:

- maintenance of the critically important ground and space-based components of GCOS,
- the existing observational network to be optimized and modernized, in particular enhancing the technologies to recover atmospheric profile and boundary layer data in remote ocean regions,
- continuing improvements in the performance of 4-dimensional variational data assimilation schemes that operate in near-real-time,

- availability of upgraded reanalysis products from ECMWF and NCEP, and
- the free and open exchange of observational data sets.

None of the above can necessarily be taken for granted but require significant attention to assure their continuation. In addition, special atmospheric observations (localized in space and time) are required to address specific issues related to improvements of the parameterizations of essential boundary layer processes in coupled atmosphere - ocean - land models or for intercomparison of measurements made with different kinds of instrumentation.

### **B. Ocean Observing Networks**

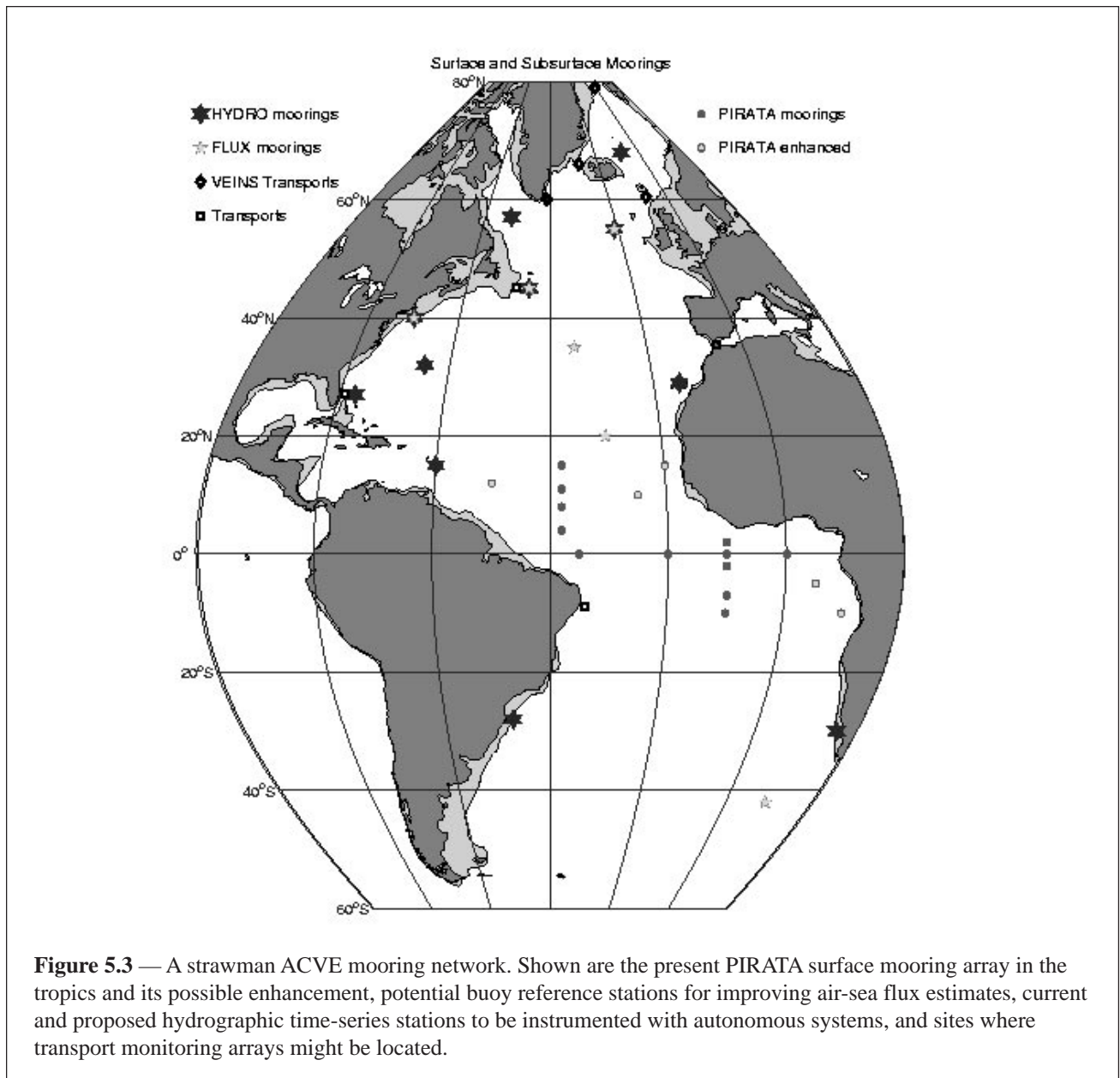
Permanent upper-ocean networks are needed to document low-latitude anomalies and the generation and subsequent evolution of higher-latitude features such as propagating SST and SSS anomalies. Some of the required information can be obtained by high-quality remote sensing data sets:

- Sea surface temperature — SST is one of the fundamental climate parameter which can be observed from space. ACVE will strongly benefit from the operational SST network.
- Sea surface elevation — Altimetry has shown to provide crucial information about changes in the geostrophic currents and heat content as a function of space and time. Continuous altimeter coverage is mandatory in the context of ACVE, since SSH data uniquely provide global information about variability in the ocean flow-field near the surface, but strongly reflecting interior dynamics. They are crucial to interpolate in time and space many of the interior measurements which are necessarily sparse.
- Surface winds — Scatterometer data are not routinely available. However, when they were available they have greatly improved the surface wind stress fields and their variability.
- Sea ice — Sea ice concentration is one of the few global measurements that we have which directly relates to upper ocean fresh water. SSMI data also allow to estimate sea ice drift

velocities.

In situ networks capable to capture climate features and their development in time will consist of the following elements, some of which are operational at the time of writing or can be anticipated to be so in the near future:

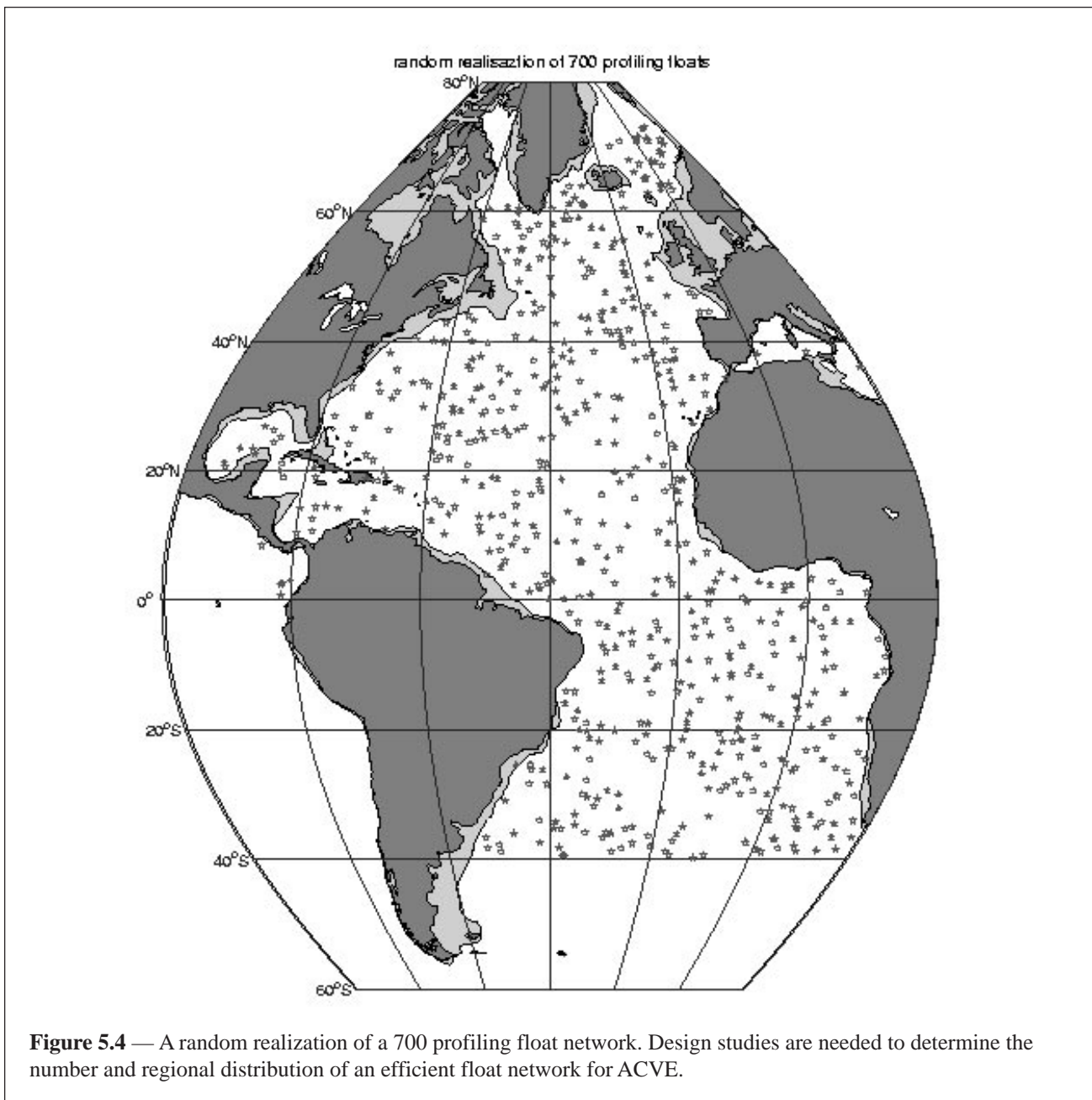
- Tropical moored array — Continuation of the present PIRATA moored array in the tropical Atlantic with an additional five stations is required to better cover anomaly patterns in the southeastern and northeastern upwelling regimes as well as the northern tropics. Western boundary observations are also needed to measure the equatorward flow of thermocline water. At present, PIRATA is only structured as a pilot project and operated jointly between Brazil, France and the United States with funding ending after 2000. It is essential to augment the PIRATA array with five extra buoys (Figure 5.3) to measure surface fluxes and the upper-ocean thermal structure. A key area for improved flux estimates is under the ITCZ where winds are weak.
- PALACE float network — A proposal has been made to deploy a global network of PALACE floats, and we embrace this concept for the Atlantic. A deployment of many hundreds floats, covering both the north and south



Atlantic, enables the evolution of T, S field to be mapped autonomously (Figure 5.4). In the tropics, the array will observe the variability associated with the southern and northern elements of the tropical ‘dipole,’ as well as the interior structure of the subsurface, equatorward-flowing branch of both the northern and southern STCs. Floats should also populate the northward-flowing branch of the MOC and the paths of the propagating mid-latitude SST anomalies. Salinity observations are particularly important in the sub-polar North Atlantic, so the floats should have

salinity sensors whenever possible. The problem of floats vacating some areas and clustering in others could be overcome in the future by new types of glider floats that can actively navigate to maintain position or carry out local surveys.

- VOS-XBT lines
  - 1) Ocean measurements — To complement the float array, particularly in regions characterized by strong currents and small spatial scales, continuation of the volunteer observing ship XBT program at the WOCE intensity is recommended (Figure

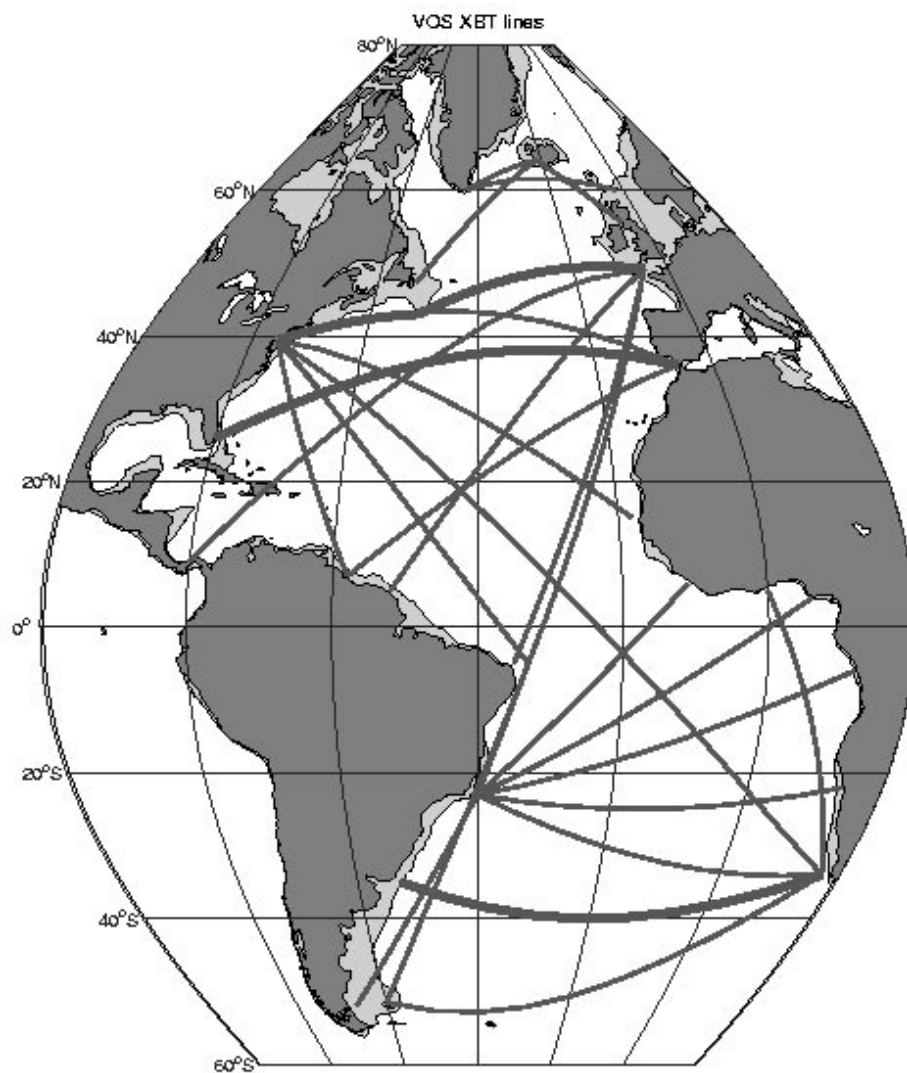


**Figure 5.4** — A random realization of a 700 profiling float network. Design studies are needed to determine the number and regional distribution of an efficient float network for ACVE.

5.5). Design studies are needed to establish where such high-density sampling is required. In the tropics, the TOGA lines should be maintained as a complement to the PIRATA and PALACE arrays until any redundancy is established. A proposed new line along 60°N (see below) should contribute valuable information on sub-polar exchanges with the Nordic Seas. Some technical issues must also be addressed. In the sub-polar North Atlantic, the depth-range of T7 XBT probes is not always sufficient to reach the mixed-layer

base. Salinity observations are particularly important in the sub-polar North Atlantic, and as reference data for floats and remote sensing instruments globally; the use of thermosalinographs on volunteer ships should have high priority.

- 2) VOS meteorological measurements — The North Atlantic is particularly well sampled by VOS meteorological observations. However, an improved accuracy of the data is required. For example the present VOS data may underestimate the heat fluxes during winter time cold air



**Figure 5.5** — The present XBT/VOS network developed under WOCE, TOGA and ACCP/ACCE. High-density lines are marked with bold lines, low-density with thin. Design studies are recommended for determining the optimal mix of high- and low-density XBT lines within ACVE in light of the proposed profiling float array, remote sensing tools, and the envisaged network of Eulerian stations.

outbreaks over the western North Atlantic. Improved instrumentation (which is being developed both in the U.S. and Europe) should be implemented on a subset of the Atlantic VOS.

- Time series stations — Continuous records at a relatively small set of stations have proven to be very effective in documenting annual-to-inter-decadal variability in the ocean. It is vitally important to continue these important stations. While originally conducted using research vessels, time series stations in future will be autonomous utilizing moored or free-floating profiling vehicles.
  - It is essential to continue stations “Bravo” and Panulirus/Bermuda in the centers of the subpolar and subtropical cells, respectively, which already demonstrated substantial value in providing information on decadal heat storage and circulation anomalies.
  - Station “Mike” in the Norwegian Sea has given insight into decadal warming of the Norwegian Sea Deep Water and propagation of the Great Salinity anomaly. This station, which monitors the properties of the northward flowing Atlantic waters that ultimately feed the deep water formation sites, must be continued.
  - The ESTOC station was begun in 1994 north of the Canary Islands in the eastern subtropical Atlantic. Together with Bermuda, hydrographic data from this station yields a baroclinic circulation index across the subtropical gyre. Its continuation is encouraged.
  - Companion station(s) on the western margin of the basin would return baroclinic circulation indices for both the Gulf Stream and the net MOC, and would monitor the meridional spreading of water mass anomalies originating in the high-latitudes.
  - Similarly, two bounding stations at the latitude of the tropical- subtropical exchanges (i.e., near 10-15°N) could provide integral measurements of the meridional baroclinic transport variability there.
- Flux monitoring systems — At key sites, direct measurement of ocean currents is envisaged. For example, long term Eulerian measurements of the dense overflows of Nordic Sea waters through the Denmark Straits and Faeroe Bank Channel will help quantify the changing climate system of the northern Atlantic. Similarly, measurements in the Strait of Gibraltar would provide integral measures of air-sea exchange with the Mediterranean and the supply of saline intermediate water to the Atlantic. Monitoring of the Florida Current heat and volume transport would facilitate study of the meridional overturning circulation’s warm limb at subtropical latitude; a companion array spanning the deep western boundary current could track the cold limb of the circulation. Developments now underway for long-term (5-year), low-cost current meter moorings with data telemetry will make such programs economically feasible.
- Drifters Surface — Drifters have proven to be a valuable resource for SST ground truth to satellite-based observing systems as noted above. Drifter data have additionally yielded information on upper-ocean circulation patterns and Ekman transports. Sensor suites on drifters may be enhanced to measure winds, atmospheric pressure and near-surface salinity. On interannual time scales, the horizontal transport of heat in the upper ocean be-

comes an important process. At the present time, there are no systematic, basin-scale measurements of upper-ocean circulation in the tropical Atlantic (unlike the Pacific and Indian Oceans) leaving this area void of any data set by which to verify modeled ocean circulations. The meridional component of ageostrophic flows (Ekman flow) is significant in the tropical region, showing speeds there that can be twice as large as the geostrophic currents. Moreover, the sparse drifter data which exists (Richardson et al., 1988), indicate a net poleward transport, whereas the surface dynamic topography indicates a net equatorward mass flux. It is therefore recommended that a basin-scale array of drifters be deployed and maintained for at least one cycle of the TAV on a resolution of 2° in latitude and 6° in longitude and within 18° of the equator.

- Tide-gauges— Although the Atlantic does not allow for an extensive tide-gauge network, as does the Pacific, a few stations located in the eastern, equatorial region are useful for monitoring the Atlantic El Niño-like phenomenon. Stations in the Cape Verde and Ascension Islands are near the centers of action of decadal dipole variability, and thus are useful indicators of net steric (storage) processes associated with SST changes. The CPACC stations along the western boundary and in the Antilles Islands are useful for monitoring changes in advection/export from the tropics via western-boundary currents on interannual time scales.
- Acoustic Tomography — The combination of altimetry and long range acoustic tomography has been shown to be an effective means of tracking basin-scale changes in ocean heat content (ATOC Consortium, 1998). Tomography can average over the noisy mesoscale eddy field, and thus greatly enhance the signal to noise ratio of climate signals. ACVE needs to explore how a few acoustic sources can be used to maximize the amount of new information.

## Recommendations:

Design studies will help to determine the most efficient mix of the above mentioned networks for sustained Atlantic climate observations. The networks will build on existing and planned global remotely-sensed data sets, those time-series stations remaining in operation, existing VOS-XBT, drifter and float programs, and the capabilities offered by newly developed floats, moorings and VOS technologies.

### 5.4 — Observing the meridional overturning circulation (MOC)

Coarse-resolution climate models have suggested scenarios for global thermohaline circulation collapse. While these model oceans are often unrealistic, the results deserve scientific attention. It is important to determine how realistic model simulations of large thermohaline circulations variations are at short (decadal) time scales under possible anthropogenic changes. For comparison with model simulations, essential parameters include observations of the meridional overturning circulation rate and the associated heat and fresh water transports. Coverage at a particular latitude might involve elements of sustained observations (see above) in combination with:

- Occasional repeated high-resolution transoceanic hydrographic ship-based sections including tracers and current measurements.
- Moored current-meter measurements at the western boundary and additional stations for monitoring integrated baroclinic transports in the interior.
- Moored bottom devices to interpolate between full-depth stations, such as barotropic flow meters and inverted echosounders.

A feasibility study for monitoring the MOC needs to be carried out, analyzing variability patterns in existing hydrographic sections and the output of high-resolution numerical models. A 48°N section (the division line between the subpolar and subtropical gyres) would be a priority candidate for a MOC monitoring section because (i) anomaly patterns suggest a dipole of North-South heat storage anomaly across this latitude, (ii) a number of WOCE sections have already

been obtained and can serve for pattern analysis, and (iii) intent has been expressed by BSH (Germany) to re-occupy this section at WOCE quality as a contribution to GOOS every three years. Other potential sections for repeat top-to-bottom hydrographic coverage, possibly combined with moored boundary arrays, are shown in Figure 5.6 and should include:

- Near 25°N, close to the heat transport maximum, where considerable prior knowledge on the variability has been built up.
- 10°S, to measure the combined effects of the shallow tropical cell (STC) and the top-to-bottom MOC
- 30°S, to measure the net heat and freshwater exchange of the Atlantic with the global circulation system .
- Two meridional sections to quantify the changes in water mass inventories of the western and eastern Atlantic basins. Sampling along 52°W longitude, which would repeat measurements that extend back as far as the 1950s, is strongly suggested. The optimal track line in the east has yet to be identified.

In conjunction with the MOC section measurements, inventory observations of water mass changes and anthropogenic CO<sub>2</sub> uptake need to be carried out in appropriate time intervals (to be determined from the WOCE/AIMS analysis).

#### **Recommendations:**

Quantitative design studies for an MOC monitoring program including measurement of the associated meridional property transports and storage changes are required. Such studies need to determine the sampling frequencies of the zonal lines required to quantify variability in the Atlantic MOC and associated meridional transports.

### **5.5 — Modeling, Theory and Ocean State Estimation**

Theory and models will play a central role in the design, implementation and synthesis of an ACVE. They will facilitate refinement of working hypothesis, which can then be tested using observations. The complexity of the models will vary from idealized studies of particular physical mechanisms to fully coupled ocean- atmospheric

models. Despite obvious shortcomings, oceanic general circulation models have achieved a sufficient degree of realism that they can now be employed to address process oriented or experiment design questions, and to synthesize diverse observations into ‘best-estimates’ of the quantities of interest.

An active program in data-model synthesis must be a component of ACVE to both help plan it and to interpret the observations. The combination of model and data fields, presuming that both contain elements of the same variability, allows for a better definition of what took place in the Atlantic Ocean than either by itself. If predictability can be established, these analyses will serve as the initial conditions for forecasts of the coupled system. A number of assimilation efforts are underway as part of WOCE AIMS and are anticipated as part of GODAE. Although technology and computer power will certainly improve over the next decade, it is fair to state that the basic “know-how” has been developed and is now available for ACVE. Additionally, the basic infrastructure which is being proposed by GODAE, including active management of data and forcing fields, will be of benefit to the ACVE research activities.

Numerical sampling studies are needed to help determine effective and efficient observational networks. High-resolution forward models can be used to investigate sampling strategies, and the rigorous framework of data assimilation can lead to objective criteria for efficiently assessing sampling alternatives.

In the following, we provide some specific recommendations for modeling studies that are highly relevant to Atlantic Climate variability:

#### *Mechanisms responsible for atmospheric variability in the Atlantic sector.*

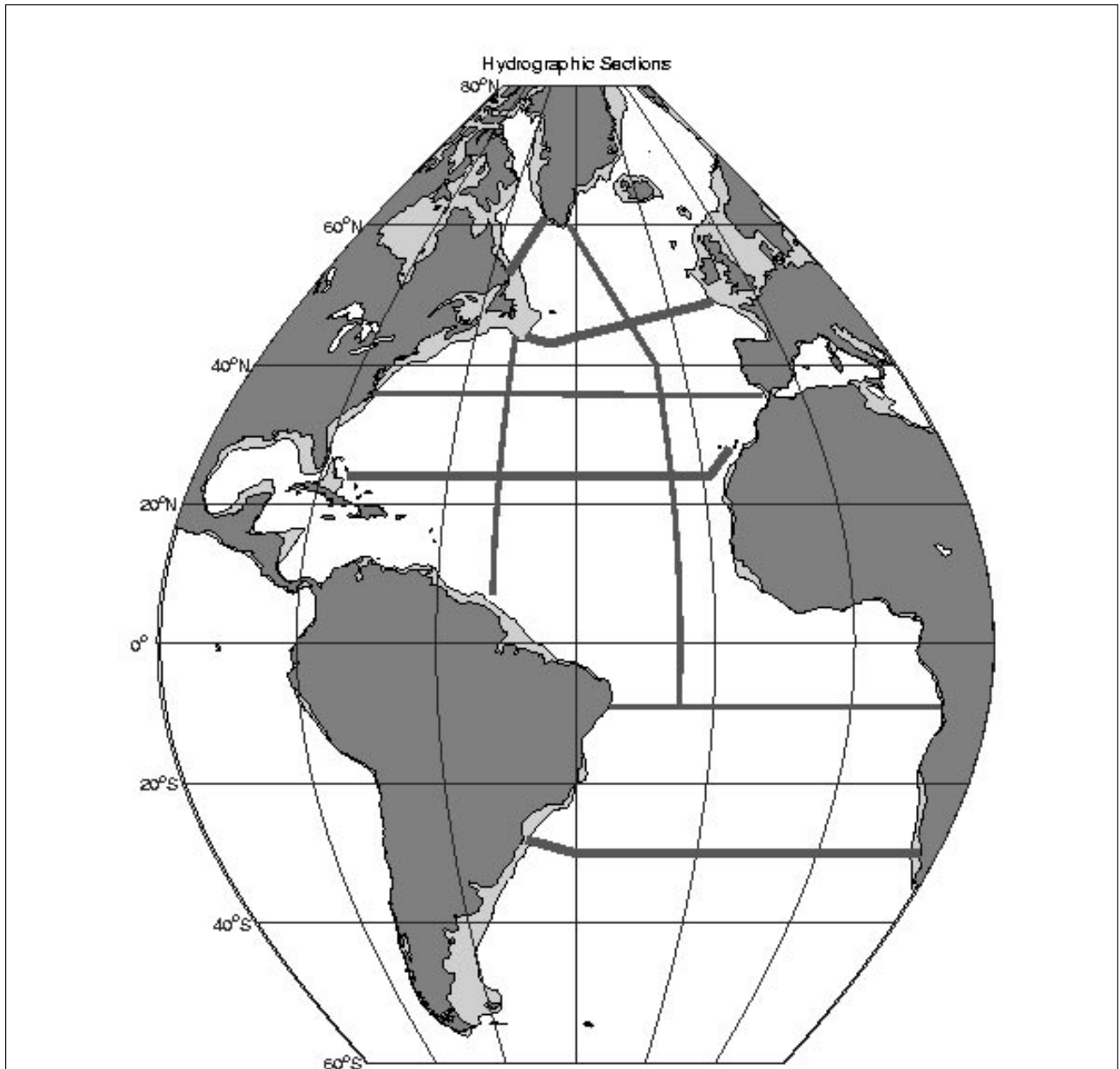
Many atmospheric GCMs still have major problems simulating synoptic and lower frequency variability in the North Atlantic region. Rather than curving northeastward, simulated storm tracks are often quite zonal. The occurrence of Atlantic blocking events is often underestimated. Lower-frequency variability such as that

of the stationary waves is often poorly represented. The difficulty experienced in trying to remedy these model problems reflects poor understanding of the processes involved. The biases in atmospheric GCMs are particularly evident in the Atlantic sector, and could lead to poor representation of interannual and interdecadal variability in such models and of the fluxes used to force ocean components in coupled models. These uncertainties need to be reduced before forecasts

using GCMs seasonal, decadal and anthropogenic-induced variability can be credible.

**Recommendations:**

- Studies using a hierarchy of atmosphere models to investigate the mechanisms responsible for atmospheric variability on time scales from days to decades, and the processes that determine the spatial coherence of this variability
- Studies to investigate the mechanisms



**Figure 5.6** — A schematic drawing of a potential ACVE repeat-section program. Hydrographic and tracer properties would be sampled on these lines on an interannual time scale to quantify net changes in water mass properties and heat content. Thick lines should be repeated more often.

behind atmospheric teleconnections into and out of the Atlantic sector. For example, how can a diabatic heating anomaly in the tropics lead to dynamical changes in the Atlantic sector? Do changes in the Atlantic subtropical jet lead to changes in the Atlantic inter-tropical convergence zone and vice versa ?

#### *Influence of the Atlantic Ocean on the atmosphere*

Long-range forecasting relies heavily on the influence that SST anomalies exert on the atmosphere. Yet the nature of this control, especially outside the tropics, is very poorly understood. Experiments in which extratropical SST anomalies are imposed in GCMs generally indicate weak response by comparison with the internal variability. But these results could be misleading. It appears that the response is unlikely to be through a simple locally enhanced heating, as is often the case in the tropics. Rather, anomalies may impact the development of individual weather systems which tend to grow over the western North Atlantic and decay over the eastern Atlantic/Western Europe. It is unknown to which space and time scales the atmosphere respond most strongly, nor the extent to which the structure of the Gulf Stream is important to the atmosphere. These questions are central to possible interactive modes of the atmosphere-ocean system and to coupled modeling of the North Atlantic in general. An issue of particular importance is whether or not the recent trend in the NAO index arose in response to changes in SST.

#### **Recommendations:**

To address these issues we need:

- Studies that investigate the sensitivity of individual weather systems to SST, initially using high resolution forecasting models and cases for which much additional observational data exist (e.g., FASTEX IOPs). The structure of the boundary layer, the magnitude of the surface fluxes, and the development of the whole system should be compared with observations, and the sensitivity to parameterizations, to the specified SST, and to an oceanic mixed layer need to

be determined. Additionally the sensitivity of atmospheric models to SST anomalies as a function of spatial resolution needs to be investigated.

- Studies that determine the scales and patterns of Atlantic SST to which the atmosphere is most sensitive, and the atmospheric predictability that derives from changing SST. Ensemble integrations of atmospheric models forced with both observed and idealized SST anomalies are needed. Particular attention should be focused on: a) whether the observed multidecadal fluctuation in the NAO index can be reliably reproduced and if so, which regions of SST are important; b) The influence of tropical and subtropical Atlantic SST anomalies on the tropical and extratropical atmosphere. Carefully controlled studies in which several different models are forced with the same SST anomalies would be useful to check the robustness of results and increase ensemble sizes.
- Studies to investigate the usefulness and limitations of atmosphere model experiments with prescribed SST anomalies. Under what circumstances are the results of such experiments misleading? To what extent can the results be related to the variability that arises when the same model is coupled to an ocean mixed layer or to a dynamical ocean model? What role do atmosphere-land surface interactions play?

Further development of data sets, for example reanalysis such as NCEP and ECMWF, to improve characterization of the observed atmosphere and ocean variability.

#### *The mechanisms responsible for variability in the Atlantic Ocean*

Recent work suggests that a large fraction of North Atlantic Ocean variability can be understood as the ocean's response to atmospheric fluctuations. These fluctuations, which are dominated by large scale patterns such as the North Atlantic Oscillation, influence the wind and buoyancy driven ocean circulations as well as the convec-

tion and subduction processes that determine the properties of the ocean thermocline. We are, however, far from understanding the detailed relationships between the surface fluxes of heat, fresh water and momentum and temporal variation of the ocean state.

Of particular importance is an improved understanding of the oceanic pathways through which fluctuations in surface exchange in one region can influence the ocean, and especially SST, in another region at a later time. For example, fluctuations in wind stress curl and flux anomalies over the subtropical gyre may promote the development of heat content anomalies that propagate northward to affect deep convection in the Greenland or Labrador Seas. Changes in deep convection may in turn impact the overturning circulation, including its contribution to Gulf Stream transport. Fluctuations in wind or buoyancy fluxes in the subtropics may also influence equatorial SST via meridional circulation cells that feed equatorial upwelling.

#### **Recommendations:**

- Model studies to investigate the local and non-local relationships between temporal variations in the surface fluxes and temporal variations in the ocean state. In the design of models and experiments special attention should be paid to the following:
  - Key processes in the ‘warm water transformation’ pathway including the mechanisms responsible for the development, propagation, and decay of heat content anomalies, the interplay of processes that influence oceanic convection, the processes that modulate the overturning circulation, and the impact MOC variations have on SST.
  - The mechanisms that determine SST variability in the tropical Atlantic, particularly the role played by dynamical ocean processes. Also the mechanisms linking the tropical Atlantic with higher latitudes including the modulation of the STC’s by subtropical winds or buoyancy fluxes and the influence of the tropical Atlantic variability on

higher latitudes.

- Studies with ocean GCMs are needed to investigate how well the observed evolution of the Atlantic Ocean can be simulated given observed surface fluxes or related quantities. (Careful thought should be given to the formulation of the surface boundary condition). Multidecade-long model simulations should be rigorously evaluated against available surface and subsurface observations, with particular attention to poorly understood phenomena such as the development, propagation and decay of heat content anomalies, and to basic features such as the distribution of principle water masses. A comparison between different GCMs would help to differentiate between the effect of surface flux errors and model errors in the solutions. Model experiments could be designed to address which features in the surface forcing are essential to reproduce key features of the observed variability. Specific points include:
  - Investigating the nature and the role in the large-scale circulation of key physical processes that are poorly represented in ocean GCMs, in particular the role of topography (especially “choke points”) and of turbulent mixing.
  - Development of ocean data assimilation systems to provide best estimates of the seasonal-to-decadal variability in the Atlantic Ocean (in close collaboration with GODAE).

#### *Variability and Predictability of the Atlantic Ocean-Atmosphere System*

Coupled ocean-atmosphere GCMs are powerful tools for understanding the climate system. However, due to biases in both the atmospheric and the oceanic components, such models often have unrealistic mean states, annual cycles, and interannual variability. Much work remains to document, understand and alleviate such problems.

Coupled GCMs are the central tools for seasonal and longer time scale forecasting. There is

evidence of seasonal predictability over Europe in spring and summer but the mechanisms that give rise to this predictability are not understood. High priority must be given to research directed at improving the realism of coupled forecast models, improving understanding of the basis for predictability, and improving forecasting techniques.

#### **Recommendations:**

ACVE will need:

- Studies that elucidate the mechanisms responsible for variability in the Atlantic Sector in coupled GCMs, and evaluate the realism with which observed seasonal to decadal variability is simulated. Insight into mechanisms may be gained through experiments in which ocean-atmosphere interactions are restricted to certain regions (such as the Atlantic).
- Studies of ENSO influence on the Atlantic Sector. What SST anomalies patterns are directly forced by ENSO force in the Atlantic? Do these anomalies in turn influence the atmosphere? How predictable is the Atlantic's response to ENSO?
- Studies to investigate the mechanisms responsible for variability in the tropical Atlantic, including the 'Atlantic ENSO'.
- Research into the use of coupled models for forecasting climate fluctuations in the Atlantic Sector on seasonal and decadal time scales, including the problems of initializing and assimilating data into coupled models, and the sensitivity of forecasts to model formulation.
- Studies to investigate how changing levels of greenhouse gases may influence climate variability in the Atlantic Sector, and how natural variability influences the response of climate system to such changes.

#### **5.6 — Regional aspects of ACVE: Process Studies**

Regional aspects of ACVE will encompass observationally-based process studies and focused modeling activities. Both will serve to enhance insight into mechanisms which, although local, effect the entire Atlantic atmospheric or ocean

circulation. In the following we highlight some regional processes that might deserve special attention and a targeted effort. Such process experiments are anticipated to be of shorter duration (one to five years) and embedded in the sustained observing networks. Focused pilot studies may also be needed to help design the sustained observational networks.

#### *Tropical Atlantic*

AGCM experiments, in which the evolving pattern of tropical Atlantic SST is prescribed, will be instrumental in examining the underlying dynamics that govern the atmospheric response. Questions to be addressed include: What are the atmospheric responses to dipole-like SST anomalies? Are the anomalous circulations due to a boundary-layer response to SST or to a whole-scale rearrangement of the circulation in the tropical Atlantic troposphere? How does the anomalous circulation pattern affect the surface heat flux? What is the role of land heat sources in driving the anomalies?

Several oceanic processes are believed to play roles in tropical Atlantic variability such as oceanic advection including cross-gyre/cross-equatorial exchanges and vertical mixing/subduction processes. However, the relative importance of these processes in decadal TAV is unknown. Experiments using models with varying degrees of dynamical complexity must be carried out to determine which oceanic processes regulate off-equatorial SST variability. For example, ocean models forced only with winds can be compared to those forced only with surface buoyancy fluxes. Emphasis should be placed on the following issues: How can subsurface thermal anomalies influence SST changes? What is the relative importance of horizontal heat transport and vertical mixing/subduction processes? How important are cross-equatorial and cross-gyre exchanges? What is the relative importance between western-boundary-current transports and interior Ekman transport? Do oceanic Rossby waves play an important role in determine SST fluctuations in the off-equatorial SST variability?

It has been demonstrated that tropical ocean-

atmosphere interactions can lead to decadal TAV in relatively simple coupled models (e.g., Chang et al., 1997). In these models, the atmosphere is assumed to be largely determined by SST in such a manner that the tropical atmospheric circulation and associated surface heat flux adjust instantaneously to changes in the SST. This “slaved” atmosphere may exaggerate the atmospheric feedback to SST changes. Additionally, there are large uncertainties in surface heat flux estimates. Such models should be regarded as being near the bottom of a hierarchy of coupled systems, ranging from intermediate coupled models to fully coupled GCMs, that are needed in order to understand air-sea coupled processes in the tropical Atlantic. Specifically, dynamically based atmospheric models must be coupled to a variety of ocean models, ranging from mixed-layer models to oceanic GCMs, in order to diagnose the important feedback loops in TAV and to identify key delays in these loops. The coupled model experiments will be crucial for addressing important questions such as: Is the dipole-like SST variability a truly coupled phenomenon? If so, where are the regions in which the key air-sea feedbacks take place? What are the fundamental oceanic and atmospheric processes that control these feedbacks? Much more modeling work is needed to fill in this hierarchy. It is not likely that a process study, focused on critical issues, can be designed until this modeling activity is well underway. Finally, it is important to emphasize that coupled models will be instrumental in evaluating the predictability of the climate phenomenon. Existing observations already point to a tight coupling between rainfall variability in Northeast Brazil and Sub-Saharan Africa, as well as Caribbean and tropical-Atlantic SST variability. Coupled model experiments must be conducted to examine the predictability of tropical Atlantic SSTs, and whether seasonal-to-interannual SST forecasts can improve seasonal rainfall forecasts.

#### *Subtropics and tropical-subtropical connections*

We propose to study tropical-subtropical interactions using model-data combinations. Ocean models will be used to study the effect of

midlatitude variability on equatorial thermocline structure and SST. Experiments with forcing confined to different hemispheres will also tell us which hemisphere is more important. Detailed analyses of models constrained by observations will indicate which oceanic processes (e.g., subduction, wave propagation and/or changes in strength of shallow meridional cells) are likely to contribute to equatorial SST variability. Resultant SST anomaly patterns from such experiments will then be fed into an atmospheric model to identify possible feedbacks. For the atmosphere-model experiments, one could specify SST in the tropical Atlantic to examine the resulting extratropical variability. Particular attention should be paid to the relationships between the Hadley cell and storm-track variability in midlatitudes. Reverse experiments can also be carried out by forcing the atmosphere in midlatitudes to examine possible NAO connections to tropical and southern-hemisphere variability. Coupled model experiments can also be carried to determine the relation between NAO and TAV. For example, one can drive a coupled model with NAO-like forcing to see how much NAO influence there is on TAV.

#### *Subpolar Atlantic and Subtropical-subpolar connections*

Among the most pressing problems to be addressed during ACVE is the complex of questions associated with the atmospheric response to midlatitude SST/heat flux anomalies, with the Gulf Stream position, and with propagating SSTAs. Although many of those questions will be addressed in a modeling framework, some enhancement of measurements in the subpolar Atlantic is required. The unknown consequences of heat content anomalies along the boundary between the subtropical and subpolar gyre might justify a targeted process experiment:

#### An anomaly process experiment

After identification by the observing system, developing upper ocean heat content anomalies will be sampled intensively to determine their evolution and propagation characteristics. Anomalies in the upper layers of the ocean, cir-

culating in both the subtropical and subpolar gyres, should be sampled intensively over several annual cycles, to determine the manner in which their associated SST and thermal anomalies are modified by air-sea interaction, and the cycle of mixing and restratification. Fluid passing through the Gulf Stream system is exposed to the influence of strong NAO forcing at the start of the Atlantic storm track. Its properties, changed by convective mixing, then flood the subpolar and subtropical gyres. We need to determine the lifetime and characteristic pathways of these anomalies, and their potential influence on the atmosphere above.

To carry this out, the upper ocean observing network would be augmented with additional floats and surveys in key areas (e.g., the region of 18 degree water under the influence of strong NAO forcing). When studied in combination with data assimilating models, the fate of the anomalies, their longevity and characteristic pathways can be mapped out. We would also like to quantify, as a function of time-scale, the role of the ocean in the advection and transfer of heat to and from the surface, through subduction, Ekman layers, geostrophic eddies etc.

An anomaly process experiment to investigate the generation, propagation and fate of temperature anomalies at the boundary between the subpolar and subtropical gyres should include: a locally augmented float and drifter array and Eulerian time-series stations at key sites of SSTA evolution, and an instrumented monitoring line at the southern outflow of the subpolar gyre (roughly 47°N), extending eastward to the mid-Atlantic ridge, to sample the deep and intermediate southward flows as well as the northward North Atlantic Current transport and T/S properties.

#### *The Polar Basins and Subpolar-polar connections*

The central questions here include understanding the variations in low-salinity surface water and deep water mass formation/export, their relationships to atmospheric and ocean processes, and the adjustment of the basin-to-global scale thermohaline circulation (in terms of physical

mechanisms and inherent time scales) to those localized changes. At these latitudes, the surface and deep waters are related through the vertical stability which in turn is strongly influenced by sea surface salinity. The time-dependent fresh water budget appears to be the clearest diagnostic, if not the controlling factor for deep convection and the water types that result.

Strategies need to be developed to investigate the following topics:

- The export of waters from the Greenland-Iceland-Norwegian (GIN) Seas including the densest Denmark Strait Overflow Water (DSOW) and the shallower boundary currents (including ice) that are important to the fresh-water balance. Close cooperation with ACSYS (joint memberships in Implementation WGs) is recommended. Monitoring the overflows over the Greenland-Iceland-Scotland sills is considered very important as these measurements may be applied as northern boundary conditions in restricted-domain Atlantic Ocean modeling efforts.
- The properties of those Atlantic waters that enter the northern seas and subsequently involved in dense water mass formation and modifying the Arctic pycnocline. This might include a proposed 60N VOS program on a 3-week repeat schedule between Denmark to Greenland.
- The actual formation mechanism(s) of the dense overflow waters to quantify how much of the newly ventilated deep and intermediate water is formed in the gyre centers versus the boundary current systems. Exploratory Lagrangian programs might follow the conversion of Atlantic Water into DSOW in or about the GIN Seas. Study of the entrainment mixing processes active within the descending plumes of dense overflow waters is also needed.
- The shallow boundary currents along the Labrador and Greenland continental shelves that, despite their small mass transports, carry very low-salinity waters and hence

have a large fresh water transport that appear able to cap off the deep convection sites.

- The energetics/boundary layer physics of ocean/atmosphere coupling at high latitude. To address this, the high-resolution ETA atmospheric model needs to be extended eastward and a reanalysis program of the standard NCEP model organized. A general goal is improved E-P and heat flux predictions. The dipolar response of sea-ice to the NAO, in the GIN and Labrador Seas.
- The ice edge provides a possibly strong ocean-atmosphere feedback through surface heat/moisture flux. This suggests a process study of upper ocean/ice measurement and atmospheric energetics.

#### **Recommendations:**

Detailed planning for these imbedded process studies within the ACVE sustained observational networks must begin immediately, building on the modeling work and observational program results of ACCE.

## **6. Programmatic context**

The Atlantic Climate Variability Experiment has been conceived as a major contributor to the CLIVAR program. As such, ACVE will provide real time assessments of the state of the Atlantic Ocean in relation to climatic variations of the atmosphere. These will be of great utility to research programs which seek to understand the role of ocean biogeochemistry in climate, and the impacts of climate variability on fisheries. Therefore strong connections exist with many other ongoing or planned programs. These are summarized below.

- **International CLIVAR Program** — An important objective of both the GOALS and Dec-Cen components of CLIVAR is to identify and exploit incremental elements of climate predictability provided by quantified modes of ocean-atmosphere variability. By developing improved understanding of the NAO and TAV, the ACVE directly addresses these CLIVAR program goals. ACVE com-

bines into a coherent effort, the elements (D1-D3) of the International CLIVAR program that deal with the Atlantic Sector. By doing so, it is hoped that a more natural and focused study will result. The Atlantic is surrounded by many developed countries which will contribute to ACVE scientifically and financially. Given the partial overlap of physical processes and scientific questions, ACVE will maintain close scientific ties with our Pacific counterpart: PBECS.

- **GODAE/GCOS/GOOS (Global Observing System)** — The proposed Global Ocean Data Assimilation Experiment (GODAE) will provide a convincing demonstration of real-time assimilation systems, with core operational activities to be carried out 2003-2005 on a global basis. The aim is to assimilate data on space-time scales of 100 km and a few days, and produce integrated global analyses that can be used to support local-scale studies and initiate model runs. This study has been received enthusiastically by the WCRP. Plans call for a multi-node operation, with different groups focusing on different oceans, although all will use a common model and format so as to produce consistent products. At present, it appears that GODAE jointly with CLIVAR UOP will foster a global profiling-float network, *ARGO*, as part of its sustained subsurface ocean observing system. The Atlantic component of this array will contribute substantially to ACVE.
- **PIRATA PACS** — The international Pilot Research Moored Array in the Tropical Atlantic (PIRATA) will maintain an array of up to 14 surface moorings in the equatorial Atlantic in the 1997-2000 period. The acquired data from this network will help guide planning for the augmented array envisioned for ACVE. The Pan-American Climate Studies program (PACS, the US component of VAMOS) aims to improve the skill of operational seasonal-to-interannual climate prediction over the Americas, with the emphasis on forecasting warm season rainfall. Focal points include the relationship between boundary

forcing and climate variability; processes governing SST variability in the tropical Atlantic and Pacific; and the development of the mixed layer. In its second phase, there are plans that PACS will shift its activities into the tropical Atlantic which will allow close collaboration with PIRATA-ACVE.

- **WOCE AIMS** — The World Ocean Circulation Experiment (WOCE) is now entering in its Analysis, Interpretation, Modeling and Synthesis phase (AIMS). In particular the results and experience gained from the Atlantic Circulation and Climate Experiment (ACCE) will benefit the planing and final design of ACVE. The analysis phase of WOCE will also provide the opportunity to inspect the historical and WOCE records in the light of the ACVE goals.
- **ACSYS** — The Arctic Climate System Study (ACSYS) aims to answer two related questions:
  - Is the Arctic climate as sensitive to global changes as models seem to suggest?
  - What is the sensitivity of global climate to Arctic processes?

Hence ACSYS will focus on the climate of the polar oceans and will be an important partner in the northern part of the Atlantic where variability in sea ice distribution, fresh water export from the Arctic and the rate of warm to cold water formation might hold the key to Atlantic variability. (<http://www.npolar.no/acsys/>)

- **PAGES** — The International Geosphere-Biosphere Program project charged with providing a quantitative understanding of the Earth's

past environment. We anticipate that long proxy records of climate variability in the Atlantic sector will come out of this effort which will contribute to the ACVE goals.

- **GLOBEC** — International GLOBEC (now an official IGBP program) is engaged in planning for the Small Pelagics and Climate Change (SPACC) program. Involved countries include Japan, U.S., Mexico, Peru and Chile. Retrospective studies, monitoring, modeling and process studies are being considered. There are clear connections between the physical elements of these efforts and ACVE.

### **Timetable**

A definitive time table for ACVE will be developed in the coming six months. Tentative plans call for core field activities beginning 2002. However, planing and implementation activities will start as early as FY 1999, these will include design studies and error estimates based on historical data and numerical studies. The ACCE data set will be a central element in these studies.

### **Budget**

A draft budget for ACVE will be assembled in advance of the December international CLIVAR meeting. It can be anticipated that a large fraction of the experiment will be covered by Euro-CLIVAR. In the U.S., the National Science Foundation and National Oceanic and Atmospheric Administration are actively involved at this time. NASA is also involved with remote sensing elements of the program. Contributions from ONR are unclear at this point.

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