COSTA

A Climate Observing System for the Tropical Atlantic

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***ABSTRACT* - *This paper summarizes the discussions that took place during the COSTA (Climate Observing System for the Tropical Atlantic) Workshop held in Miami, during May 1999. The main objective of the workshop was to coordinate the present efforts in the region and to set the scientific basis for an extended and more permanent observing system. The intent of the COSTA workshop, based in the CLIVAR (global) and ACVE (basin) experience, was to formulate the basis for an extended and more permanent (regional) tropical Atlantic observing system, building on the present existing monitoring programs and process studies, and the current scientific underlayment. The first part of this paper establishes the importance and the role of the tropical Atlantic in climate fluctuations and their impact in society. This followed by a description of the climate variability in the Atlantic sector, its relationship to tropical Atlantic variability (TAV), especially sea surface temperature (SST), and to the North Atlantic Oscillation (NAO) and the meridional overturning circulation (MOC). The possible mechanisms behind tropical Atlantic SST fluctuations and their relation to climate, is also discussed, highlighting in particular the role of surface fluxes in the off-equatorial regions, the equatorial ocean-atmosphere interactions, and their relationships to movements of the Inter-Tropical Convergence Zone (ITCZ). The second part of this paper summarizes the scientific discussions and recommendations from the working groups who centered their discussions in the following themes: 1) sea surface temperature (SST) and surface fluxes; 2) sea level and subsurface structure; 3) circulation; and 4) modeling and data assimilation. Finally, the present status of the observing system and a summary of recommendations is presented.*

1- INTRODUCTION

The over-arching justification for implementing an ocean observing system in the Atlantic is the need for improved climate predictions with lead times from 1-2 seasons to 1-2 years. Much of the focus in the new climate programs -- CLIVAR, through its interanual-to-decadal subprogram (GOALS) and Atlantic-relevant components (e.g., VAMOS) -- is predicated on the notion that climate predictability can be further improved from its present Pacific-only, ENSO basis. This is to be done primarily by incorporating the effects of other ocean domains (extratropical, and non-Pacific tropics) on the atmosphere. The Atlantic is an important component of this extended dimension of climate research.

Much of the Atlantic sector climate variability is directly or indirectly associated with the tropical Atlantic, where surface temperature variability and associated changes in the winds, sea level pressure (SLP), inter-tropical convergence zone (ITCZ) and the Hadley circulation occur on interanual to decadal time scales. These covariant fluctuations are collectively called Tropical Atlantic Variability (TAV). The climate effects directly associated with TAV vary geographically from NW Africa through northern South America to Central America, the Caribbean and the southern United States. Moreover, a sizable portion of TAV is also coherent with the larger scale climate variability known as the North Atlantic Oscillation (NAO) and with the meridional overturning circulation (MOC). It is the TAV association with the latter modes of variability that account for the indirect effects of TAV on climate.

Attention to the Atlantic promises to deliver significant improvements in predictability. Recent work suggests that the tropical Atlantic both absorbs from and actively feeds back onto the atmosphere and that at the very least the TAV is responsible for additional stability, persistence and robustness in the climate signals. For example, through air-sea interaction the ocean may be responsible for modulating the phase and intensity of the NAO on decadal timescales. Externally imposed predictability also exists in the form of Pacific ENSO forcing of the tropical Atlantic SST [Enfi 97]. Modeling experiments suggest that such ENSO extensions in other ocean basins are crucial, since if they are ignored (in model forcings), the observed tropospheric teleconnection patterns associated with ENSO cannot be replicated accurately [Lau 94]. It seems clear, however, that the non-ENSO aspects of TAV are as important as ENSO itself, for land areas extending from northern Brazil through NW Africa and the Caribbean, and as far north as the southern tier of the United States [Enfi 96], [Sara 99]. In particular, [Chan 97] use statistical and coupled ocean-atmosphere models to show that the tropical North Atlantic has significant predictability with the required lead times. This predictability is internally driven, independent of the enhanced predictability expected from the Atlantic extension of the Pacific ENSO cycle, and extends to longer than interanual time scales.

Consistent with the seminal suggestion by Jacob Bjerknes that climate variations are strongly affected by changes in large-scale SST gradients, the tropical Atlantic appears to affect land climates in two fundamental ways: through meridional (cross-equatorial) gradients, and through zonal (interocean) gradients. The impact of meridional Atlantic SST gradients on rainfall in NE Brazil and NW Africa has been amply demonstrated [Mour 81], [Nobr 96], [Foll 86]. More recently it has also been shown that inter-ocean SST gradients between the eastern Pacific and tropical Atlantic have a notable effect on the climate of the Caribbean and surrounding regions [Enfi 99], [Gian 99], while we have more recently become aware of the importance of Atlantic-to-Indian Ocean contrasts on African climate (personal comms., A. Busalacchi, M. Jury).

The ways in which the TAV-related features in SSTA are generated form the crucial working hypotheses for TAV research and provide guidance for the design of an improved Atlantic observing system. In the Pacific, ocean dynamics over a relatively narrow equatorial band interact with SST through vertical mixing and zonal advection. Although this also occurs in the equatorial Atlantic, it has a shorter time scale and does not produce self-sustaining oscillations of large magnitude [Phil 86], [Zebi 93], [Dele 94]. Of greater consequence in the Atlantic are the cross-equatorial interactions over basin-scale regions at 5 to15 degrees of latitude on either side of the equator, producing the critical variations in the meridional SST gradient that control the non-seasonal displacements of the Atlantic ITCZ. In those off-equatorial regions the SST variability appears to be strongly affected by surface fluxes and (perhaps to a lesser extent) vertical mixing at the base of the mixed layer. These, in turn, are related to persistent changes in the trade winds themselves. This is true of both the externally forced ENSO variability [Enfi 97] and of the non-ENSO variability [Delw 98], [Rodw 99]. The persistence of the trade wind anomalies may result from a positively reinforced coupling between SST and winds [Cart 96], [Chan 97].

Several areas of TAV research are unresolved at present. One involves the importance of dipole configurations between the tropical North (TNA) and South Atlantic (TSA): how common are dipoles? Are they a manifestation of an internal mode of TAV, and what is the nature of such a mode? Statistical analyses suggest that the overall SST variability of the TNA and TSA regions have infrequent dipole configurations that occur no more commonly than expected by chance [Enfi 99]. However, the dipoles tend to be temporally aggregated about the interdecadal extremes of the inter-hemispheric SST difference (TNA minus TSA; [Serv 91], see Figure 1), suggesting that a mode may operate at the 8-15 year time scale. Such a mode, if it exists, is presumed to involve the thermodynamical coupling noted by [Cart 96] and [Chan 97] combined with a phase-switching mechanism (as yet poorly understood).
Another area of research involves the more dominant, random relationship between TNA and TSA. Are the largely uncorrelated warm/cold switches between TNA and TSA caused through separate external forcings by global scale climate modes, such as ENSO and the NAO? How do those forcings occur and does the tropical Atlantic feed back onto the larger scale modes?

The meridional overturning circulation is another area of inquiry. Cold water from the North Atlantic is traded by warm water from the South Atlantic with a net positive heat transported to the North making the Atlantic a unique ocean. How much heat is transported into the North Atlantic and from where? How is the upper limb of the "conveyor belt" circulation supplied? What is the role of the TAV in this process? What are the main pathways of the transports and the mechanisms that originate these transfers?

The above considerations bear on the need for, and design of, an extended and more permanent observation system in the tropical Atlantic. Participants at the May, 1999 COSTA Workshop agreed that the observing system must accomplish a number of basic things: (1) it must monitor the key processes thought to be most important in describing the tropical Atlantic role in TAV,

the NAO and the MOC; (2) it must provide a core network of ongoing observations that will be useful as a larger-scale context for conducting relevant process studies; (3) it must interact with modeling studies by providing relevant data for model-data assimilations and as verification for diagnostic and prognostic models; and (4), it must build upon the traditional and pilot observation systems that are presently in place. In order to accomplish these aims, it was felt that four working groups should examine the priority requirements for the future observing system as regards to four fundamental aspects: SST and surface fluxes; sea level and its related upper ocean thermal structure; the circulation; and modeling aspects. The next four sections deal with the results of the working group deliberations for these broad categories.

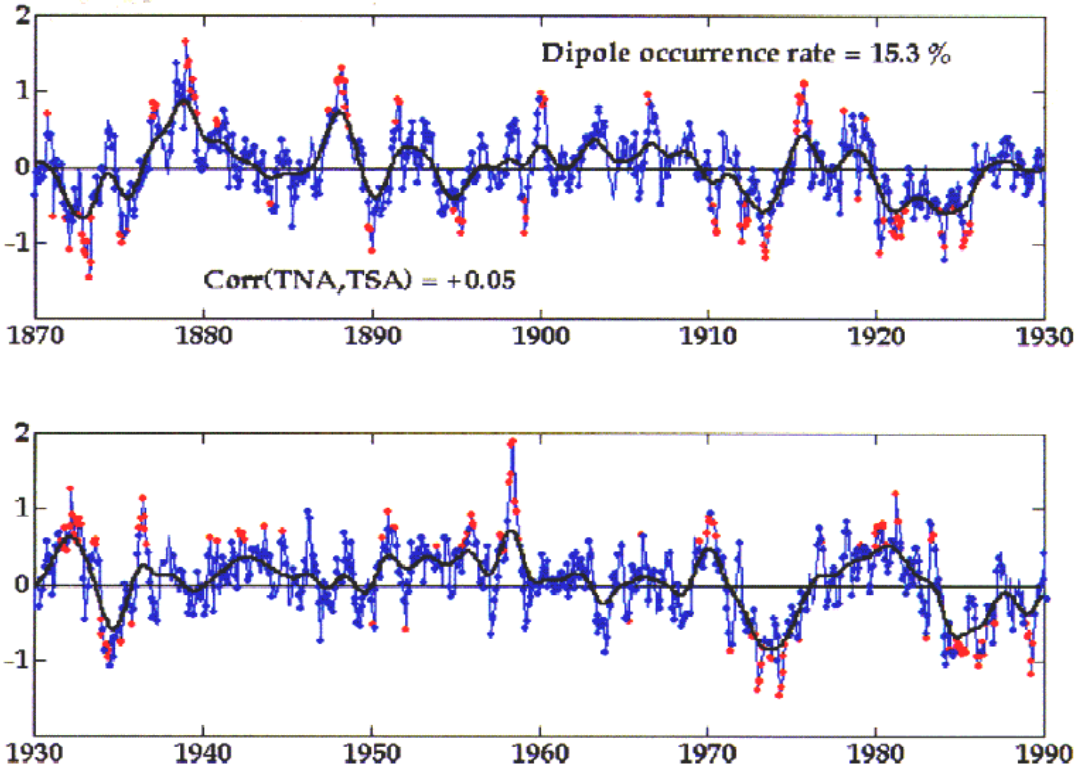

Figure 1. Time series of the tropical Atlantic gradient index, formed by the difference between SSTA area indices for the tropical North (TNA) and South Atlantic (TSA). Colored dots are monthly averaged data and the smooth black curve is the triple 13-month running mean of the data. Magenta-colored dots mark monthly averages where TNA and TSA were of opposite sign and their magnitudes exceeded 0.2 °C (dipole configurations). Blue colored dots indicate months when the tropical Atlantic was not in a dipole configuration.

2- THEME I: SST & SURFACE FLUXES

A number of studies attest to the comparatively important role of surface fluxes in driving the off-equatorial SST tendency. Other research attests to the role of positive feedback mechanisms (e.g., the gradient mode of [Chan 97] and large scale climate forcing (e.g., the NAO) for providing persistence to the SST anomalies (SSTA), both of which are expected to force SST through surface fluxes. Hence, while SST is the important target variable, the surface heat balance is the nexus between temperature change and the candidate forcing mechanisms. Under this theme we are concerned with the SST and the surface fluxes primarily involved in that balance. A number of science questions drive the observational requirements for an improved observations system:

1) Is the surface heat balance primarily vertical (1-D), as implied by the supposed importance of surface fluxes? By focusing on a 1-D null hypothesis, the vertical balance can be tested and the modifying effects of advection and mixing can be accounted for (or some of them, at least). The object of observations is to reduce the errors in the estimation of the surface flux terms to the point that they do not overwhelm the residual difference between the SST tendency and the net surface flux (which must be accounted for by other means).

2) Which terms in the vertical balance control the SST tendency? While we know that the evaporative heat flux (Qe) will be larger than the sensible (Qh) and long-wave radiative (Qb) fluxes, the solar short-wave flux (Qs) will likely be comparable to Qe. On average, the latent/sensible terms (net loss) offset the radiative terms (net gain) and the seasonal cycle of SST occurs as the balance changes over the year. We wish to know which terms are primarily responsible for the seasonal change, and whether the same terms are responsible for nonseasonal changes (anomalies).

3) How does the vertical balance vary geographically? We expect that the answers to the previous question will vary with region. In the western North Atlantic, between the northwestern reaches of the PIRATA array and the Leeward Islands, evaporation may dominate, while radiation (clouds effects) should become increasingly important in the ITCZ region, near the coastal upwelling zone off NW Africa, and in the Gulf of Guinea cold tongue. Especially significant is the question of the partition of Qe between its wind-related and humidity-related components. Finally, we also wish to inquire as to the relative importance of the mixing term (base of mixed layer) and how that changes with mixed layer depth from one subregion to another.

4) What is the seasonality of the key processes? Whatever the processes that control the vertical balance, there is ample evidence that SST anomaly forcing and persistence vary with season. Thus, for example, we know that the remote El Niño signal enters the North Atlantic (via tropospheric fluctuations) mainly during the boreal winter and early spring, while decadal dipole variability is also evident during the same season but absent during the summer-fall season. Does this occur due to the modifying effects of near-surface stratification on the vertical balance, or to some other factor?

Observational requirements

In terms of the above science questions, SST is the target variable, and the SST tendency is critical for examining the surface heat balance. Drifters have been shown in the Pacific to be the single most effective source of in-situ SST data for the elaboration of reliable blended SST products (NCEP optimal analyses). However, the relatively poor density of drifters in the Atlantic has resulted in biases due to the effects of atmospheric aerosols on uncorrected satellite infra-red estimates. The consequent large uncertainties have resulted in large disparities in the analyzed Atlantic SST from operational centers such as NOAA/NCEP and ECMWF. The problem is particularly severe in the critical North Atlantic region between

NW Africa and the Caribbean, where Saharan dust is swept westward off the NW African coast during the boreal summer-fall season.

Wind speed is critical for the estimation of sensible and latent heat fluxes through bulk aerodynamic formulae. Unlike the Pacific, the PIRATA array presently only provides reliable wind measurements at one longitude of each hemisphere. VOS sampling covers more areas but large gaps exist, while the observations suffer from variations in measurement height and superstructure impedance of the airflow. As a result, the Atlantic wind analyses of the perational centers verify poorly against in situ winds and differ with respect to each other. Satellite-based estimates of wind may explain some of the discrepancy, inasmuch as ECMWF now uses ERS (scatterometer) winds and NCEP as yet does not. However, inter-comparisons amongst satellite wind estimates also indicate uncertainties that vary geographically. Hence, a single line of buoy observations is probably not sufficient to provide ground truth for satellite estimates over broader regions.

Other moorings are required, which initially at least, should have enhanced capabilities for directly estimating surface fluxes. The coefficients used in the bulk aerodynamic formulae (needed to make estimates from Atlas moorings) vary geographically due to changes in friction layer stability, mean wind speed and other factors. Only high quality, direct measurements of the surface fluxes can 'calibrate' the coefficients and thus allow flux uncertainty reductions to near the ± 10 W/m^2 level. In view of the small amplitude of the SST variability in the Atlantic, this is probably the level of uncertainty required to attack the science questions. Finally, in-situ flux estimates of both kinds (bulk aerodynamic and direct) will be useful in assessing and calibrating the newer, satellite-based methods of flux estimation.

3- THEME II: SEA LEVEL AND SUBSURFACE THERMAL AND SALINITY STRUCTURE

Considering T-S variability in the upper ocean first, heat content integrated to 400m exhibits seasonal changes within 15° of the equator, which have been shown to be largely dynamically forced. But what are the effects on SST? On seasonal time scales, it is known that equatorial SST in the eastern Atlantic is strongly influenced by the upwelling of thermocline water above the core of the equatorial undercurrent. Does this hold on interanual time scales?

Salinity plays an important role in controlling near surface vertical mixing, with relevant vertical scales that are smaller than those of the surface isothermal layer detectable from XBT sampling. This is especially true in areas of excess precipitation, where it can strongly stratify the near- surface region and decrease the response time of SST to surface fluxes. Where does this happen and what role does it play in the interanual variability of SST? Geographically, these effects are strongest in the eastern Gulf of Guinea, where buoyancy forcing from the Congo and Niger River outflows produces a marked seasonal modification of the near-surface density field. Salinity data are also very helpful in understanding the evolution and geographical distribution of water masses. The thermocline water near the equator is currently mostly of south Atlantic origin, while to the west of the Gulf of Guinea there is a transition towards northern water, most pronounced north of the Equatorial Undercurrent (EUC) and the North Equatorial Countercurrent (NECC). What are the geographical and temporal variations of these water masses? Modulation of the shallow subtropical cells or of the circulation could manifest itself in changes of subsurface salinity.

To obtain upper ocean T and S fields, it is interesting to consider both the information provided by direct in situ observations (largely from PIRATA, ARGO and the VOS XBT lines) as well as by sea surface height anomalies (sea level corrected for changes in global fresh water budget and sea surface pressure). Sea surface height changes are strongly correlated in the tropics with changes in thermocline depth. But how can these two streams of information can be optimally combined? A careful examination of hydrographic data identifies various features where the subsurface signal differs from the one resulting from a simple vertical displacement of the T, S structure, so the problem is not a trivial one.

Turning to deep ocean variability (below 1000 m), these waters are renewed through inflow from high latitude, and in particular through western boundary currents. Can changes in these water characteristics be indicative of changes in the transport of the MOC or are they related to changes in the source properties? The tropical Atlantic poses specific challenges and opportunities compared to other parts of the Atlantic. The southward path of the deep waters formed in the northern North Atlantic (the "cold limb") is along the western boundary, although with variable paths at different depths and intense recirculations in the ocean interior, and the circulation is rather well known at a few locations where repeated work has been carried in the past, so that there is a history of water mass characteristics. But what is the spectrum of the variability, and what is the time scale of renewal of the deep water masses in the equatorial Atlantic? The water masses present a large evolution when crossing these basins at any depth. Is this evolution related to intensified vertical mixing near the equator? On what time and space scales does this happen?

Observational Requirements.

The desired observing system should consist of subsurface T-S measurements and should include sea surface height observations from satellite altimeters, supported by tide gauge measurements. The altimetric fields should provide estimates of sea surface height to within a 2 cm uncertainty on a monthly time scale (2 cm is equivalent to a 10m displacement of the thermocline, or a change of 0.2 in salinity over 100m). Presently, these fields have a spatial resolution of a couple of degrees when a combination of the available altimeters is used. TOPEX/Poseidon and its successors (JASON) provide the most accurate product, although if only these altimeters are used, the resolution is somewhat lower. The tide gauge measurements are used to assure that the altimetric products are not subject to low frequency drifts. The techniques for doing this were established during the TOPEX/Poseidon mission [Mitc 98]. At present it is possible to constrain the altimetric drift to be less than 1 mm/yr, and the technique is continuing to improve.

In addition, pairs of tide gauge across important straits will provide an important estimate of the variability of the upper ocean transport. In particular the straits along the eastern side of the Caribbean are important to monitor, and a set of gauges in this region that were installed as part of the CPAAC project should be carefully maintained, and the data flow insured. It is also important to note that the altimetric-based system needs to be complemented by long, historical tide gauge measurements where these can be retrieved. Precision altimetry began in 1992 with the launch of the TOPEX/Poseidon mission, and hence the time series will be relatively short for studying interanual to decadal variability for some time to come. Therefore it is important to maintain the historical context for these measurements by assembling and quality controlling the long tide gauge records that are available. Although these records are spatially sparse, it is possible to estimate the long-term modulation of events seen in the altimetric record and to determine the temporal representativeness of the period covered by the altimetric time series. The spatial domain for the tide gauge effort should be the entire Atlantic basin because the amount of effort required to provide the sea level data from tide gauges is not large enough to justify treating the tropics separately.

For subsurface T and S the observational requirement is to be able to resolve spatial scales on the order of a couple of hundred kilometers on seasonal time scales. The resolution typically can be coarser in the open ocean, and needs to be somewhat finer near South America and near the equator. The actual requirement in terms of the number of profiles to reach those scales has not yet been carefully evaluated, and will probably vary spatially. Based on the experience in the equatorial Pacific, this will fit with what was discussed for WOCE, but has not been available until recently for temperature (and not yet for salinity).

The desired observing system should contain an array of moorings in key positions with respect to the expected modes of climate variability. In addition to the maintenance of the current PIRATA array for a period of 5 additional years, some extensions are desired. The recommended approximate locations are shown on Fig.3: along the easterly wave track (20N/38W - 15N/42W); within the tongue of up welled water off northeast Africa (20N/20W); in an area where it seems that the air-sea feedback is positive (15N/51W); at the NECC ridge (10N/25W); and at sites of negative feedback of the air sea fluxes on SST (10S/10E and 5S/5E). The moorings provide time series from which adequate statistics of the variability can be derived, and have the advantage of being concomitant with the flux measurements, so that the 1-D hypothesis can be directly tested.

To complement the moored array VOS-based observations of T(z) and surface salinity should be obtained along specific repeated lines, (Fig.2 bottom) providing time series that can be related to earlier periods. Finally, an integrated profiling float observing system should provide the basic T(z) coverage of the basin in the upper and intermediate ocean. It is recommended that salinity capabilities be added to the floats. These measurements will complement monitoring of the western boundary with geostrophic moorings, providing a constraint on the heat and fresh water exchanges between the tropics and the higher latitudes.

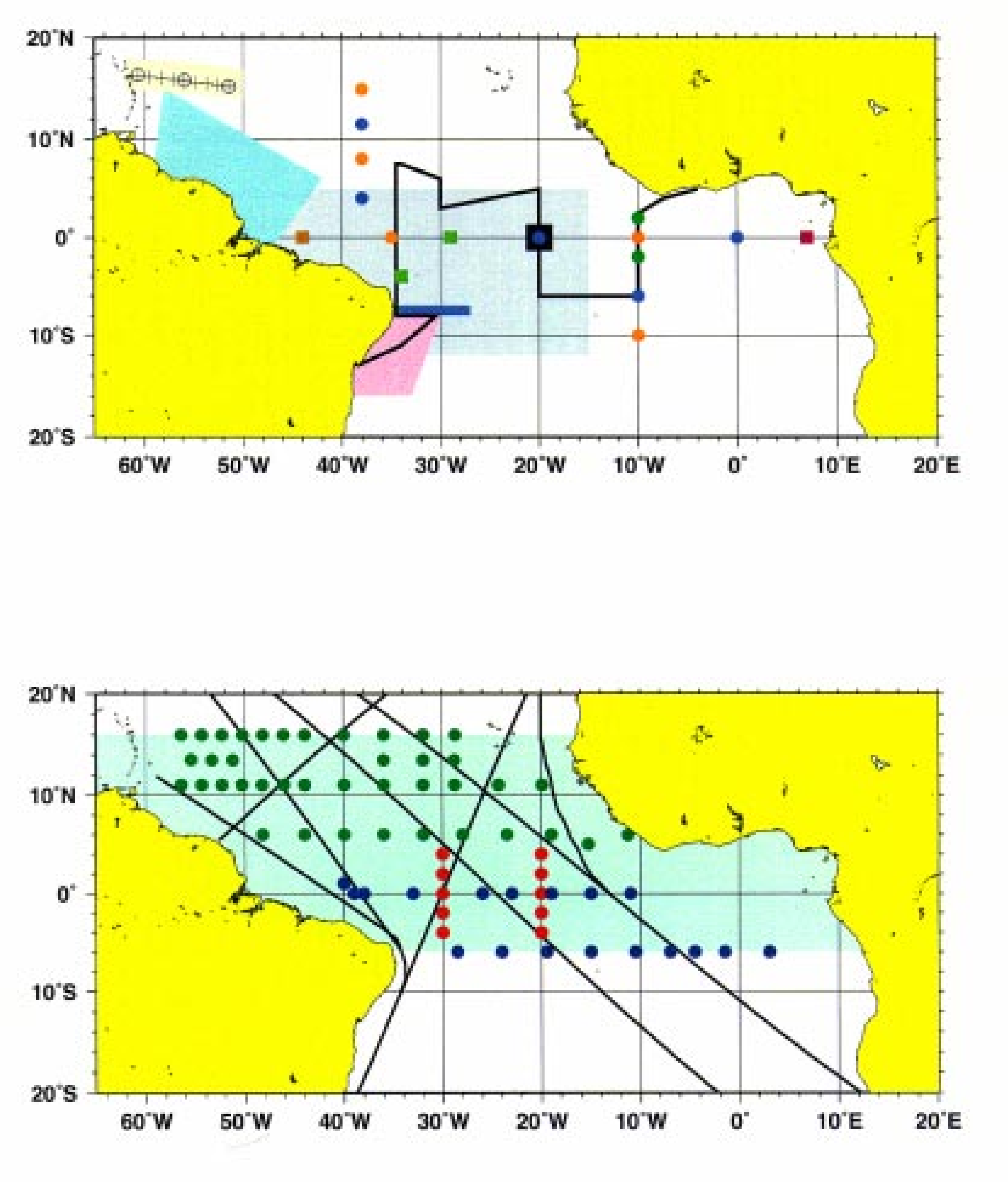

Figure 2: Top: Circles: Pirata Atlas moorings; black square: ADCP; brown square: meteorological buoy; green square: island wind/sea level; purple square: island sea level; black line: Equalant cruise tracks. Shaded areas: on going process stuies. Bottom: XBT lines and Palace Float deployment locations.

4 -THEME III: CIRCULATION

The meridional overturning circulation (MOC) consists of upper (warm) and lower (cold) limbs,
with the transport differences between these limbs accounting for the net northward inter-hemispheric transport of internal energy. The pathways and mechanisms by which this transport is achieved remains unclear, along with the rectifying influence of the seasonal cycle.

The upper limb currents, the dynamic height gradients, and the surface winds all vary seasonally with the ITCZ such that the surface dynamic topography is relatively flat in boreal winter/spring and maximally corrugated in boreal summer/fall. The circulation is also fully three-dimensional. The net internal energy transport entering the equatorial region is geostrophic, but upon exiting, it is ageostrophic and confined to the surface Ekman layer (Roemmich, 1983). Thus, a large vertical circulation must exist near the equator. One manifestation of this is the equatorial cold tongue which sets the stage for the air-sea interactions that drive the winds and account for the increase in net northward internal energy flux across the equator. With SST being the basis for ocean-atmosphere coupling, and the cold tongue providing most of the seasonally varying SST gradient, the cold tongue is important in Atlantic climate studies. What exactly is the ocean circulation’s role in controlling the seasonal evolution of the SST gradient? What are the thermocline ventilation pathways from the subtropics to the equator that provide for equatorially upwelled water? What mechanisms modify the water properties and account for the pathways as fluid transits the tropical Atlantic Ocean? For example, the western boundary current transports water northward across the equator, offsetting the southward basin-interior Sverdrup transport. After crossing the equator some of this water retroflects seasonally into the NECC and the EUC, and some is transported farther north as NBC rings. The transport partition between the retroflected interior circulation mode (Mayer and Weisberg, 1993) and the western boundary eddy mode (Johns et al., 1990; Fratantoni et al., 1995) requires further elucidation.

The lower limb contains two deep current cores, the upper North Atlantic Deep Water (NADW) and the lower NADW, that combined flow southward as the Deep Western Boundary Current (DWBC). North of the equator, the DWBC transport is larger than the net inter-hemispheric NADW transport, with the excess transport recirculated in the Guiana Abyssal Gyre (e.g., Rhein et al., 1995). Near the equator, the DWBC splits, feeding zonal currents and recirculating countercurrents. These zonal currents also vary seasonally and appear to act as temporary reservoirs for NADW on it's way southward, with the seasonal pulsations providing a mechanism for mixing. At deeper depths, the northward flowing Antarctic Bottom Water (AABW) also splits near the equator, part flowing eastward and part continuing northward and merging with the lower NADW in the Guiana Abyssal Gyre [Rhei 98].

Observational Requirements

Process experiments are necessary to describe and understand the mechanisms and to improve model physics and parameterizations. This is particularly true of the three-dimensional, time dependent tropical Atlantic circulation which may be tied to non-isentropic processes. Specific recommendations are:

1) Improved descriptions of the seasonally varying surface and upper ocean currents are needed. Surface drifters, satellite altimetry, and surface wind fields can map the surface currents using Ekman and geostrophic assumptions. These surface currents and thermal wind shear fields from profiling floats will provide upper ocean circulation maps. Adding Lagrangian floats at thermocline depths will help refine the thermocline ventilation pathways between the subtropics and the equator.

2) The Guiana Abyssal Gyre Experiment (GAGE) and the Meridional Overturning Variability Experiment (MOVE) will monitor the cold limb at 16°N in the western Atlantic with a combined array of 10 moorings. Using current meters and bottom pressure gauges these dynamic height moorings will estimate the baroclinic shear and quantify the deep recirculation cell of the Guiana Basin. The GAGE/MOVE array could be enhanced to a complete MOC monitoring array by adding moorings, new instrumentation (profiling CTD and velocity devices), and calibrating telephone cables between the windward islands for monitoring transport. Some of these mooring sites can also include surface flux measurements.

3) Pathways and water mass transformations of the deep water in the equatorial belt are poorly understood, but may play an important role for inter-hemisphere exchange of NADW and AABW. During 2000-2004, a moored array near 7.5°S will monitor the DWBC, supported by PALACE floats and shipboard hydrographic and current profiling observations. To quantify the DWBC variability this deep array should be extended to the mid-Atlantic ridge using similar moorings as at 16°N (see point 2, above).

4) The relative importance between ocean dynamics and surface fluxes in the equatorial cold tongue evolution is unresolved. The ocean adjusts its surface heat fluxes to dissipate anomalous SST, so numerical experiments alone using CGCMs show difficulty in assessing the evolution of the equatorial coupled ocean-atmosphere system. An equatorial divergence array, measuring velocity, temperature, salinity, and surface fluxes, is needed to provide an independent *in-situ* data set to clarify the mechanisms of cold tongue evolution, test and improve models, and provide further insights into water mass modifications. These measurements could be extended deeper to observe the zonal pressure gradient reversal, the poleward export into the thermostad, and the Tsuchiya jets. The array should be centered on the equator at mid-basin, where the zonal component of wind stress (Ekman divergence) and zonal pressure gradient (geostrophic convergence) are both seasonally strong.

5) Other upwelling regions (within the NECC trough, and along the NW and SW African coasts) add to the net surface heat flux in the tropical Atlantic. It is important to determine the annual cycle and interannual variability in the net surface heating and ocean dynamics influences on SST in these regions. Surface flux moorings are recommended for these upwelling areas to diagnostically determine bulk transfer parameterizations. Once these are determined, a less expensive set of monitoring instruments could be substituted.

6) The seasonal and interannual variability of the SEC, NECC, and the southern part of the NEC are important in the meridional heat transport across the tropical Atlantic. The 38°W PIRATA line can be instrumented to provide indices of the variability of these currents. Design studies can determine what instrumentation may be needed and whether the mooring locations should be adjusted to better frame the latitudes of these currents.

Extending the line to the South American coast would provide an index of western boundary cross-equatorial flow for comparison with the interior zonal flows. Additional moorings near the western boundary along 10°N will further help to clarify the partition between the northward upper limb transports either directly or through NBC eddies, as contrasted with transports in the basin interior by the seasonally varying Ekman layer.

5 - THEME IV: MODELING

Climate variability in the tropical Atlantic region is known to be influenced by many different physical processes, including air-sea feedbacks local to the tropical Atlantic and remote influences due to other climatic modes of variability, such as Pacific ENSO and the North Atlantic Oscillation. The relative importance of various processes to TAV can vary from region to region within the tropical Atlantic. Numerical modeling studies can be extremely valuable in dissecting the underlying physical processes, thereby providing useful information about the design of the observing system. Development of a data assimilation system will further aid to the understanding of the various oceanic processes in TAV.

The ultimate goal of the modeling effort should be to develop a forecast system for predicting climate fluctuations in the tropical Atlantic sector. An improved understanding of some key scientific issues will be essential to achieve this goal. What is the role of land-atmosphere-ocean interaction in tropical Atlantic variability? Like the eastern tropical Pacific, the tropical Atlantic ocean is marked with a well defined ITCZ/cold tongue structure and a pronounced annual cycle. While the Pacific ITCZ system interacts with the equatorially symmetric ENSO mode, the Atlantic ITCZ appears to be more intimately coupled with the inter-hemispheric SST gradient variation. Although the coupling mechanism for the Atlantic ITCZ variability has not been understood, recent modeling studies suggest that it may involve both thermodynamic and dynamic feedbacks. The former involves the interaction between wind-induced surface heat flux and SST off the equator, contributing primarily to the variation in cross-equatorial SST gradient [Cart 96], [Chan 97] and [Xie 99], the latter involving the interaction between the trade wind and SST along the equatorial wave guide [Zebi 93]. A more recent modeling study suggests that the continental heat source over the Amazon basin may also be a crucial player in the variability of cross-equatorial SST gradient [Batt 99], personal communication). Further modeling studies are required to shed light on the role of regional feedbacks in TAV.

To what extent and through what physical mechanisms is tropical Atlantic variability influenced by basin-to-basin interactions? It has been well established that ENSO exerts a strong influence on seasonal-to-interanual SST variation in the tropical Atlantic Ocean [Serv 91], [Cart 94], [Enfi 98], [Sava 99]. However, the detailed dynamical processes that control this remote influence are not entirely clear. Two mechanisms have been proposed: one involves atmospheric teleconnection via the Pacific-North America (PNA) route and the other involves changes in tropical Walker circulation. The two mechanisms could well be interrelated. Further modeling studies are needed to explore the relationship between the two processes and their contributions to tropical Atlantic variability.

What is the relationship between TAV and NAO? The NAO is the most dominant climate signal in the extra-tropical Atlantic and may provide a major source of forcing to tropical Atlantic variability [Xie 98]. On the other hand, tropical Atlantic SST may dictate the NAO via influencing the Hadley Circulation [Robe 98]. The dynamic linkage between NAO and

TAV are not well understood. Furthermore, in the ocean the tropical thermocline is connected to extratropical processes via both the ventilation/subduction processes and shallow meridional circulation. Modeling and data assimilation studies are needed to explore the connections between the tropics and extratropics in the Atlantic sector.

How does interhemispheric ocean exchange influence TAV? [Yang 99] presents intriguing observational evidence that the Labrador Sea Water (LSW) thickness variations precede changes in cross-equatorial SST gradient by about 5 years. This raises the possibility that the tropical Atlantic variability is linked to the variability in the Meridional Overturning Circulation (MOC). Of particular interest is how the upper limb of the MOC can affect inter-hemispheric heat transport and what the ocean circulation pathways are in transporting the heat. Ocean modeling/data assimilation studies will be crucial in testing the existing hypotheses and identifying key oceanic processes involved in inter-hemispheric exchanges.

How predictable is tropical Atlantic variability? Numerical models will be critical in understanding the predictable dynamics and determining the intrinsic predictability limit of climate variability in the tropical Atlantic. Of particular importance are the predictability of tropical Atlantic SSTs and the extent to which it can impact seasonal rainfall forecast in the region. The requirement of accurate initial conditions means that ocean data assimilation will be an integral part of this effort.

6 - THE OBSERVING SYSTEM

An observing system for the Tropical Atlantic should build upon the existing monitoring systems, process studies and the scientific knowledge of the region. It should be directed to answer the main scientific questions that will lead to a better understanding of the role of the Tropical Atlantic in climate. Observations should be collected in a cost effective manner to provide the necessary information that will answer those questions. At the time of the OCEANOBS 99 meeting, observations were collected in the Tropical Atlantic routinely and in real time mainly through the Voluntary Observing Ships (VOS) who deployed expendable Bathythermograph (XBT), collected meteorological and oceanic surface data, deployed surface drifters for the Global Drifters Program, and profiling floats. As part of these programs, several XBT lines are operational in the Tropical Atlantic maintained by the US, France and the UK (Fig.2b lower panel). Along those lines, meteorological, and hydrographic (XBT) observations are routinely collected 4 times a day. Three of the lines operated by France, also collect sea surface salinity (TSG).

Satellite-tracked drifting buoy data are being collected by numerous investigators and agencies in several countries as part of an international program designed in an effort to improve climate prediction. A basin-scale array of drifters in the tropical Atlantic (20S - 30N) will be deployed and maintained for at least one cycle of the "tropical dipole” with an average resolution of 2.5 x10^5 km^2 (approximately equal to 2° latitude by 12.5° longitude). This will require a steady-state array of 142 drifters, which requires deploying 87 drifters per year. As part of this, an array of 10 or more SVP-WOTAN drifters, which measure winds, will be deployed for the hurricane season to help with the forecasts of hurricane development and hurricane tracks.

Profiling floats deployments started in the Atlantic Ocean during 1997 as part of ACCE, the Atlantic Circulation and Climate Experiment. Deployments for the period 1997–2000 are shown in Figure 2, top panel. An international proposals for massive deployment (about 3000) profiling floats, ARGO, is under consideration. A pre-ARGO proposal has been already funded in the US to develop the infrastructure for the large-scale experiment. The infrastructure will be developed in the context of float deployments the tropical Atlantic north of the equator to study subtropical cells. If funded, float deployments will probably begin towards the end of calendar-year 1999.

In 1997, a multinational (Brazil, France and the US) pilot experiment of operational oceanography called PIRATA (Pilot Research Moored Array in the Tropical Atlantic) was started for three years (1997-2000). This programs was conceived as an Atlantic extension of the Pacific TAO array, and consists of 12 ATLAS moorings spanning along the equator and two meridional lines (Fig.2, bottom panel). 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 500 m), and subsurface pressure (at 300 m and 500 m). An acoustic Doppler current profiler mooring is proposed for 0°N-20°W to monitor current variations in the central Atlantic where high zonal current variability occurs. The first and second phases of the ATLAS deployments were made during the end 1997-early 1999 years. The final phase of deployment is scheduled for July 1999.

Wind measurements and tide-gauge data are scheduled to be available in real-time from a few equatorial sites: St. Peter and St. Paul Rock island (0.7°N-29.2°W), Atol das Rocas (3.9°S-33.5°W), Sao Tomé island (0.5°N-6.5°E), and on a coastal meteorological buoy (0°N-44°W). A complete description of the programs mentioned above as well of all other programs existing and proposed in the Tropical Atlantic is given in the COSTA Workshop Report (1999).

Based on present knowledge, the scientific questions to be answered and the status of the present observing system, recommendations for the establishment of a climate observing system for the tropical Atlantic were made. They can be summarized as follows:

1. *Maintain and enhance the present monitoring systems for a transition period of 5 years.*

Moored Array

- Maintain the current PIRATA array for the transition period 2000-2005.
- Extend the PIRATA array with pilot sites during the transition period. Figure 3 shows the location of the proposed moorings sites. Note that sites with arrows indicate a region more than an exact location.
- Maintain and enhance the present tide-gauge array. Enhancement of observations at each side of the Caribbean straits, plus activation of cable monitoring.
- Add SLP capabilities to drifters and Atlas moorings, when possible, for altimeter corrections.
- Review and improve current Atlas mooring instrumentation to improve estimates of surface fluxes and geostrophic transports.

Lagrangian measurements

- Continuation of the current profiling floats programs in the Tropical Atlantic and extension of the observations to the region 20°N to 20°S. Salinity measurements should be included if possible.
- Continuation and enhancement of the Tropical Atlantic array of surface drifters in the region 20°N to 20°S.

VOS/XBT

- Maintain the XBT observations from the VOS system. Increase resolution in time and space on AX-29. Resume XBT sampling in the central Tropical Atlantic
- Augment and improve TSG measurements along these lines and add real time transmission capability.
- Continue the improvement of VOS sensors

2. Implement process studies built upon the existing monitoring systems to enhance the design of the observing system and the interpretation of the data collected.

The following areas of research have been identified as important for undertaking design studies and to perform pilot experiments that will enhance the observing system and the interpretation of the observations:

- Upper Ocean MOC for recirculation and water mass modifications.
- Western boundary currents and Caribbean passages for heat and mass transport studies.
- Mid Tropical Atlantic Circulation for inter-basin exchanges
- Upwelling regions and the Atlantic cold tongue, for surface heating and influence on SST.

3. Implement modeling studies, combined with data assimilation, to enhance climate forecast and to improve the design of the observing system.

- Ocean and atmosphere coupled experiments.
- Developing of a hierarchy of models with the goal of seasonal forecast in the Tropical Atlantic.
- Model validation and verification
- Predictability studies

4. Generate field products that combine all observations and model products.

- Generation of data products (T, S fields, dynamic height, surface currents, etc.)
- Altimetric fields supported by tide gauge measurements.
- Data archeology of tide gauges records.
- Combine the data products with other products (models, assimilation, inverse model, etc.)

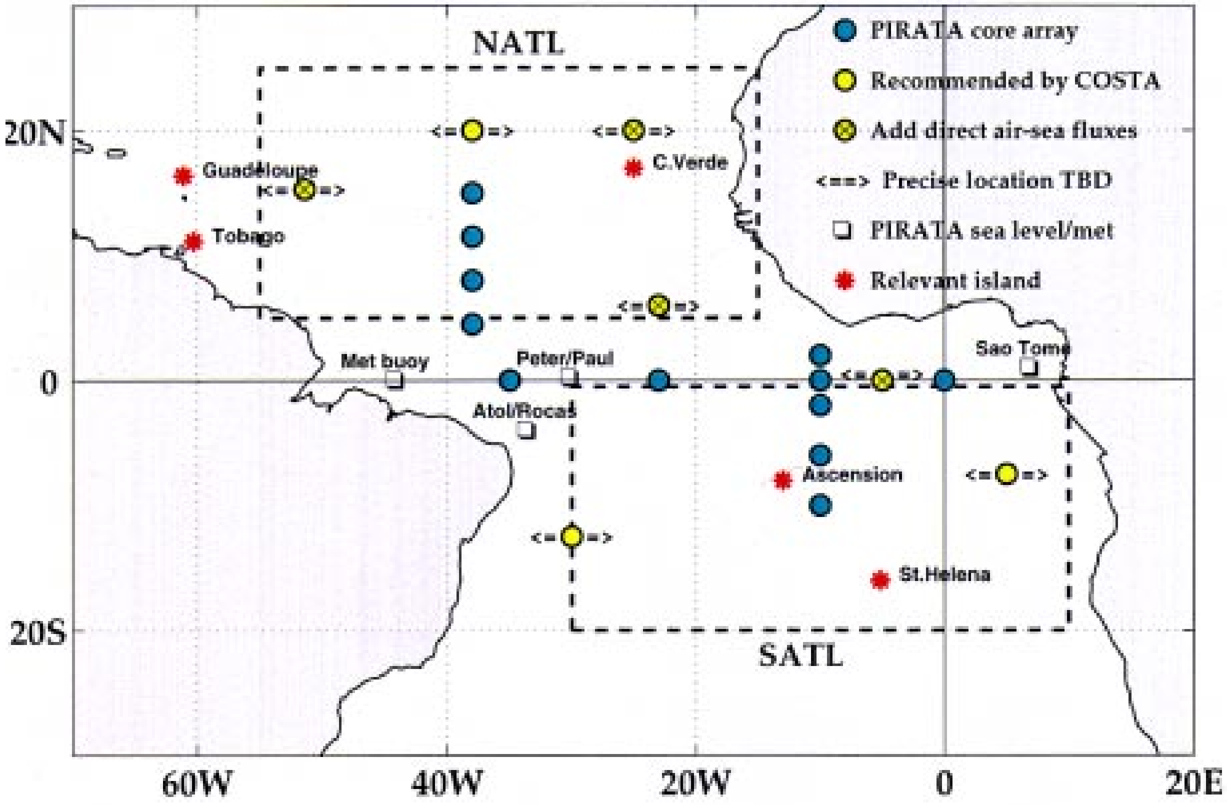

Figure 3. Elements of the existing PIRATA array (blue circles, squares) and of the recommended (or possible) extensions for the COSTA observing system (yellow circles, red asterisks). Left-right arrows surrounding a symbol indicates an area, not a precise location.

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