ATLANTIC CLIMATE VARIABILITY (ACVE)

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ABSTRACT *- 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 with a myriad of well documented impacts on society and the environment. 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 understanding of mechanisms and models of atmospheric and ocean processes that lead to climate variability in the Atlantic and its global consequences. 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 meteorologist and oceanographers that last a decade or longer.*

1 - INTRODUCTION

Studies of Atlantic climate variability are becoming a central focal point for climate research for the next decade. Scientist in both Europe and the United States are beginning to coordinated observational, modeling and theoretical efforts focussed on Atlantic climate variability as central elements to WCRP’s CLIVAR program. We anticipate a major advancement of our current understanding of Atlantic Climate Variability, leading to a) a possible development of a climate forecast capability in the tropical Atlantic; and b) development of an observing system to monitor changes in the thermohaline circulation.

Climate variability in the Atlantic Sector comprises three major, possibly interrelated phenomena: The North Atlantic Oscillation (NAO), - a fluctuation in sea level pressure difference between the Icelandic Low and the Azores High; Tropical Atlantic Variability (TAV), - a covarying fluctuation of tropical SST and trade winds straddling the ITCZ; and changes of the Atlantic Meridional Overturning Circulation (MOC), - fluctuations in the Atlantic ocean's thermohaline circulation which may play a role in abrupt climate change.

The North Atlantic Oscillation (NAO) is an atmospheric mode of variability associated with changes in the strength and pathways of winter storms crossing the Atlantic from the North American seaboard to Europe. It is the major factor controlling air-sea interaction over the Atlantic Ocean and modulates the site and intensity of the sinking branch of the ocean's thermohaline circulation, the MOC. The NAO also seems to play a central role in real or perceived anthropogenic climate change. Understanding of the NAO and its time-dependence appear central to three of the main questions in the global change debate: has the climate warmed, and if so why and how? Its impacts on land are relatively well documented and of relevance to the economies of countries on both sides of the Atlantic. The NAO is closely related to the Arctic Oscillation (AO), which can be thought of as a more zonally symmetric version of the NAO with the possibility of a coupling to the stratosphere. However, we have not (yet) been able to predict any aspects of the NAO and are just beginning to understand the underlying dynamics. One of the central questions is the interaction between the upper ocean and the atmosphere in the extra-tropics. Improved understanding of this process may very well hold the key to some form of predictability for the NAO. What is needed is an international effort to observe the interactions between the upper ocean and lower atmosphere in combination with diagnostics of historical data and theoretical and numerical experiments.

Tropical air-sea interactions have been shown to generate large scale climate variability in the Pacific. The basin geometry and presence of a mean cross equatorial oceanic heat flux results in a different tropical mode of variability in the equatorial Atlantic. Changes in the cross equatorial sea surface temperature gradient can trigger a positive feed back in the trade wind strength of both hemispheres. This in turn effects the mean position of the atmospheric inter tropical convergence zone (ITCZ) which dramatically influence the location and amounts of rainfall. What is less clear is how the initially positive feedback is destroyed and one typically appeals to changes in the upper ocean heat content and ocean dynamics. Variability in the rainfall of northeast Brazil correlates strongly with this inter-hemispheric SST anomalies in the tropical Atlantic. Rainfall in subtropical West Africa also displays considerable dependence on the inter-hemispheric SST anomaly. Furthermore, Atlantic equatorial SST anomalies appear to have a significant impact on anomalous rainfalls in the Guinea coastal region. It is expected that during CLIVAR we will enhance the upper ocean and air-sea flux observations in the tropical Atlantic. Some recent climate model experiments have suggested that tropical Atlantic variability (TAV) may be able to influence the phase of the NAO via an atmospheric teleconnection. The reverse might also be true due to NAO driven changes in the oceanic tropical-subtropical heat exchange.

Finally, there is some concern that increasing levels of greenhouse gases in the atmosphere might cause dramatic change in the strength of the oceanic overturning circulation. Under present conditions the Atlantic ocean carries about half of the total northern hemispheric equator to pole heat transport via a vigorous overturning circulation (MOC) unequaled by any of the other oceans. A reduction by only 30% would trigger changes in the climate of North America and Europe which we have not seen since the last ice age. The oceanic overturning also allows the Atlantic to be the largest ocean sink of anthropogenic CO2. A reduction in the overturning strength will reduce the oceanic CO2 uptake and might cause an even stronger climate response to anthropogenic CO2 emissions. We need to pioneer strategies to monitor the Atlantic overturning circulation. One would hope that such a system would enable us to give early warning signs for dramatic climate change and, at the same time, allow to monitor oceanic CO2 uptake as an important part of the global CO2 budget.

2 - A PROPOSED RESEARCH PROGRAM

During the last decade progress has been made to describe and understand aspects of individual mechanisms that contribute to each of the three phenomena, however it remains largely unclear if and how these modes of Atlantic Climate Variability are connected to each other. As a contribution to the World Climate Research Program on Climate Variability and Predictability (CLIVAR) we propose a focussed Atlantic Climate Variability Experiment (ACVE). The planning is well underway with input from several workshops on both sides of the Atlantic (http://www.ldeo.columbia.edu/~visbeck/ACVE). Its specific objectives are to:

- Describe and model atmosphere-ocean interactions in the Atlantic sector, quantify their influence on the regional and larger scale climate system, and investigate predictability.

- Assemble quantitative historical and real time data sets 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 a broad-scale study of the entire gyres or basins in the context of the global atmosphere; other topics can be examined in focussed 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. This yields several key elements of the basin scale ACVE: - analysis of historical and proxy data, - basin scale observational networks, - modeling, theory and state estimation (data assimilation), - process studies embedded in the observational networks (Fig. 1).

For the purpose of this position paper we only elaborate on the basin scale observational network needs.

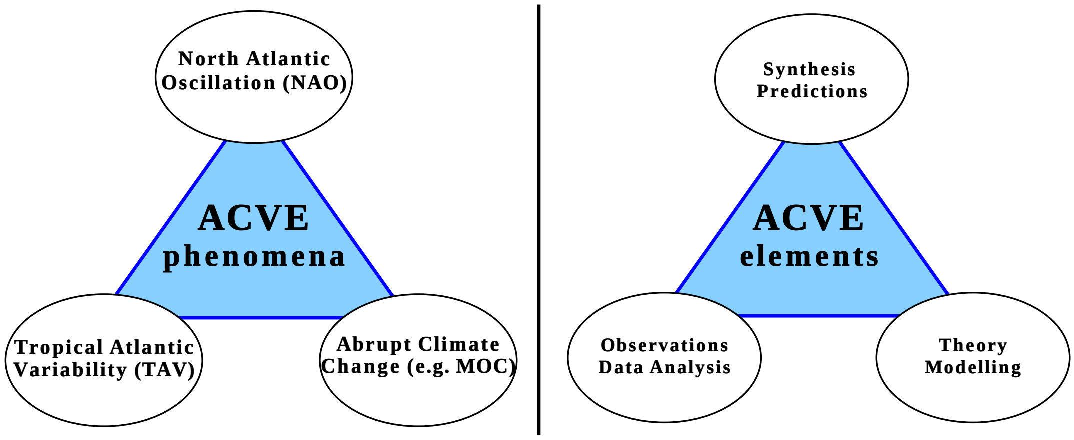

Fig. 1: Elements of an Atlantic Climate Variability Experiment

3 - SUSTAINED OBSERVATIONS IN THE ATLANTIC SECTOR

Two categories of measurements are needed to form the observational basis of ACVE:
(i) sustained, Atlantic-wide observing systems in the atmosphere, ocean and surround land; and
(ii) shorter-term enhanced pilot monitoring 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 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 and momentum flux, and establish the atmospheric and oceanic processes that determine it. It is imperative 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.

For convenience we discuss the observational requirements for an upper ocean observing system separately from those for the MOC. Together they will form the observational basis for oceanic state estimation efforts in close collaboration with the U.S. NOPP nodes and GODAE.

3.1 - Upper 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 in combination with an existing in situ network. 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 in near real time. 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. However, ice thickness is also needed to estimate freshwater fluxes.

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 extra buoys (Figure 3.1) 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 (ARGO), 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. 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 Subtropical Convergence Zones. 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 subpolar 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 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. 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 60N should contribute valuable information on subpolar exchanges with the Nordic Seas. Some technical issues must also be addressed. In the subpolar 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 subpolar North Atlantic, and as reference data for floats and remote sensing instruments globally; the use of thermosalinographs on volunteer ships should have high priority.

- *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 outbreaks over the western North Atlantic. Improved instrumentation (which is being developed both in the US 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. One station near the eastern boundary might be part of the PIRATA array; its western counterpart should be located close to the boundary (e.g., near the Lesser Antilles). Other stations are under consideration for observing the temporal evolution of heat content and water mass properties in association with the PALACE array, and/or providing baroclinic transport time series for key advection elements in the subpolar and subtropical domains. Expansion of the time series network into the South Atlantic should be considered.

-*Flux monitoring systems*: At key sites, direct measurements of ocean currents are 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 (for example by telephone cables) 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.

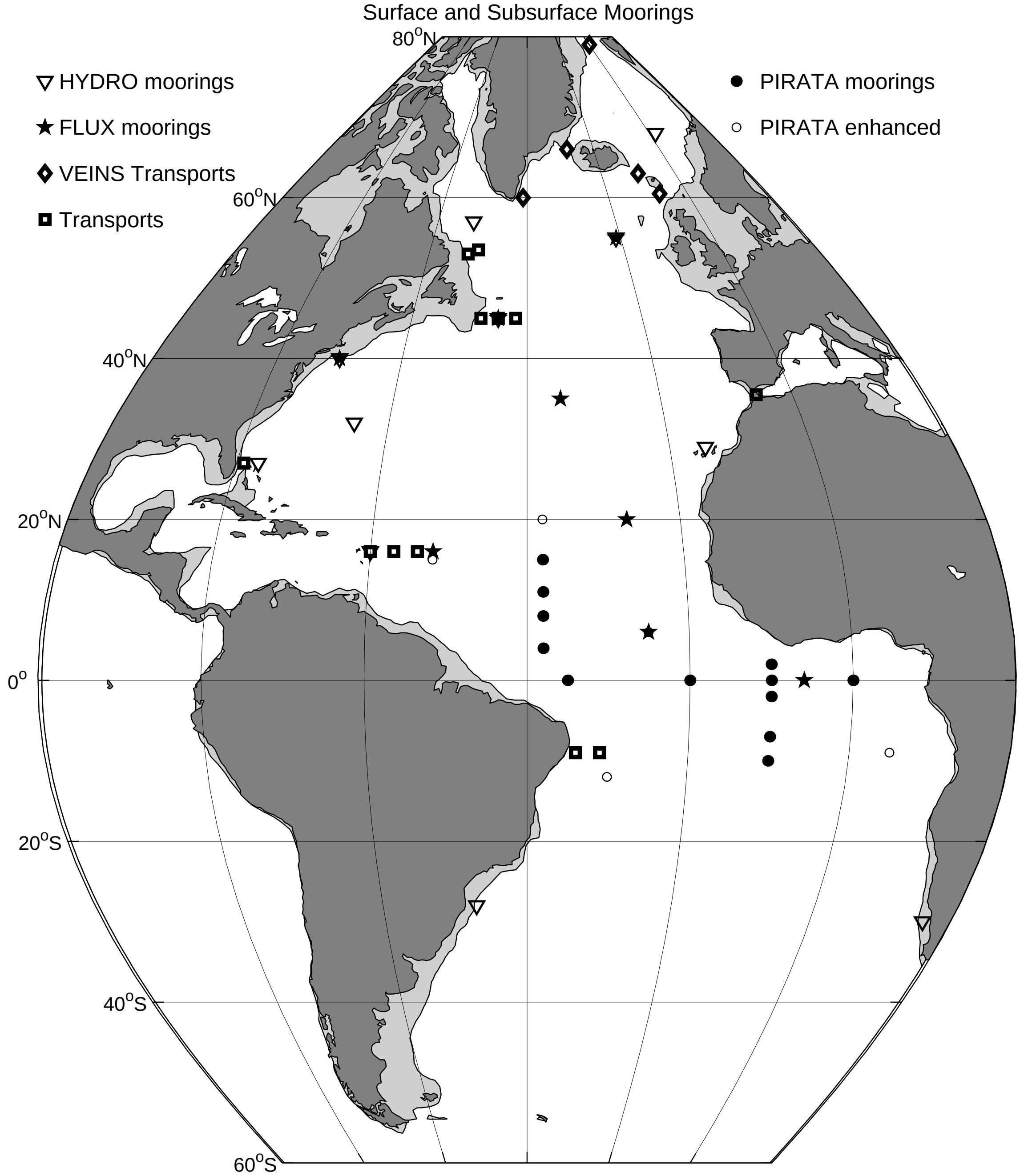

Fig. 3.1: A strawman ACVE mooring network. Shown are the present PIRATA surface mooring array in the tropics and its possible enhancement, potential buoy reference stations for improving air-sea flux estimates, current and proposed hydrographic time-series stations to be instrumented with autonomous systems, and sites where transport monitoring arrays might be located.

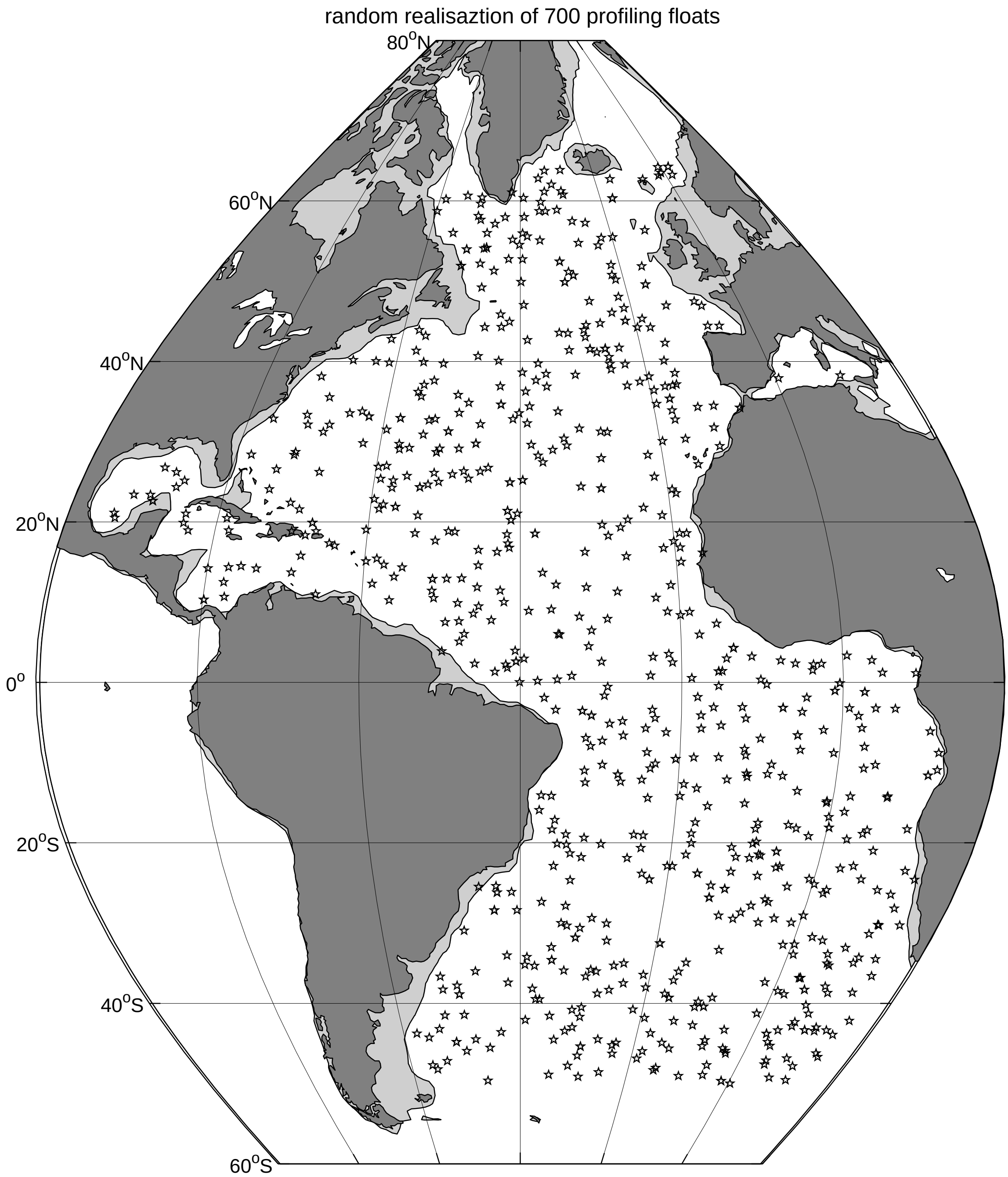

Fig. 3.2: A random realization of a 700 profiling float network. Design studies are needed to determine the number and regional distribution of an efficient float network for ACVE.

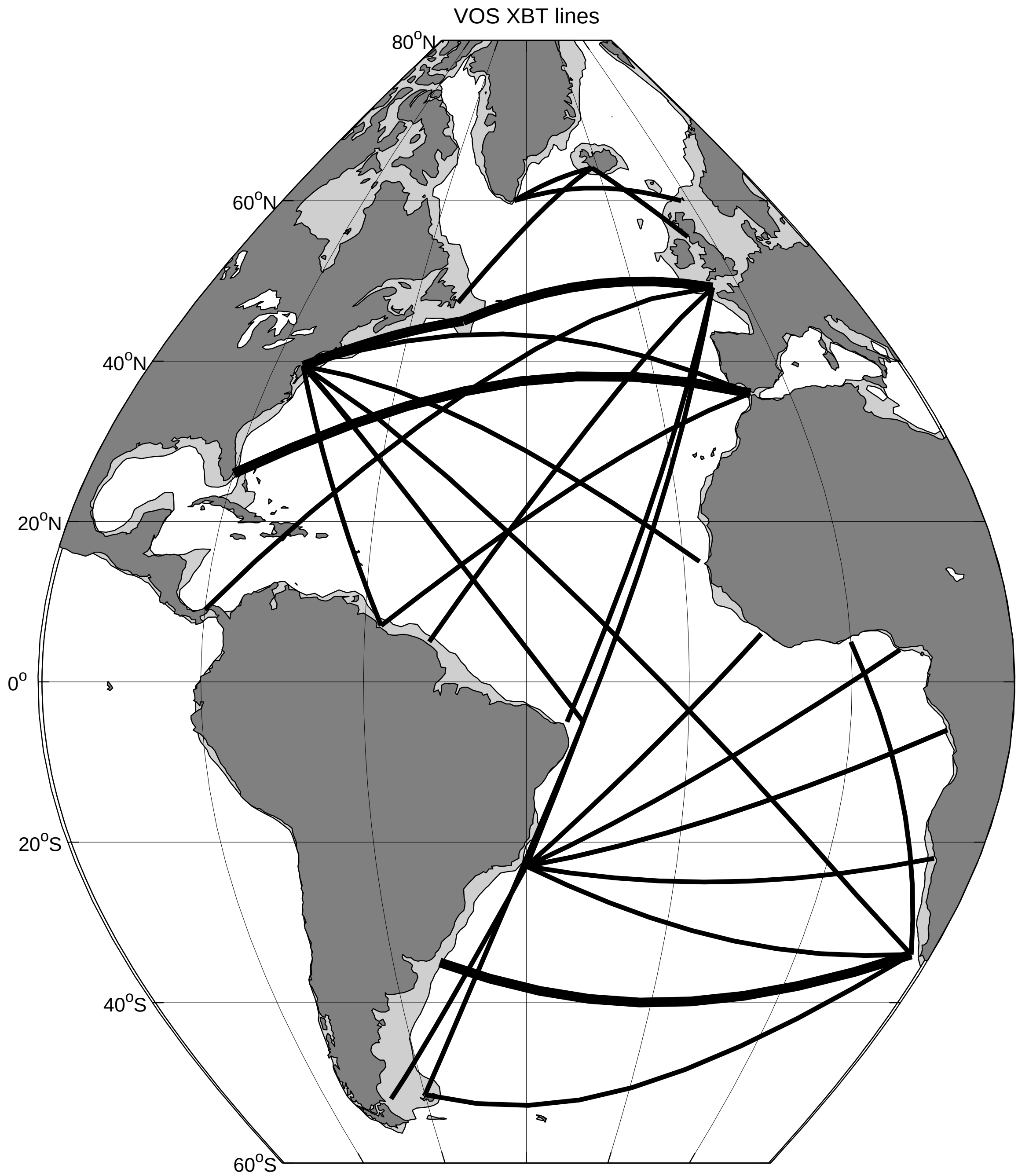

Fig. 3.3: The present XBT/VOS network developed under WOCE, TOGA and ACCP/ACCE. High-density lines are marked with bold lines, low-density with thin. Design studies are recommended for determining the optimal mix of high- and low-density XBT lines within ACVE in light of the proposed profiling float array, remote sensing tools, and the envisaged network of Eulerian stations.

-*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 becomes an important process. A basin-scale measurements of upper-ocean circulation in the tropical Atlantic has just begun. 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, 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 Nino-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. 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.

3.2 - 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 48N 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 acontribution to GOOS every three years. Other potential sections for repeat top-to-bottom hydrographic coverage, possibly combined with moored boundary arrays, are shown in Fig. 3.4 and should include:

- near 25N, close to the heat transport maximum, where considerable prior knowledge on the variability has been built up.
- 10S, to measure the combined effects of the shallow tropical cell (STC) and the top-to-bottom MOC
- 30S, 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 52W longitude, which would repeat measurements that extend back as far are 1950’s, 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_2 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 needs to determine the sampling frequencies of the zonal lines required to quantify variability in the Atlantic MOC and associated meridional transports.

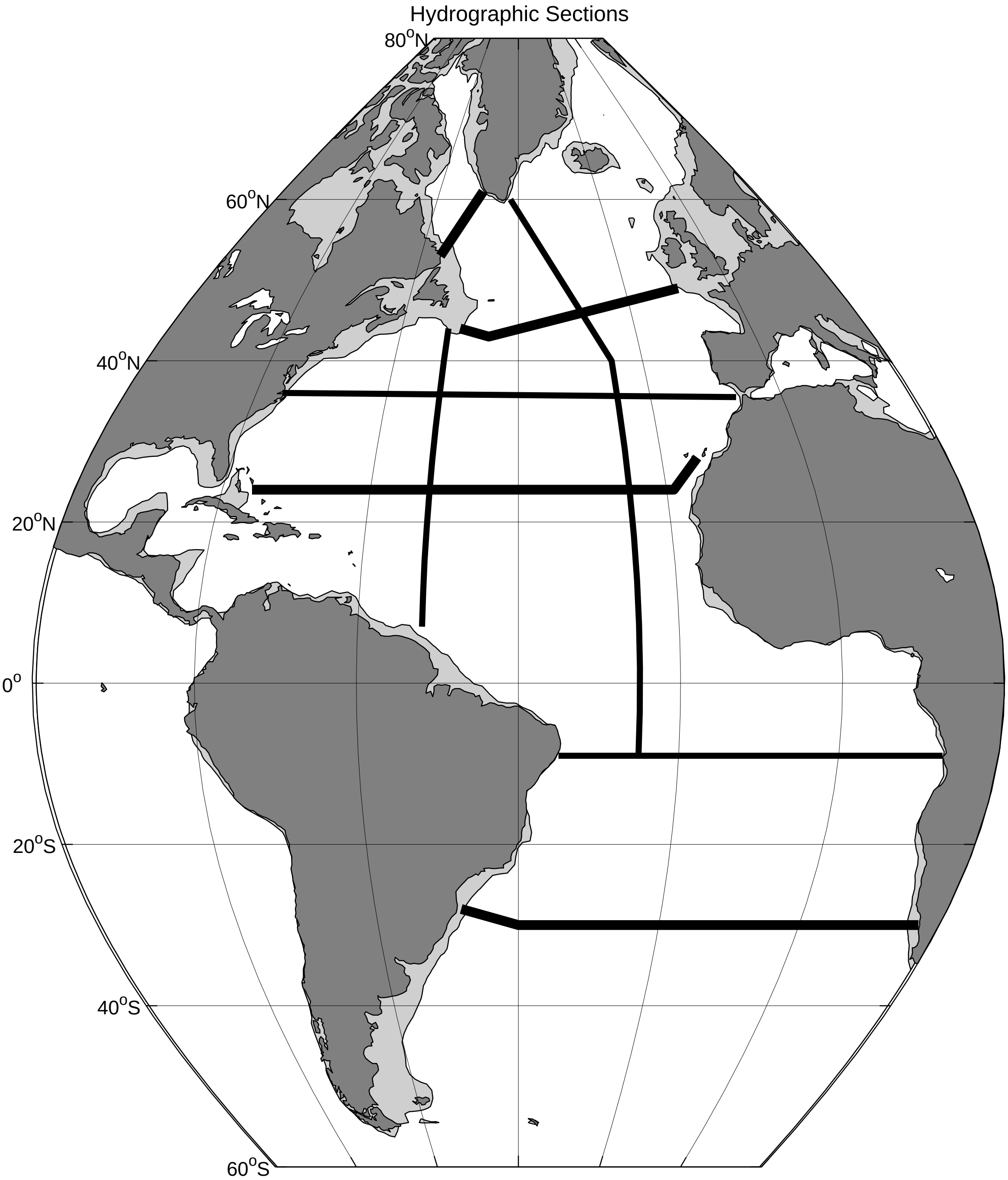

Fig. 3.4: A schematic drawing of a potential ACVE repeat-section program. Hydrographic and tracer properties would be sampled on these lines on an interannual time scale to quantify net changes in water mass properties and heat content. Thick lines should be repeated more often.

4) PROGRAMATIC CONTEXT

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. In particular, an active program in data-model synthesis will be a central 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 been established, these analyses will serve as the initial conditions for forecasts of the coupled system.

In the U.S., two new activities were sponsored by the National Ocean Partnership Program (NOPP) to bring ocean state estimation from its present experimental phase into a more mature and semi-operational form. One of those "nodes" is a consortium between JPL, MIT, and SIO, on "Estimation of the Circulation and Climate of the Ocean" (ECCO) which builds on a number of assimilation efforts are already underway. Within the next two years a full assimilation capability will be developed by which all available in-situ and remotely sensed data will be part of the estimation system.

An active program such as ECCO will be a component of ACVE to both help plan it and to interpret the observations. It is likewise 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.

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

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 on-going or planned programs such as GODAE/GCOS/GOOS as highlighted in this position paper; PIRATA and PACS for enhanced monitoring of the tropical Atlantic; WOCE AIMS for input on the design of an pilot array to observe variability of the MOC; ACSYS to improve our understanding of the role of Arctic processes. We are also establishing connections with the CO2 community to asses joint observational needs.