US - CLIVAR Atlantic Implementation Plan

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US - CLIVAR Atlantic Sector Implementation Panel

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Preface This document has been prepared for consideration by the US CLIVAR Scientific Steering Committee (SSC) of those activities needed to achieve the scientific goals of CLIVAR in the Atlantic Sector. It is a synthesis of several existing reports brought to the US CLIVAR Atlantic Implementation Panel for consideration; in particular, the Atlantic Climate Variability Experiment (ACVE) prospectus and implementation plan (Visbeck et al. 1998; Joyce and Marshall 2000; see http://www.ldeo.columbia.edu/~visbeck/acve). It also incorporates recommendations from the COSTA (Climate Observing System for the Tropical Atlantic) meeting report (Garzoli et al. 1999; see http://www.aoml.noaa.gov/phod/COSTA), as well as the input from several individuals external to the panel.

Summary

US CLIVAR research activities in the Atlantic sector will reach their full scale in 2003 and last until about 2015. The program is designed to simultaneously investigate the ocean-atmosphere-land interactions associated with three major climate phenomena: the North Atlantic Oscillation (NAO), Tropical Atlantic Variability (TAV), and changes in the ocean's meridional overturning circulation (MOC) that might possibly be associated with abrupt climate change.

The proposed implementation strategy is to maintain a balanced and integrative approach between existing and new observations, modeling and theory, as well as diagnostic studies, to better understand the primary climate phenomena, their interactions and the potential for predictability. A network of sustained, basin-wide observations will be augmented through regional and process studies needed to improve understanding of particular regions and/or key processes. Comprehensive, three-dimensional observations of the entire Atlantic Ocean, including its shallow and deep boundary currents, air-sea fluxes and the overlying atmosphere will be collected over a period of 15 years. Data assimilating atmospheric and ocean models will bring the different elements together, thereby facilitating quantitative diagnoses of the mechanisms involved in Atlantic climate variability.

The legacy of Atlantic CLIVAR will include the following:

- An Atlantic sector contribution to a global climate observing system that will be able to constrain coupled climate models

- Improved coupled climate models that are able to simulate the observed climate variability of the last few decades and, hence, will be the basis for future climate predictions on seasonal to multi-decadal time scales

- Comprehensive data sets of observed and/or analyzed fields that form the basis for Atlantic climate variability studies.

The US strategy has been developed largely through a series of open community meetings that are summarized in the Atlantic Climate Variability Experiment (ACVE) prospectus and implementation plan (Visbeck et al. 1998; Joyce and Marshall 2000). It has also been developed with the emerging plans and priorities of other programs and nations in mind. For instance, close

collaboration with the Arctic Climate Systems Study (ACSYS) and the Study of Environmental Arctic Change (SEARCH) initiatives are needed to ensure that freshwater export from the Arctic to the North Atlantic is adequately monitored and key processes are understood. Similarly, coordination with SPARC (Stratospheric Processes and their Role in Climate) is required to achieve a better understanding of the dynamics of the NAO, and coordination with PAGES (Past Global Changes) is needed to ensure the extension of important instrumental records throughout the Atlantic basin. Monitoring of the southern ocean (south of 30°S) is not directly addressed in the current US implementation strategy. Effective communication with international partners and US interest groups is, therefore, necessary to ensure better understanding of inter-ocean exchanges and their importance for the climate of the Atlantic sector. Since about 60% of the global oceanic CO_2 uptake takes place in the Atlantic sector as a consequence of its intense MOC, coordination with the emerging US carbon cycle initiative is also required.

1. Introduction

The climate of the Atlantic sector and surrounding continents exhibits considerable variability on a wide range of time scales. This variability is manifested as coherent fluctuations in ocean and land temperature, rainfall and surface pressure with a myriad of impacts on society and the environment. Improved understanding of this variability is essential for assessing the likely range of future climate fluctuations and the extent to which they may be predictable, as well as understanding the potential impact of climate change due to human activities.

Of central importance are three interrelated phenomena: Tropical Atlantic Variability (TAV), the North Atlantic Oscillation (NAO), and the Atlantic Meridional Overturning Circulation (MOC). The former refers to substantial variations on interannual and interdecadal time scales in tropical Atlantic sea surface temperature (SST) with direct impacts on the climates of Africa and the Americas, among other, at this point more tentative, links. The NAO dictates much of the climate variability from the eastern seaboard of the United States to Siberia and from the Arctic to the subtropical Atlantic, and its intensification in recent decades has contributed significantly to observed global warming. Fluctuations of the NAO and TAV alter the wind stress on the ocean, as well as air-sea heat and freshwater fluxes. These in turn induce substantial changes in the wind- and buoyancy-driven ocean circulation, as well as in the site and intensity of water mass transformation, so that the strength and character of the Atlantic MOC is influenced. Indeed, the atmosphere drives much of the observed ocean variability over the Atlantic; however, the response of the atmosphere to changes in tropical and extratropical SST distributions and the role of land processes and sea ice in producing atmospheric variability are problems central to US CLIVAR.

This document describes what needs to be done over the next decade to observe and to understand the phenomena of climate variability in and around the Atlantic basin in support of Atlantic CLIVAR programs. It sets out a prioritized and integrated plan for sustained observations[1], modeling and theoretical investigations of the atmosphere-ocean-land coupled system. A central element is model-data synthesis so that the mechanisms, processes, and global teleconnections can be addressed quantitatively inside of an improving coupled climate model framework.

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[1] Sustained observations are those that must be maintained over the next decade and are to be assimilated into models.

Embedded in the network of sustained observations will be a small number of regional scale shorter duration studies to enhance our understanding of climate relevant regions or mechanisms.

An important aspect of the modeling studies is assessment of predictability. This is especially so for the tropical Atlantic, where it has been shown that the atmosphere is sensitive to local SST forcing. Additionally, large remote influences from the Pacific further add to the predictable dynamics in the tropical Atlantic sector.

The long-term goals of Atlantic CLIVAR are to:

1. Describe and model coupled atmosphere-ocean-land interactions in the Atlantic sector, quantify their influences on and interactions with the regional and global climate system, and determine their predictability.

2. Assemble quantitative historical, proxy and real time data sets that may be used to test, improve and initialize models of coupled Atlantic climate variability.

3. Investigate the sensitivity of the MOC to changes in surface forcing.

4. Assess the likelihood of abrupt climate change.

The regional scope of the US CLIVAR Atlantic program is north of 30¡S, including recognition of the importance of studying and monitoring subpolar atmosphere/ocean/ice processes and the gateway to the Arctic. It is designed to complement and interweave with ongoing and proposed investigations of European and Canadian colleagues, as well as with other developing programs such as the Arctic Climate System Study (ACSYS), the Study of Environmental Arctic Change (SEARCH), the Stratospheric Processes and their Role in Climate (SPARC) program, and the emerging US carbon cycle initiative.

The organization of this document is as follows. The principal climate phenomena in the Atlantic basin are reviewed in the Section 2. In Section 3 the observations and model/data synthesis required to describe the phenomena are discussed. The nature of the data analysis, process studies, modeling and theory required to understand the basic mechanisms, develop models of the coupled system and improve representations of crucial processes within them are outlined in Section 4. One of main objectives is to assess the predictability of Atlantic climate variability, and this is highlighted in Section 5. Finally, the programmatic context of Atlantic CLIVAR is summarized in Section 6, with an estimated timeline and budget in Sections 7 and 8.

2. The phenomena of Atlantic Climate Variability

The science and phenomenology of Atlantic climate variability is reviewed in detail in the ACVE prospectus (Visbeck et al. 1998). A brief survey of the NAO, TAV and MOC is presented below, including a discussion of the prevailing views concerning the mechanisms of Atlantic climate variability.

2.1 The NAO

The NAO refers to a north-south oscillation in atmospheric mass between the Icelandic (Arctic) low- and the Azores (Subtropical) high-pressure centers. The spatial signature and temporal variability of the NAO are usually defined through the regional SLP field, for which some of the longest instrumental records exist, although it is also readily apparent in meteorological data throughout the troposphere to the lower stratosphere. During the months December through March, when the atmosphere is dynamically the most active in the Northern Hemisphere (NH), the NAO accounts for more than one-third of the total variance in SLP over the North Atlantic, substantially more than any other pattern of variability. Moreover, the NAO exerts a dominant influence on NH (and global) temperatures, and changes in the phase of the NAO are associated with pronounced changes in the intensity and number of storms, their paths, and their associated weather, especially precipitation.

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

A possible exception is the observed interdecadal NAO variability, especially the strong trend toward the positive index polarity of the oscillation over the past 30 years. Multi-century AGCM experiments like those described above do not reproduce interdecadal changes of comparable magnitude to the recent trend.

At present there is no consensus on the process or processes that most influence the NAO on long (interdecadal) time scales. Indeed, the several different forcing mechanisms are likely to be important

The equivalent barotropic vertical structure of the NAO reaches high into the stratosphere. The leading pattern of geopotential height variability in the lower stratosphere is also characterized by a seesaw in mass between the polar cap and the middle latitudes, but with a much more zonally symmetric (or annular) structure than in the troposphere. When heights over the polar region are lower than normal, heights at nearly all longitudes in middle latitudes are higher than normal. In this phase, the stratospheric westerly winds that encircle the pole are enhanced and the polar vortex is "strong" and anomalously cold. It is this annular mode of variability that has been termed the Arctic Oscillation (AO)[2], and the aforementioned conditions describe its positive phase.

During winters when the stratospheric AO is positive, the NAO also tends to be in its positive phase. There is a considerable body of evidence to support the notion that variability in the troposphere can drive variability in the stratosphere. However, the opposite view is much less commonly held.

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

[2] The signature of the stratospheric AO in winter SLP data, however, looks very much like the anomalies associated with the NAO with centers of action over the Arctic and the Atlantic. The "annular" character of the AO in the troposphere, therefore, reflects the vertically coherent fluctuations throughout the Arctic more than any coordinated behavior in the middle latitudes outside of the Atlantic basin. That the NAO and AO reflect essentially the same mode of tropospheric variability is emphasized by the similarity of their time series, with differences depending mostly on the details of the analysis procedure.

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

The amplitude and phase of the NAO could also be modulated by interactions with the underlying Atlantic Ocean. In the extratropics, it is clear that the atmospheric circulation is the dominant driver of upper ocean thermal anomalies. Indeed, the leading pattern of SST variability over the North Atlantic (the so-called North Atlantic tripole, see Fig. 1) emerges principally as a result of NAO forcing, although there is some evidence that advective effects play an important role in producing heat content anomalies in some regions of the tripole. A long-standing issue, however, has been the extent to which anomalous extratropical SST feeds back to affect the atmosphere. Most evidence suggests this effect is quite small compared to internal atmospheric variability. Nevertheless, the interaction between the ocean and atmosphere could be important for understanding the details of the observed amplitude of the NAO, its interdecadal variability, and the prospects for meaningful predictability. Some AGCMs, for instance, show modest skill in reproducing aspects of the observed NAO behavior, especially its interdecadal fluctuations when forced with the time history of observed, global SSTs and sea ice concentrations over the past 50 years or so.

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

The response of the extratropical North Atlantic atmosphere to changes in tropical and extratropical SST distributions, and the role of land processes and sea ice in producing atmospheric variability, are problems that will be addressed in US CLIVAR. Until these are better understood, it is not possible to evaluate the realism of more complicated hypotheses that rely on truly coupled interactions between the atmosphere, ocean, land and sea ice to produce North Atlantic climate variability. It is also a prerequisite for evaluating the extent to which interannual and longer-term variations of the NAO might be predictable.

2.2 Tropical Atlantic Variability

The tropical atmosphere is generally sensitive to changes in surface conditions. Two major heat sources influence the atmosphere over the tropical Atlantic. The first is the Inter-Tropical Convergence Zone (ITCZ), whose intensity and position is particularly sensitive to SST. The second is deep convection over the Amazon River basin, which is affected by the land and adjacent ocean surface conditions.

Anomalies in tropical Atlantic SST are primarily driven by changes in surface winds, which can be forced either locally or remotely. Local forcing, for instance, arises from changes in the position and intensity of the ITCZ or in convective activity over the Amazon, creating the potential for active local land-atmosphere-ocean feedbacks to exist, although the detailed mechanisms for such local feedbacks are not well understood. Neither is it clear whether local feedbacks can produce preferred time scales of variability in the tropical Atlantic. On the other hand, advective and other processes in the ocean can counteract local feedbacks and introduce "ocean memory" into the system.

The dominant low-frequency climate phenomenon in the tropical Atlantic is the co-varying fluctuation of tropical SST and trade winds. These fluctuations, which display markedly large power on time scales of 8-16 years, exhibit a pattern of large-scale SST anomalies straddling the mean position of the ITCZ. The NH trades, and the associated cross-equatorial flow, seem to depend sensitively on SST. Very little wind variability south of the equator is associated with this mode. Weaker-than-normal trades are associated with positive local SST anomalies, and vice versa. The northern trades and location of the ITCZ are also affected by SST changes south of the equator, such that colder than normal SST in the South Atlantic leads to a reduced southward extension of the ITCZ during boreal spring with weaker than normal trades in the tropical North Atlantic. Variations in SST on either side of the equator are poorly correlated, suggesting that it is the change in the cross-ITCZ SST contrast to which the trades respond.

The northern subtropical Atlantic trades are also affected by NAO variability. The wind variability produces changes in latent heat flux and, consequently, changes in SST. These SST anomalies can affect the ITCZ and the Amazonian heat source, which in turn may affect the NAO through an "atmospheric bridge" mechanism akin to the extratropical forcing by ENSO in the Pacific.

Considerable SST variability also occurs in the Southern Hemisphere (SH). The nature of this variability is not resolved, but it appears to be linked to the interannual variability of the South Atlantic subtropical high-pressure center.

A mode of variability similar to the Pacific ENSO has also been identified in the tropical Atlantic Ocean. Although it is weak relative to the Pacific variability, the Atlantic equatorial SST anomalies affect regional rainfall, such as the Gulf of Guinea. Equatorial waves and remote wind forcing play a significant role in the generation of SST anomalies on interannual time scales.

The Atlantic sector also responds significantly to the El Nino/Southern Oscillation (ENSO) phenomenon in the Pacific. This remote forcing is strongest over the northern tropical Atlantic during boreal spring and early summer. Pacific ENSO affects the climate of the Atlantic sector through both direct and indirect (via SST changes) effects.

2.3 Atlantic meridional overturning circulation

The mean circulation of the ocean plays a key role in the meridional transport of 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 carries about 1.2 PW (petawatts) of heat northward. This is approximately 60% of the net poleward ocean flux and 30% of the total flux by the ocean and the atmosphere at this latitude. This poleward heat flux is intimately associated with the water mass transformations that take place as thermocline waters move north and are ultimately converted by air-sea interaction and entrainment into cold North Atlantic Deep Water.

The role of the MOC in a world of increasing carbon-dioxide emissions is receiving increased attention. About 60% of the global oceanic CO_2 uptake may take place in the Atlantic sector, a consequence of its intense MOC. Some model projections suggest, however, that in only a few decades Atlantic climate might radically shift into a different equilibrium with a much-reduced

MOC and associated ocean heat transport. Evidence for rapid climate shifts in the past has been found in several paleo-records and is coincident with 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_2 uptake and rapidly cool Europe and northeastern America.

2.4 The need for a basin-wide focus in a hemispheric/global context

As discussed above, the NAO, TAV and the Atlantic MOC are interrelated. For instance, TAV may force remote atmospheric responses that affect the amplitude and time scales of NAO variability, while the NAO may act as an important extratropical forcing to excite TAV. The NAO appears to orchestrate changes in the water properties and sea ice distribution of the North Atlantic and Arctic Oceans, including the distribution and intensity of the sinking branches of the MOC, and the spatial pattern of the leading mode of SST variability (the Atlantic SST tripole) can largely be understood as the passive response of the ocean to NAO forcing (Fig. 1). On the other hand, the frequency content of the tripole may contain signatures of coupled air-sea interaction and, on multi-decadal time scales, internal ocean advection (including modulation in the strength of the MOC and hence ocean heat content and SST) might influence the overlying atmosphere.

The spatial extent of these phenomena covers the entire Atlantic basin, including the Arctic, from the deep ocean to the upper stratosphere. Moreover, the NAO may be alternatively viewed as a hemispheric-scale oscillation (the AO or the northern "annular mode"), and the Atlantic MOC is part of the global thermohaline circulation. Successful implementation must, therefore, include the whole Atlantic sector, rather than just part of it, and also be aware of influences on and by the global circulation.

3. Observations

Two categories of measurements form the observational basis of Atlantic CLIVAR:

1. Sustained, Atlantic-wide observing systems of the atmosphere and ocean, and

2. 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.

A comprehensive description of the oceanic and atmospheric circulations associated with Atlantic climate variability is the goal of the sustained observing elements. 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 critical to measure subsurface thermal structures, since ocean circulation and SST anomalies are typically associated with large changes in thermocline depth. In the following the measurements that will be the central elements for testing hypotheses of coupled climate variability in the Atlantic sector are explicitly outlined.

3.1 Ocean

The US CLIVAR Atlantic plan is a whole ocean plan, including some links to the Nordic and Arctic Seas so as to help close the planning "gap" that is so common between those areas and the Atlantic. It essentially embraces the recommendations of the COSTA report that emerged from an internationally well-attended tropical Atlantic observing system meeting held in conjunction with a PIRATA meeting in May 1999. Only very limited plans are currently presented for the extratropical South Atlantic, where we depend on our international partners to plan and lead large scale initiatives.

The key elements of ocean observation are:

- Basin-wide sustained observations using in situ measurements, satellites, and assimilation models

- Enhanced sustained measurements at particular locations important for climate variability

- Augmentation of observing/modeling systems to focus on key mechanisms important to climate variability.

- Development of new tools for improving the planned system

All of the above are necessary for Atlantic CLIVAR to succeed. Basin-wide sustained observations and model/data synthesis are essential to describe the broad picture and make sense of regional studies. Without them nothing else can proceed, and for this reason they must have the highest priority. But the regional enhancements and foci are also very important, because through them key regions of the climate system can be monitored, leading to further refinement of hypotheses of the mechanisms of climate variability. Finally, new technologies to observe the ocean and to assimilate these observations into models must not only be embraced, but also encouraged.

The Atlantic observational plan outlined below has been developed with the emerging measurement plans and priorities of other nations in mind. It relies and builds upon several existing or emerging activities such as PIRATA (Pilot Research Array Moored Array in the Tropical Atlantic) and ARGO (global array of profiling floats in the ocean). It includes charts showing observing system elements (Figs. 2-5). These begin with "preservation", so that in the process of enlarging the observing system critical existing elements are retained. Indeed, the envisioned future evolution of the observing system is predicated on this preservation. In addition, the charts assume the complete implementation of the North and Tropical Atlantic sector of ARGO. It is to be noted, however, that with the drive for a global ARGO system a dilution of the Atlantic efforts may result.

3.1.1 Basin-wide sustained observations

Satellites: The principal satellite sensors needed for Atlantic CLIVAR are the altimeter and the scatterometer. Altimetry provides information about the barotropic mode of the ocean circulation that is essential for the assimilation of other ocean data, such as that from ARGO floats. Scatterometry provides surface wind vectors that are otherwise unobserved over much of the ocean. It is assumed that other existing operational instruments will remain available (e.g., Advanced Very High Resolution Radiometer (AVHRR) for SST). Barring an early failure of Topex/Poseidon, the follow-on JASON-1 mission should provide a continuation of altimetry. Quickscat and ADEOS II (Advanced Earth Observing Satellite), carrying the SeaWinds scatterometer, will provide measurements of the surface wind field without a gap, if all goes according to plan.

ARGO floats: To provide the desired 3° coverage north of 30°S in the Atlantic, approximately 550 floats are required. This resolution is needed to reduce upper-ocean temperature errors to ~ 0.5°C. At this accuracy seasonal changes in upper-ocean heat content can be known well enough to usefully constrain estimates of air-sea heat exchange[3]. With European and Canadian plans, it appears that about half of that number of floats will be deployed over the next three years. Thus, the US plan would require 280 floats throughout the program. All floats should have temperature and salinity sensors.

Surface drifters: Satellite tracked surface drifters provide calibration and validation for the SST data obtained from satellites, surface meteorological observations in both remote areas and areas that experience severe weather, independent verification data for ocean data assimilation models, and observations for process studies. A basin-wide array is needed. For calibration and validation purposes a 5° array is required. A continuation of this density is funded for the next 3 years in the tropical band, 20°S-30°N, and this should be augmented by an extension northward, by the inclusion of atmospheric pressure and wind speed on a subset of the buoys, and by the addition of some conductivity cells for improved surface salinity measurements.

Expendable Bathythermographs (XBT): The XBT network provides measurements of the intraseasonal to interannual variability in the tropical oceans and of the seasonal to interannual fluctuations in the transport of mass, heat, and freshwater across ocean spanning transects. XBT lines are needed to determine the spatial and temporal variability of the temperature and geostrophic velocity and their correlations with other fields. They provide information about the temporal variability of important boundary current regions. They are needed to characterize baroclinic eddies and fine structure and to estimate their significance in the transports of heat and water masses, information that will aid the development of model parameterizations and assimilation schemes. Finally, they contribute to regional studies by identifying persistent small-scale features and by measuring the seasonal and interannual fluctuations in the transport of mass, heat, and freshwater through the perimeter of large ocean areas.

Existing Atlantic VOS-based high resolution XBT sections should be continued. In addition, high-resolution sampling on five lines (AX2, AX8, AX18, AX29, and AX32) should be implemented (Fig. 2). Some of these lines should also support upgraded meteorology and surface flux observations. Remaining low-resolution lines should be phased out once ARGO is fully operational.

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[3] ARGO design and implementation document - (http://www.argo.ucsd.edu/)

Basin-wide hydrography: Repeat hydrography remains the only means of directly measuring on basin scales the full suite of ocean water properties at high-vertical resolution over the entire water column. The WOCE Hydrographic Program was largely designed with this approach in mind. Results reveal marked changes in water mass properties and volumes on decadal time scales, leading to speculation about changes in water mass formation, the meridional overturning circulation, and global climate. The repeat-hydrography program within Atlantic CLIVAR will build on this history.

One element of the field program will consist of full-depth basin-scale section reoccupations. While useful by themselves to document water mass variability, these data will additionally provide valuable constraints on models now under development that will assimilate observations from other observing systems. Of greatest value is anticipated to be the estimated volumetric and property changes by density class that reflect the time-integrated effects of air-sea exchange and ocean circulation. Observed changes in transient tracer distributions may also prove useful in constraining model circulations and water mass renewal rates.

As part of the international effort on carbon sequestration in the ocean, a tentative array of hydrographic sections to be reoccupied on 5 to 10 year intervals is being planned. In collaboration with this carbon effort, Atlantic CLIVAR recommends that the US maintain two repeated zonal trans-ocean hydrographic lines near 16°N and 30°S, and two meridional hydrographic lines along 65°W and 50°W (Fig. 3). The picture one gets from zonally integrated sections shows the vertical structure of the MOC, but masks the fact that most of the cold water return is concentrated in the western Atlantic. For this reason, the two meridional lines are proposed. These not only sample the interior of the basin for deep temperature and salinity variability, but also cross the deep western boundary current at 4 points along its southward path. The best overlap with European plans suggests 2003 as the first target date.

Time-series hydro stations: The cornerstone of the hydrographic station plan is the continuation of Station S off Bermuda and Station Bravo in the central Labrador Sea (Fig. 4). The US has long been involved in sustaining Station S, and that support should be continued with a possible upgrade to a moored system. The U.S. has had more limited involvement in Station Bravo; it is now a Canada/Germany/US group effort which should be continued. The Labrador Sea mooring has demonstrated the utility of velocity measurements, as well as temperature/salinity, in the convection/re-stratification cycle that is important for deep-water formation and thus the MOC. The data from Bermuda and the Labrador Sea dominate the time-resolved picture of interannual/decadal changes in the North Atlantic Ocean, complementing the time integrated effects perceived by differencing sections separated by years or by differencing composite data maps for various epochs. A moored system is also recommended for use inshore of the Gulf Stream south of New England near 40°N, 70°W. Together with the European stations (ESTOC and Porcupine Bank), these stations represent a large-scale baroclinic transport index array for the extratropical Atlantic.

Improved Surface Fluxes: Reliable fluxes in reanalysis products are required. Additional US surface flux sites are required as "ground truth" (Fig. 5). Their main goal is to improve surface flux estimates locally and, through volunteer observing ships, to extrapolate them spatially. By comparing with numerical weather prediction and satellite estimates, this will provide improved basin-wide estimates of surface fluxes and guide improvements in parameterization. Atlantic CLIVAR recommends the establishment of 4 surface flux reference sites in the Atlantic, with the highest priority for initial deployment in the tropical Atlantic warm pool (16°N, 54°W and 6°N, 25°W) where a thermodynamic feedback is likely operating, near the Azores (35°N, 35°W), and in the high flux regime inshore of the Gulf Stream (40°N, 70°W). Additional sites should be defined as part of special focus studies (see below).

3.1.2 Enhanced sustained measurements

Tropical Atlantic: A comprehensive observing system in the tropical Atlantic is crucial to advance understanding of the underlying physics of TAV. PIRATA (Pilot Research Moored Array in the Tropical Atlantic) provides a backbone observing system, which can be viewed as an Atlantic extension of the Pacific TAO array. Its configuration consists of 12 ATLAS moorings extending along the equator and two meridional lines, along 38°W in the tropical North Atlantic and 10°W in the Tropical South Atlantic. This design provides basic equatorial coverage of wind forcing in the western basin and seasonal-to-interannual SST variability in the central and eastern basin, as well as the off-equatorial regions of high SST variability in the tropical North and South Atlantic. The variables measured are surface winds, SST, sea surface conductivity (salinity), air temperature, relative humidity, incoming short-wave radiation, rainfall, subsurface temperature (10 depths in the upper 500 m), subsurface conductivity (3 depths in the upper 500m), and subsurface pressure (at 300 m and 500 m). An acoustic Doppler current profiler mooring at 20°W on the equator and two high resolution XBT lines (AX8 and AX27) will allow monitoring of current variations in the tropical Atlantic. This observing array should provide the basic, direct observations necessary to test the hypotheses for TAV. Thus, Atlantic CLIVAR recommends its full support.

The need for further enhancements to the observing array in the tropical Atlantic should also be emphasized. In particular, there is a pressing need to improve the accuracy of surface flux measurements in critical regions where coupling between the ocean and atmosphere is believed to be strong. A combination of high quality surface flux measurements from VOS lines (AX8) with a small number of surface flux buoys is recommended (Section 3.1.1). Consideration should also be given to extending the 38°W PIRATA line to the South American coast to provide an index of cross-equatorial flow along the western boundary. Simultaneous information on the western boundary current near the equator, the interior zonal flows along 38°W, and the upstream North Brazil Current near 7.5°S (German mooring array) would help to provide an improved understanding of the role of ocean dynamics in the coupled system.

Western Boundary Currents: Western boundary current measurements at strategic locations remain one of the most useful and powerful constraints on models to determine if they are accurately reproducing the large-scale circulation and variability in the oceans. Monitoring of upper ocean western boundary currents such as the Florida Current, the Gulf Stream south of New England, and the Labrador and North Atlantic Currents off Newfoundland is needed to understand how these currents respond to the NAO, and to determine what role they play in coupled atmosphere-ocean interactions that affect heat transport and heat storage.

In addition to the fixed-point time series hydrographic stations and repeat-sampled hydrographic sections outlined in Section 3.1.1, the existing network of telephone cable-based transport measurements in the Florida Straights should be continued. In addition, newly instrumented lines between the Caribbean Islands and South America should be evaluated and, if successful, maintained. In addition, some discussion has been given (Joyce and Marshall 2000) to the need for at least one moored array, most likely between existing (German) arrays in the subpolar basin and the tropics. Further monitoring of the Atlantic western boundary currents will be dependent on the development of new, cost-effective technologies and methodologies.

Labrador Sea: The major effort in the Labrador Sea convection experiment has shown the importance of peripheral exchange as a means of regulating convective activity and restratification. Enhancement of the single mooring at Bravo by additional Argo floats is recommended. The 3° array (Section 3.1.1) translates to only about 5 floats in the Labrador Sea. An augmentation of 30-40 floats is required in this key region. Another possibility is the use of newly developing glider technology. These additions would provide an improved spatial resolution necessary to monitor temporal variability.

Freshwater input and the Arctic: A key need of Atlantic CLIVAR is to monitor the freshwater and heat exchange with the Arctic Ocean. Principal freshwater sources for the Arctic are river discharge and the import of low-salinity water through Bering Strait. Major freshwater outflows are through the Fram Strait, largely in the form of sea ice, and the Canadian Arctic Archipelago (CAA). Warm, salty Atlantic water enters the Arctic Ocean through the Fram Strait and across the Barents Sea shelf.

Within ice-covered sectors of the Fram Strait and Davis Strait, for instance, moored arrays with upward looking sonar are needed to measure ice drift and monitor temperature, salinity and water velocity. Point data from such arrays will be complemented with estimates of ice velocity and mass flux from remote sensing.

Two technical problems are common to measurements of fluxes in the far North Atlantic. One is the measurement of ocean properties in the surface waters of an ice-covered area. Much of the lateral freshwater flux occurs there, but instruments fixed at shallow depth are destroyed by thick ice. The anticipated solutions are profiling instruments or specially reinforced sensors. The other challenge is to obtain repeated hydrographic sections at adequate resolutions. It is anticipated that new automated profiling floats and gliders will be able to make such sections repeatedly over long periods of time, at least in the only partially ice covered regions.

In addition to close collaboration with ACSYS and SEARCH, US Atlantic CLIVAR recommends coordination with the emerging international Arctic-subarctic ocean flux array (ASOF) program presently funded though individual grants, predominantly in Europe. ASOF is targeting the year 2003 to develop a coordinated international funding umbrella.

3.1.3 Observations and Data Assimilation

Model development: Atlantic CLIVAR recognizes the need for continued efforts in process modeling. Key oceanic processes include poorly resolved topographic effects, ice dynamics, boundary currents and shelf circulations, bottom topography, mixing processes in both energetic and quiet parts of the ocean, convection, entrainment, and upper-ocean subduction.

Data assimilation: To achieve CLIVAR Atlantic objectives, an optimal combination of ocean, atmosphere and land observations and numerical models is required that can only be achieved through rigorous data assimilation. For ocean (and land) research, this represents a new paradigm. Such an effort will produce estimates of the time-dependent ocean circulation and associated property fluxes. Ultimately the objective is to use ocean and atmosphere models in tandem to improve ocean surface flux estimates.

Currently, several efforts are underway to develop a credible methodology for combining different types of observational data into a numerical model of the ocean. The goal is to elevate global ocean state estimation from its current experimental status to a quasi-operational tool for climate research, to integrate the modeling and observational communities, and to provide high-quality estimates of the evolving Atlantic Ocean in support of Atlantic CLIVAR. Such a model-data synthesis can provide the following:

- An estimate of the monthly mean state of the ocean.
- Surface fluxes of momentum, heat, and freshwater consistent with the estimated ocean state
- Time series at specific positions at daily resolution
- Estimates of advective transports of mass, heat and freshwater
- The strength of the MOC

Given a credible assimilation product, it might also be possible to change the mix of observations, investing resources in observations that the models cannot reproduce well.

Climate study demands ocean state estimates over many decades, possibly starting from 1950, perhaps at 1° spatial resolution. Such analyses are similar in spirit to long atmospheric reanalysis efforts. They also compliment the atmospheric estimates in that the ocean state estimation will provide adjustments to the surface fluxes of momentum, heat and freshwater which can then be compared with the atmospheric products. Discrepancies will point to errors in either the atmospheric or the ocean model, or both. The final result will be a 50-year global history of the ocean and respective surface forcing fields that will be consistent with available data and with the model physics. Such estimates will be fundamental for enhancing our understanding of variability in the ocean on interannual to decadal time scale. The ocean reanalysis products will also be a necessary ingredient for understanding coupling mechanisms between the atmosphere and the ocean, and they will important to evaluate the extent to which ocean dynamics play an active role in climate variability. Ocean reanalysis is also a crucial and necessary first step toward one of the main goals, a coupled atmosphere-land-ocean data reanalysis.

Present limitations on computer power are a major obstacle. Resources are needed to both improve the spatial resolution of the models as well as to perform the reanalysis of data going back to the 1950s. The Atlantic focus will ultimately allow employment of very high-resolution ocean models (during the next decade 1/10° resolution should be routinely achievable if computing power continues to grow as expected).

3.2 Atmosphere

3.2.1 In situ observations

The backbone of the atmospheric observing network are the World Weather Watch/Global Climate Observing System (WWW/GCOS) surface and upper-air sounding stations located on the periphery of the world oceans and a 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.

Several regions within the Atlantic sector remain devoid of in situ atmospheric observations. More generally, the WWW network has deteriorated since the 1960s in terms of the number of stations and the frequency of observations, especially in the upper troposphere and lower stratosphere. Existing records are universally inhomogeneous. Funding limitations has driven much of the

WWW decline, but it is also partly due to the advancing technology and methods of the weather research and prediction community.

The need to create a long-term observational record suggest the following steps to improve the in situ atmospheric observing system for Atlantic CLIVAR:

- Focus on implementing the GCOS network. High priority should be placed on maintaining existing surface and upper-air stations with long, uninterrupted records. Highest priority for new observations should be in data-sparse regions and key climatic regions, and on providing adequate temporal resolution

- Continue data prospecting to improve the past climate record, and continue efforts to document and assess the impact of changes in the observing system

- Explore the use of new, cost-effective technologies for in situ monitoring in data sparse areas

- Insure open, low-cost and easy access to in situ atmospheric observations. All data should be archived in a timely manner to assure their assimilation into the climate analyses

3.2.2 Data Assimilation

Global analyses for weather forecasting purposes have been produced over roughly the past two decades by operational centers such as the National Centers for Environmental Prediction (NCEP) and the European Centre for Medium Range Weather Forecasts (ECMWF). Operational analyses, however, are not well suited for climate purposes; in particular, changes implemented to improve weather forecasts (e.g., changes in numerical weather prediction models, data handling techniques, initialization, etc.) disrupt the continuity of the analyses. *Reanalyses* of atmospheric observations, using fixed state-of-the-art data assimilation systems, yield much-improved estimates of the global atmosphere free from such discontinuities. Moreover, they are not produced under operational (e.g., time) constraints so that, for instance, observations from all sources can be gathered, and the analysis at a particular time can also potentially take account of “future” observations (true four-dimensional data assimilation).

Three major global atmospheric reanalyses have been carried out to date, and a fourth is underway at ECMWF (ERA-40). These products have been of tremendous value to an impressive range of scientific studies and applications. Moreover, reanalyses will improve as CLIVAR-coordinated climate observing systems are implemented, as the science and technology of data assimilation improves, and from competition between different approaches. Global reanalysis should be viewed, then, as an ongoing program of technology and data integration.

Within the U.S., there are no firm plans to perform the next generation of global reanalyses. This issue was addressed at a recent workshop held at the University of Maryland, June 5-6 2000 (see http://www.usclivar.org/Mtg_US_Reanaly_WS_0600.html). A principal conclusion of the workshop was that global reanalyses of atmospheric (as well as land and oceanic) data should be institutionalized, and reanalyses should be carried out roughly every 10 years. This is the time scale during which major improvements in models and data assimilation aggregate, making previous reanalyses obsolete. It is important to realize that the core of such a program is not the production effort itself, but the necessary scientific analysis and technology development, as well as the continual organization and archival of observations, that will drive such production activities. US CLIVAR will focus on these activities as part of an ongoing, iterative process to improve climate data sets.

One of the biggest challenges of direct relevance to CLIVAR is to develop new technologies that better address climate-specific issues and, thus, yield better estimates of longer-term climate variations, as opposed to those of most relevance to numerical weather prediction. Climate model biases, observing system biases and inhomogeneities, handling of changes in observing systems, physical consistency of budgets, and improved estimates of physical processes are examples. Deficiencies in clouds, precipitation and surface fluxes are shortcomings that have been highlighted in the past, as they have limited the utility of current reanalysis products. Other issues, such as improved gravity-wave parameterization schemes and increased spatial resolution, are also important for a number of applications. These aspects are discussed in more detail in the aforementioned reanalysis workshop report.

One of the largest activities in reanalysis is the organization of the input data base. The assembling and organization of the data itself is an extremely valuable activity for climate studies. These data, as well as the analysis products and the information on the acceptability and possible biases in the observations, need to be freely and openly available and easily accessible to all researchers in order for them to contribute in a significant sense to the success of CLIVAR.

3.3 Short duration regional and process studies

A number of process experiments and regional studies will likely be required to fully understand Atlantic climate variability. There are special regions where ocean-atmosphere-land coupling seems to be high, where interactions between ocean basins are not well quantified, and where key mixing processes are not well understood. The basin-wide observations will not be adequate to address these uncertainties.

In the Atlantic, the community (Visbeck et al. 1998; Joyce and Marshall 2000) has initially expressed interest in three regions: air-sea interactions along the North Atlantic storm track; atmosphere, ocean and land interactions between the tropical North Atlantic and the Amazon; and fresh water fluxes between the North Atlantic and Arctic Oceans.

These studies, which are not mentioned at the exclusion of other possible studies, are envisioned to be investigator planned , as opposed to nationally planned studies such as ACVE. The Atlantic Sector Implementation Panel and the US CLIVAR SSC will review them on their potential to improve the overall understanding, parameterization and treatment of key processes in predictive climate models. Special attention will be paid on readiness to accomplish the goals and cost-effectiveness.

4. Data analysis, modeling and theory

The overarching question of the Atlantic CLIVAR program is, in what ways does coupled atmosphere-ocean dynamics in the Atlantic sector play an active role in climate variability? A primary goal is to quantitatively test and improve our understanding of mechanisms and models of atmospheric and ocean processes that lead to climate variability in the Atlantic and its global consequences. Parameterizations of key processes in models must also be improved: it is the only hope to improve the coupled-GCM climate predictions that are widely taken as the scientific consensus. 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, their representations of sea-ice, clouds, deep and shallow convection etc., is a central part of Atlantic CLIVAR.

A key question that pervades much of the discussion of the role of the Atlantic Ocean in climate variability is the sensitivity of the middle-latitude atmosphere to changes in surface boundary conditions, including SSTs and sea ice, snow cover, and soil moisture. WETS, the Workshop on Extra-Tropical Sea-surface temperature anomalies addressed some of these issues, and made significant progress in extracting the robust results from two decades of experiments in which AGCMs were forced with prescribed SST anomalies. The recommendations from the workshop provide the basis for many of the modeling recommendations in this section.

Additionally, variability in the middle latitudes (e.g., the NAO) is tied to SSTs over the tropical oceans, including the tropical Atlantic. Variations in the tropical Atlantic are substantial and involve strong interannual and decadal variations of meridional SST gradients. Such variations, which affect the local Hadley circulation, potentially modulate North Atlantic atmospheric variability through an atmospheric bridge mechanism akin to that acting over the Pacific.

Observations suggest that the atmosphere may be most susceptible to the influence of the ocean in early winter rather than the middle of winter. Therefore, atmospheric simulations are needed in which seasonally evolving SST anomalies are imposed under an atmospheric model with a realistic seasonal cycle. Preliminary modeling results indicate that the response to anomalies in sea-ice extent, for example along the Greenland Coast, may be as strong or stronger than that to SST anomalies. More experiments are needed to look at the atmospheric response to sea-ice anomalies, and, since SST and sea-ice anomalies do not occur independently in nature, experiments are needed using physically reasonable combinations of sea ice and SST forcing. Key analyses for these simulations include the vertical structure of the atmospheric response, comparisons of the response structure with that of the model's internal variability, quantitative estimates of the signal-to-noise ratio of the response, and analyses of the role of the storm track.

While atmosphere-only simulations are useful for studying the dynamics of the atmospheric response, they fundamentally misrepresent the nature of extratropical air-sea coupling. In the extratropics, at most places and times, atmospheric forcing creates SST anomalies, so that heat fluxes into the ocean are positively correlated with the SST, the opposite of what happens in uncoupled experiments. Thus, a program of experimentation with coupled models is needed. This program should include:

- Experiments that directly address the influence of variations in extratropical SSTs on the predictability of the coupled system. Such simulations should involve large ensembles and be carried out with a hierarchy of representations of the ocean, from simple slab mixed layer models to mixed layer models with prognostic mixed-layer depths, to full dynamical oceans.

- Experiments to address the connections, suggested by recent observational analyses, between SSTs in summer and the state of the atmosphere in the following winter, and between the SST in the winter and the atmospheric state in the following spring.

- A similar hierarchy of coupled model experiments to address the interactions of the extratropical ocean with tropical forcing. Because there are invariably phase errors in the modeled atmospheric response to tropical SST anomalies, it is unlikely that the responses to tropical and extratropical SST anomalies will be aligned correctly in a model when the global SST field is prescribed. This points towards a need for more experiments in which tropical Pacific or Atlantic SSTs are prescribed, but SSTs elsewhere are simulated.

- The analysis of long control integrations of coupled atmosphere-ocean GCMs. These models can provide a much longer record of the coupled system than is available from observations. Such integrations are being carried out at a few climate research centers as controls for greenhouse gas simulations. The results from such runs should be analyzed for evidence of extratropical ocean-atmosphere coupling, and the dynamics of such interactions then diagnosed using uncoupled models. Comparisons of such analyses with observations would provide useful input to the anthropogenic climate change community regarding the reliability of the internal variability in their models.

- Recent observational analyses and atmospheric model experiments suggest the NAO extends from the ocean up to the wintertime stratospheric polar vortex. This possibility demands that, despite the high computational cost, we conduct experiments, both with and without anthropogenically altered trace gases, with coupled atmosphere-ocean models in which the atmosphere includes a well-resolved stratosphere.

Finally, continued analysis of historical instrumental and proxy data records is an essential component of Atlantic CLIVAR. 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.

5. Predictability

One of ultimate goals is to develop a forecast system for predicting climate fluctuations in the Atlantic sector. Modeling studies will be critical in understanding the predictable dynamics and determining the intrinsic predictability limit of climate variability in this region. To fully explore the predictability of climate in the Atlantic sector close collaboration with prediction agencies, such as NCEP, are required. The goal is to develop fully coupled prediction systems in coordination with the SIMAP panel/working group.

5.1 Tropical Atlantic

Of particular importance is the predictability of tropical Atlantic SSTs and the extent to which they can impact seasonal rainfall forecasts in the region. The requirement of accurate initial conditions means that ocean data assimilation will be an integral part of this effort. Enhanced sustained observations, such as PIRATA, will be crucial in improving and constraining coupled models and developing a predictive system in the tropical Atlantic sector.

5.2 Trend in the NAO

It has been suggested that increasing levels of CO_2 and lower levels of ozone are responsible for the strengthening of the northern stratospheric vortex. This could lead to a strengthening of the tropospheric jet stream and hence be one cause the observed trend in the NAO. If correct this would provide a means to predict some aspects of the NAO over the next decades. Similarly, recent model experiments point toward tropical SST forcing of the NAO on decadal time scales, which could also enhance predictability.

5.3 Reduction of the MOC

The potentially large societal impacts of a rapid climate shift warrant some investment into studies to investigate the possibility of MOC predictability. This is largely unexplored territory and might strongly depend of the success of an initial MOC observing system.

6. Programmatic context

Atlantic CLIVAR will provide real time assessments of the state of the Atlantic Ocean in relation to climatic variations of the atmosphere and their impacts on land. These will be of great utility to research programs that 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 on-going or planned programs. These are summarized below.

- The international CLIVAR Program. An important objective of both the Global Ocean Atmosphere Land System (GOALS) and Decadal to Centennial Climate Variability (DecCen) 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, Atlantic CLIVAR directly addresses these CLIVAR program goals. The program combines into a coherent effort the elements (D1-D3) of the International CLIVAR program that deal with the Atlantic Sector. By so doing, it is hoped that a more natural and focused study will result.

- GODAE. 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. The World Climate Research Program (WCRP) has received this study enthusiastically. 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 will foster a global profiling-float network, ARGO, as part of its sustained subsurface ocean observing system. The motivation for the Atlantic sector of this observing system is given here.

- PIRATA. The International Pilot Research Moored Array in the Tropical Atlantic (PIRATA) will maintain an array of surface moorings in the equatorial Atlantic (see Section 3.1.2). This observing array should provide the basic, direct observations necessary to test the hypotheses for TAV, and the data will help guide planning for an augmented array. Thus, Atlantic CLIVAR recommends its continued support.

- PACS. The Pan-American Climate Studies program (PACS), the US component of Variability of the American Monsoon Systems (VAMOS), aims to improve the skill of operational seasonal-to-interannual climate prediction over the Americas, with an emphasis on forecasting warm season rainfall. Focal points include the relationship between boundary forcing and climate variability, and processes governing SST variability in the tropical Atlantic and Pacific.

- WOCE AIMS. The World Ocean Circulation Experiment (WOCE) has entered 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 planning and final design of Atlantic CLIVAR. The analysis phase of WOCE will also provide the opportunity to inspect the historical and WOCE records in the light of the Atlantic CLIVAR 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, and 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 to Atlantic CLIVAR.

- PAGES (Past Global Changes). PAGES is the International Geosphere-Biosphere Program project charged with providing a quantitative understanding of the Earth's past environment. Long proxy records of climate variability in the Atlantic sector will come out of the PAGES-CLIVAR intersection, which will contribute to Atlantic CLIVAR goals.

- GLOBEC (Global Ecosystem Dynamics). International GLOBEC, now an official part of the International Global Biosphere Program (IGBP), is engaged in planning for the Small Pelagics and Climate Change (SPACC) program. Involved countries include Japan, the US, 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 Atlantic CLIVAR.

- SEARCH. A US program developing in parallel with US CLIVAR, Study of Environmental Arctic Change. Because of the importance of freshwater export from the Arctic to the Arctic Ocean, it is important that planning for this program be linked to Atlantic CLIVAR.

- US Carbon Cycle Science Initiative. The carbon cycle science initiative has as one of its goals to quantify and understand the uptake of anthropogenic CO_2 in the ocean (http://www.carboncyclescience.gov). There are obvious connections to CLIVAR goals and good coordination in particular with regards to shared observational platforms is imperative.

- SPARC. The WCRP initiative Stratospheric Processes and their Role in Climate will contribute to a better understanding of the stratospheric climate, including the links between this region and the troposphere. Some in the scientific community believe stratospheric processes contribute to tropospheric variability, largely in the form of the NAO over the Northern Hemisphere. A better understanding of this link is crucial for the success of Atlantic CLIVAR activities.

7. Timeline

Atlantic CLIVAR is expected to last about a decade. Starting in 2001 the observing system and modeling capabilities will build and the full scale will be reached by 2003. The period between 2003 and 2005 overlaps with the demonstration phase of GODAE and, thus, needs to be met.

Starting about 2003 a series of focused regional studies, each lasting about 2-5 years (Section 3.3) is anticipated.

8. Cost estimate

- Throughout the lifetime of Atlantic CLIVAR empirical studies in the atmosphere and ocean need to be supported. The anticipated level is $3-5 million per year.

- Profiling floats, as proposed under ARGO, will cover a large fraction of the required float effort in the Atlantic. Certain regions, however, may require enhanced resolution for a shorter period of time at an anticipated funding level of $0.5 million per year.

- Upgrades to XBT lines would need funds on the order of $1 million per year. It is hoped that this cost will be shared with the emerging GOOS and GCOS efforts.

- Additional surface flux sites, plus upgrades to IMET sensors of some VOS vessels, will require about $2 million per year.

- Upgrades to two existing time series hydro stations, plus a new station, will require about $1.5 million per year.

- Transport moorings might be needed for a few years in one or two places, at an anticipated cost of about $1.5 million per year.

- The annual cost for new hydrographic sections will be about $1 million per year.

- About $1 million per year is anticipated to help support the maintenance and/or reestablishment of atmospheric soundings especially over parts of South America and Africa.

8. Appendix:

Recommended Sustained Ocean Observations for US contribution to Atlantic CLIVAR

Observation type	**Comments**
Satellites	Altimeter Wind Stress SST
Floats (ARGO)	Large scale (South and Tropical Atlantic mostly), 280 floats Augmentation in the subpolar gyre/Labrador Sea
XBTs	Coarse resolution: continue until ARGO fully operational High Resolution: increase on 5 lines in the Atlantic
Surface Drifter	Improve satellite SST fields. 150 drifters over 4 years.
Hydrography	4 hydro lines to be done at 5-10 year intervals, start 2003
Hydro Moorings	1 new (south of New England) 2 upgrades in support of continuing work in Labrador Sea & Bermuda
Surface Flux Moorings	4 sites: Tropics, Azores, in shore of Gulf Stream
VOS upgrades	All HR XBT lines to have IMET systems & thermosalinographs
Mooring Arrays	PIRATA to continue in tropics. For extratropics, no definite plans, but priority should be given to 2 possible phenomena: the DWBC and freshwater flux from Arctic

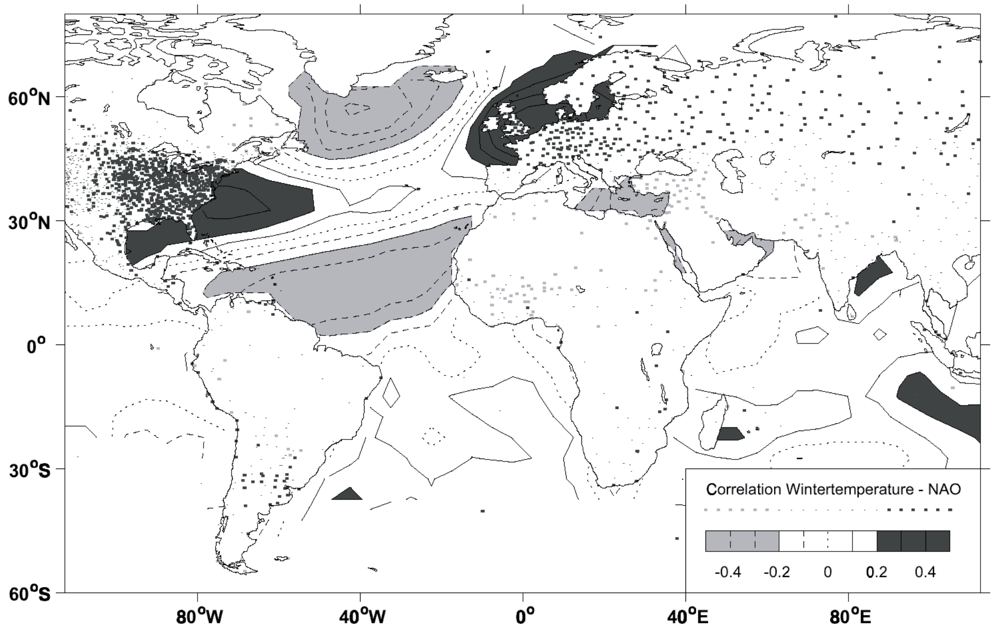

Figure 1. Regression between winter SST and land surface temperatures and the NAO index showing the tripole (courtesy of M.Visbeck and H. Cullen).

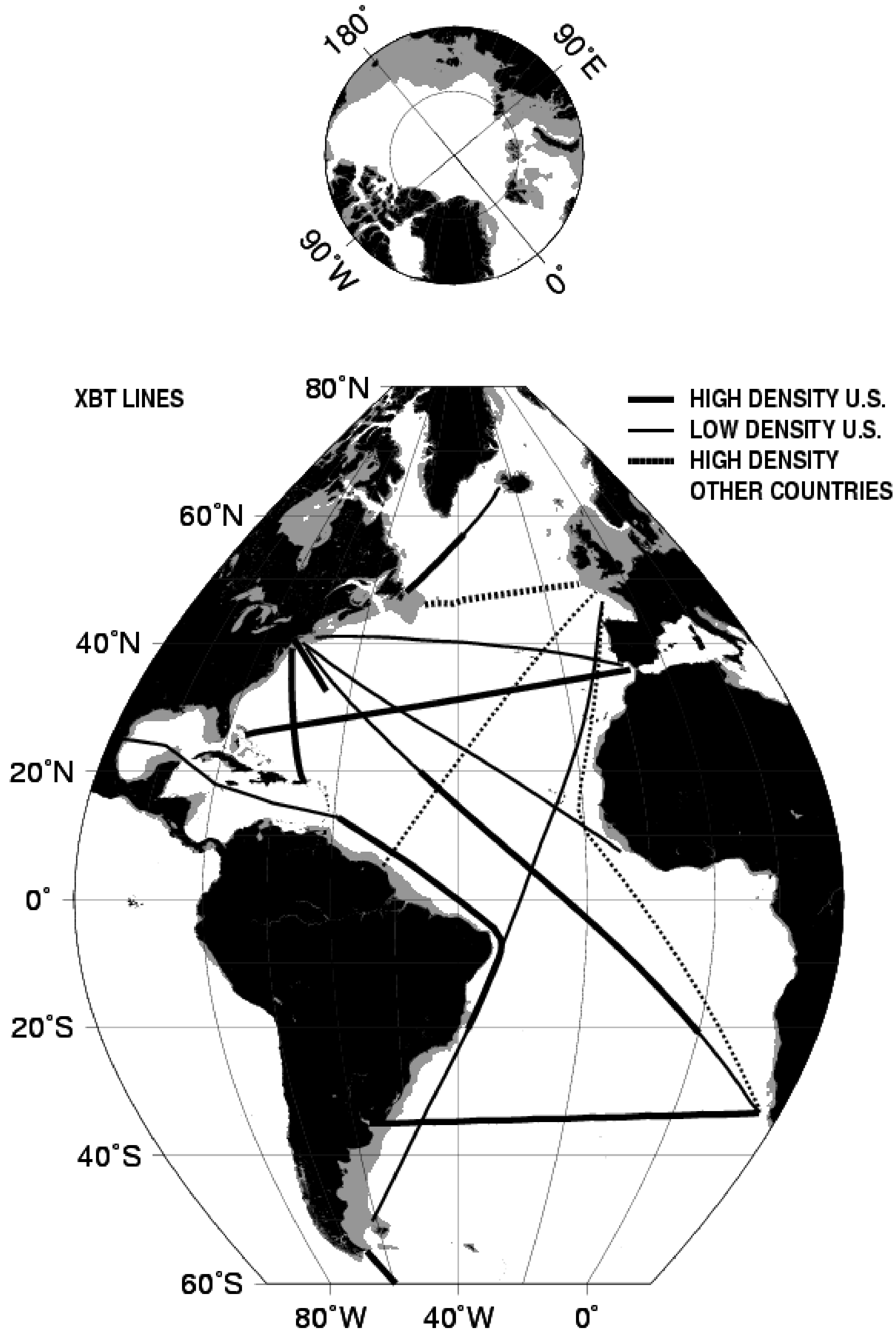

Figure 2: Atlantic XBT lines to be considered for Atlantic CLIVAR. Possible U.S. lines are in solid lines with thick lines for high resolution sampling and thin lines for low-resolution.

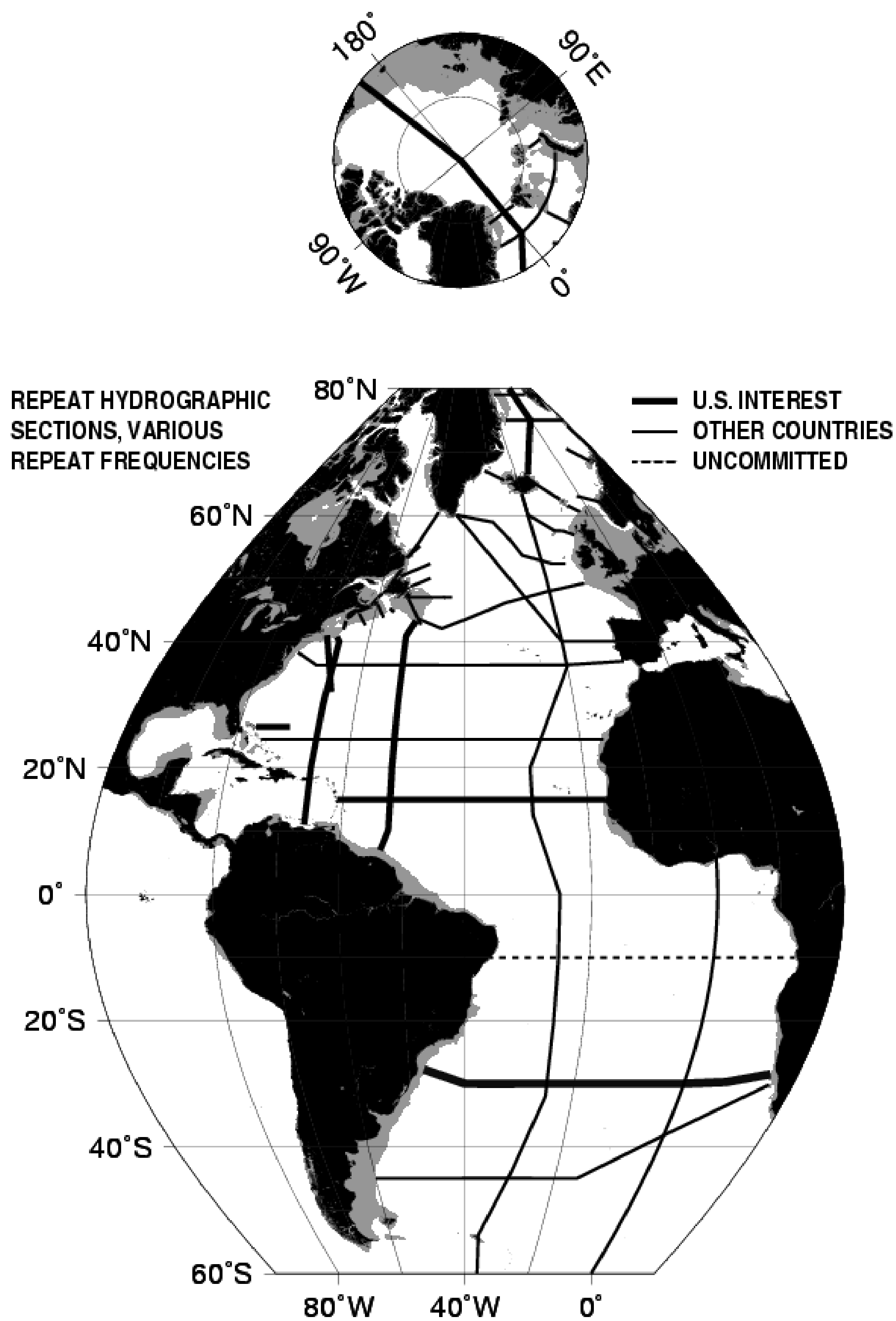

Figure 3: Repeat hydrographic lines under consideration for Atlantic CLIVAR. Thick solid lines are possible U.S. contributions, thin lines are non-U.S. while dashed lines represent 'uncommitted' sections.

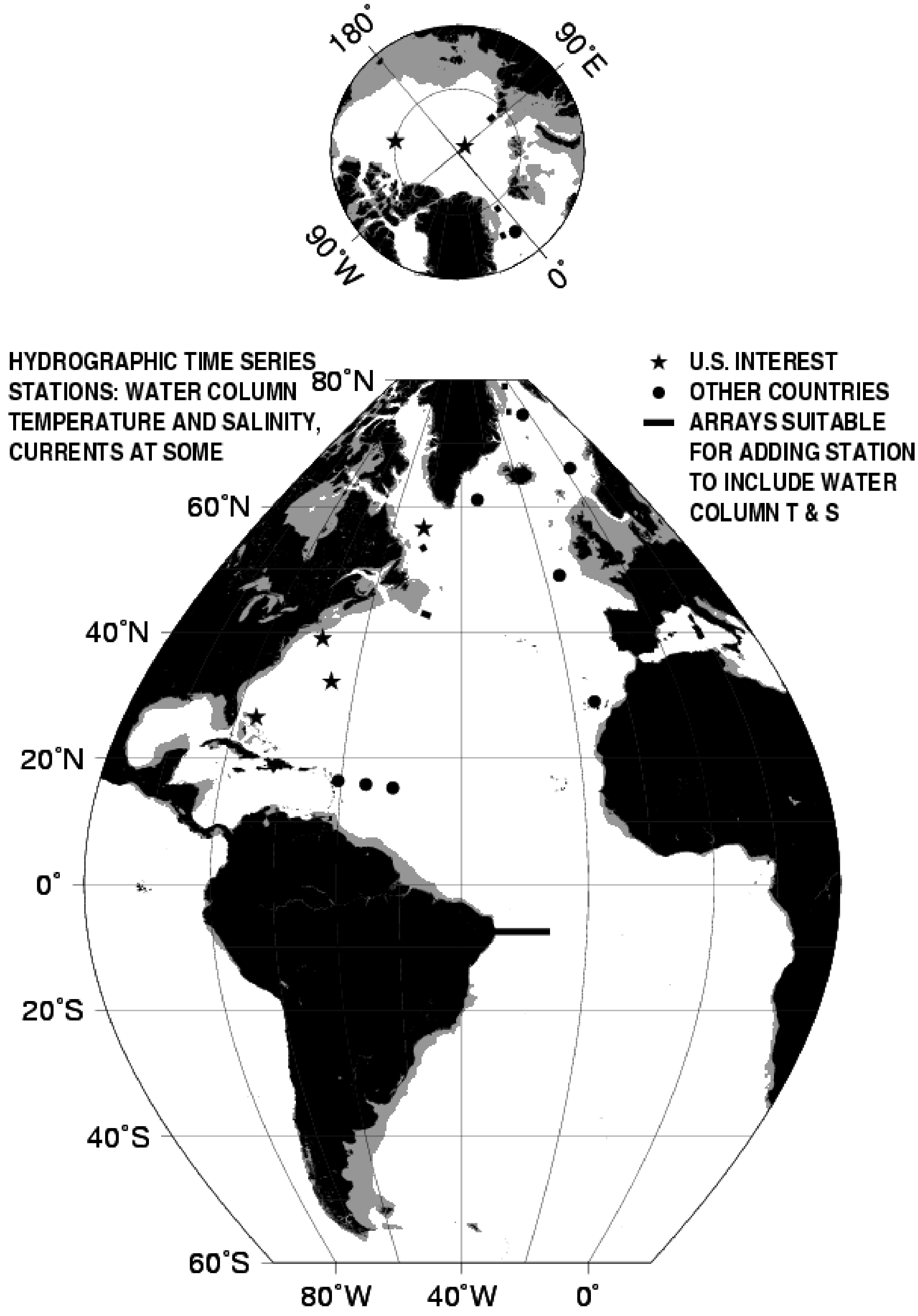

Figure 4: Hydrographic time series sites that are possible U.S. contributions to Atlantic CLIVAR are shown as stars while non-U.S. sites are solid dots. Short line segments represent moored arrays of instrumentation already underway or planned by non-U.S. groups.

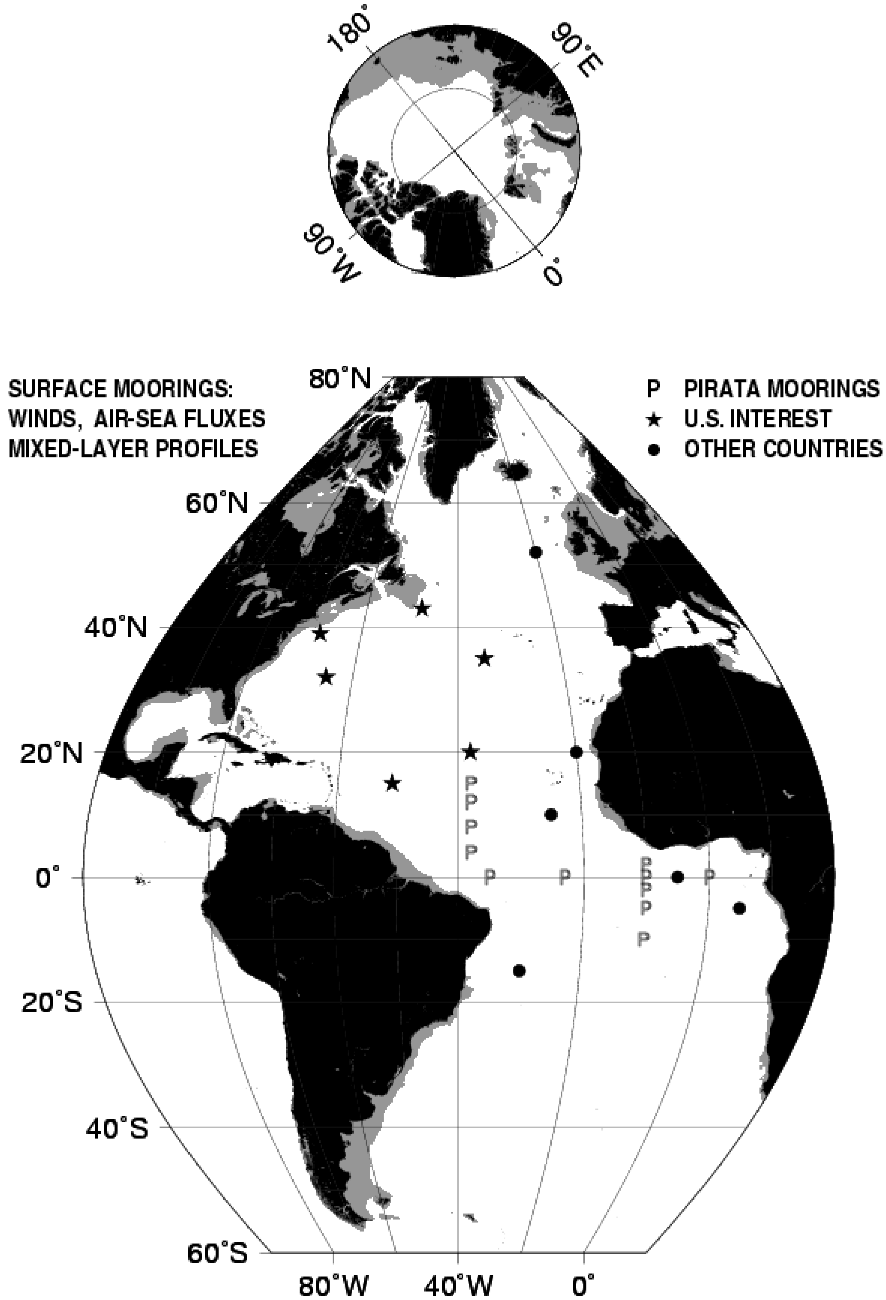

Figure 5: Surface moorings in the Atlantic during CLIVAR. The present PIRATA array is shown as well as additional surface moorings including possible U.S. sites (stars) and non-U.S. sites (solid dots). U.S. enhancements of PIRATA are mainly to provide improved surface meteorology flux reference sites and near-surface measurements in the water column.