

COSTA

Climate Observing System for the Tropical Atlantic

Workshop Report
Miami, May 4-7 1999

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September 1999

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PREFACE

Recognizing the important role the Tropical Atlantic Ocean plays in climate, and the deficiency of observations in this ocean during TOGA, a group of scientists from Brazil, the US, and France met during the 4th TAO Implementation Panel Session that took place in Fortaleza, Brazil during September 1995. The group decided to put together a pilot experiment in the Tropical Atlantic as an extension of the TAO array in the Pacific. PIRATA, the Pilot Research Moored Array in the Tropical Atlantic, was conceived at that meeting and subsequently funded for the period 1997 to 2001. || ? ?

Simultaneously, other programs were ongoing in the region. Several VOS/XBT lines, maintained in the Atlantic by the US, France, and the UK, collected meteorological and hydrographic data. The Global Drifter Center deployed surface drifters collecting SST and velocity trajectories. Several process studies were carried out by US, French, Brazilian, and German scientists.

Acknowledging the need to coordinate present measurement efforts in the Tropical Atlantic, and with the pilot phase of PIRATA coming to an end, the Climate Observing System for the Tropical Atlantic (COSTA) Workshop was held at National Oceanic and Atmospheric Administration/Atlantic Oceanographic and Meteorological Laboratory in Miami from May 4 to May 7, 1999. The PIRATA- 6 Meeting took place on May 3-4, 1999 at the same site.

The objectives of the COSTA Workshop were to review the status of existing programs, determine the need for new observations in support of climate studies, and lay the groundwork for coordinated multi-national observing system in the Tropical Atlantic.

Sixty four scientists from Brazil, France, Germany, Morocco, South Africa, Venezuela, and the US attended the workshop. This report is a review of the discussions and the recommendations produced by the workshop participants. The recommendation draws are viewpoints expressed by those at the conference, and are not intended to be exhaustive. Rather, we hope that they will serve as the starting point for the design and implementation of a sustained climate observing system for the Tropical Atlantic.

The COSTA Organization Committee was comprised of:

Silvia L. Garzoli (NOAA/AOML; US) Chairman
Mike McPhaden (NOAA/PMEL; US)
Gilles Reverdin (CNES; Fr)
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EXECUTIVE SUMMARY

This document summarizes the discussions that took place during the COSTA (Climate Observing System for the Tropical Atlantic) Workshop held in Miami, from May 4 through 7, 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.

Previous to the COSTA workshop, a large effort was already underway to study the tropical Atlantic and its importance for climate. On the global scale, the CLIVAR initial implementation plan underlines the need to establish a tropical Atlantic observing system based on the PIRATA array. EuroCLIVAR recommends that this array be maintained and makes recommendations on how to expand it. On the basin scale, the Atlantic Climate Variability Experiment (ACVE) prospectus also recommends observations of the tropical Atlantic for climate purposes.

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 tropical Atlantic observing system, regional building on the present PIRATA moored array, other existing monitoring programs and process studies, and the current scientific knowledge.

The meeting started with a series of keynote presentations that established the importance and role of the tropical Atlantic in climate fluctuations (Chapter 1) followed by a review of all existing programs in the area (Chapter VI). The keynote talks described 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). They also summarized present scientific thinking as to the possible mechanisms behind tropical Atlantic SST fluctuations and their relation to climate, 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 scientific discussions provided the basis for forming separate working groups centered on four important themes: 1) sea surface temperature (SST) and surface fluxes; 2) sea level and subsurface structure; 3) circulation; and 4) modeling and data assimilation. The discussions and recommendations from the working groups are summarized in chapters II through V.

The recommendations provided by the working groups were presented and discussed in a plenary session on the last day of the workshop (Chapter VII). They may be summarized as follows:

It was recommended;

- to maintain and enhance the present monitoring systems consisting of the PIRATA moored array, surface drifters, XBT observations from volunteer observing ships (VOS) and to continue the current PALACE floats program in the Tropical Atlantic.
- to implement process studies built on the existing observations, to enhance the design of the core observing system. Process studies will be directed to monitor the MOC, the western boundary currents and Caribbean passages, the mid tropical Atlantic circulation, the cold tongue and the upwelling regions.
- to perform modeling studies to enhance the physical understanding obtained from data sets

and to unify the observations into integrated products through data assimilation.

- to produce integrated products (data and model products) available for scientific analysis and prediction activities.

The workshop also discussed how to proceed with the data collected and how to make it available to the community. The consensus was to continue the data collection and quality control through the existing data centers presently responsible for the observations. Recommendations included the need to make the data available in near real time for model forecasts.

I. RELATION BETWEEN THE TROPICAL ATLANTIC AND CLIMATE.

I.1 Atlantic-sector climate variability

Roughly since World War II, we have witnessed a large multi-decadal swing in the Atlantic sector climate, which we believe is directly attributable to interactions between the Atlantic Ocean and the overlying atmosphere. Countries surrounding the Atlantic Basin have, in the last fifty years or so, experienced dramatic changes in climatic conditions. Since the mid-1960s there has been a steady increase in wintertime storminess in the northeastern Atlantic and the North Sea. At the same time northern European countries bordering the Atlantic have experienced an upward trend in winter rainfall, while from the Iberian Peninsula to Turkey there has been a steady decline in rainfall. Winter air temperatures over northern Europe and Asia, from Scandinavia to Siberia rose steadily from the mid-1960s. During the same period the Middle East and North Africa cooled. Over Greenland and the Canadian arctic strong cooling occurred while the eastern half of the United States warmed slightly. Some of these climatic trends may have been felt as far south as the semi-arid region of northeast Brazil, where austral summer rainfall, regulated by the annual migration of the Inter-tropical Convergence Zone (ITCZ), has displayed an upward trend.

Climate fluctuations like these have been best documented after about 1950, but are by no means limited to this modern period, which is punctuated by a global warming trend as well as inter-decadal swings. For example, decadal changes in the Sahelian climate and associated changes in the frequency of landfalling hurricanes in the United States - both robust aspects of the Atlantic decadal climate milieu - have occurred at least since the start of the 20th century (Landsea *et al.*, 1992).

These climate swings appear to be 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 interannual 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.

An especially significant aspect of TAV is how it can affect the frequency of landfalling hurricanes in the Caribbean and on the North American mainland. In sub-Saharan Africa, rainfall steadily decreased after the wet decade of the 1950s, turning the Sahel into a drought-stricken region. At the same latitude, mid-summer to late autumn tropical storms which were frequent during the 1940s and 1950s became less frequent from the 1960s onwards. Figure I.1 shows a dramatic shift in the frequency of major hurricanes originating as NW Africa easterly waves, between the 1947-69 period and the 1970-87 period (Gray, 1990). This is significant because the major regime shift most frequently cited in relation to the NAO occurred from the late 1960s to the early 1970s. Interestingly, NAO-related sea surface temperature anomaly (SSTA) and pressure indices seem to indicate that a similar, reverse shift may have occurred in the mid-1990s and is coincident with a recent increase in hurricane activity (Landsea *et al.*, 1999).

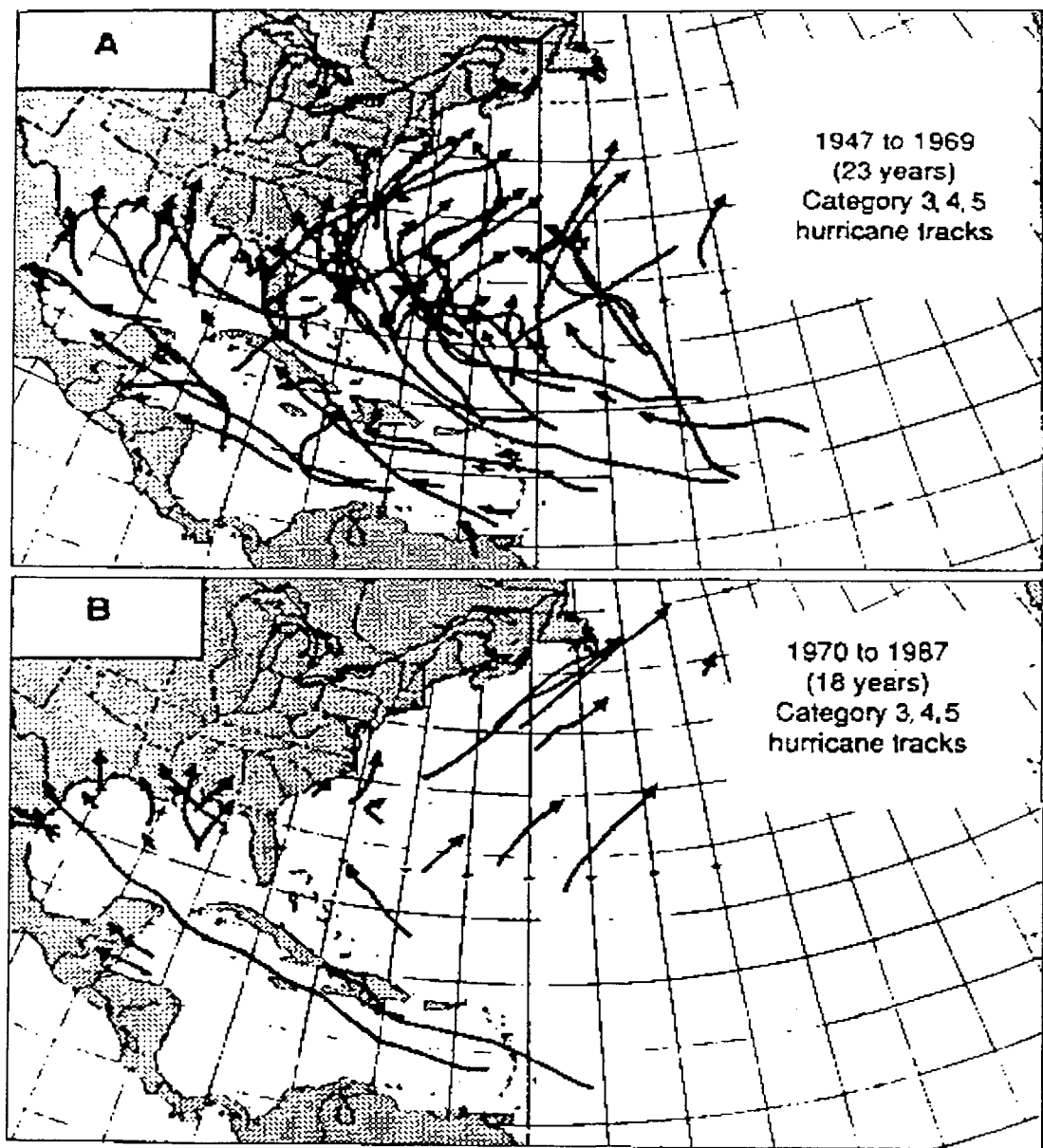


Figure I.1. Interdecadal variability in the frequency of major Atlantic hurricanes (category 3, 4, 5). Top: Tracks of major hurricanes from 1947 through 1969 (23 years). Bottom: Same, but for 1970-1987 (18 years). (Gray, 1990)

1.2 The goal: Improve climate predictions

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 interannual-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.

It is, of course, possible to argue that even variability with long time scales, like the NAO, is mainly driven by the atmosphere and that the ocean is simply "along for the ride", passively responding to the atmosphere (Hasselmann, 1976; also, Sarachik *et al.*, 1996). Such a scenario bodes ill for the prospects of increased predictability. However, recent work suggests that the ocean both absorbs from and actively feeds back onto the atmosphere and that at the very least it 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. More specifically, Chang *et al.* (1997) show that the tropical North Atlantic has significant predictability with the required lead times using statistical and coupled ocean-atmosphere models. 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 interannual time scales.

Recent research has shown that the NAO and TAV fluctuate in unison with changes in the properties of water masses that are subducted from surface layers at high latitudes during northern winters (Yang, 1999). As these deep waters are carried southward and out of the Atlantic, warm surface water enters the South Atlantic and works its way into the North Atlantic, eventually completing the MOC. Although TAV and the MOC are both related to the NAO, we do not yet understand what their respective roles are in giving persistence to NAO climate phases or in switching from one phase to another. Understanding these relationships and simulating them with models will be of fundamental importance to extending climate predictability.

1.3 Why does the tropical Atlantic matter?

That TAV is important for the large scale climate modes is suggested by the modeling study of Lau and Nath (1994), who force a global atmospheric model alternately with observed sea surface temperature (SST) over the global ocean (GOGA), or over the tropical Pacific only (TOGA), with climatologically specified SST elsewhere (Figure I.2). The dominant atmospheric response of both forcings is a tropospheric northern hemisphere pressure pattern that we now identify as PNA (Pacific North American). However, only the GOGA response is comparable in its intensity to the PNA pattern seen in data, while the TOGA response is weak. The inclusion of Atlantic SSTA in GOGA, which contains a remotely induced component from ENSO (via a tropospheric bridge; Enfield and Mayer, 1997) is thus essential for obtaining a robust PNA pattern.

The tropical Atlantic produces climate responses over the inter-American region that are comparable to those of ENSO in the Pacific (Enfield, 1996; Figure I.3). Warmings in the tropical North Atlantic are associated with comparable, but opposite rainfall effects as compared with those of El Niño, and thus cannot be attributed to the remote ENSO signal in Atlantic SSTA. The uniqueness of Atlantic-only climate variability and its comparability with ENSO is further evident in the modeling analysis of Saravanan and Chang (1999). In an approach similar to the Lau and Nath study, they alternately force a global atmospheric model with global (GOGA), all tropical oceans (TOGA) and tropical Atlantic only (TAGA). The negligible differences between the GOGA and TOGA responses illustrate the importance of the tropical ocean as compared with the extratropics. More significant is the result obtained when the TAGA response is subtracted from TOGA (yielding only the Indo-Pacific effects of ENSO) and this (TOGA-TAGA) is compared with the Atlantic-only forcing (TAGA) (Figure I.4). Outside of the equatorial Pacific

and west coast of South America, only one area responds more strongly to ENSO than to the Atlantic: the western tropical Atlantic just south of the equator and east of NE Brazil. The entire region north of the equator from the Guinea coast of Africa westward to Central America responds more strongly to the Atlantic and with opposite sign. This is consistent with data diagnostics and suggests that ENSO and the Atlantic can produce a very strong climate response over that region when the Pacific and Atlantic SSTA are of opposite sign (east-west dipole), especially the tropical North Atlantic with respect to the Pacific. The importance of east-west interocean contrasts is also consistent with other recent data-based studies (Enfield and Alfaro, 1999; Giannini *et al.*, 1999).

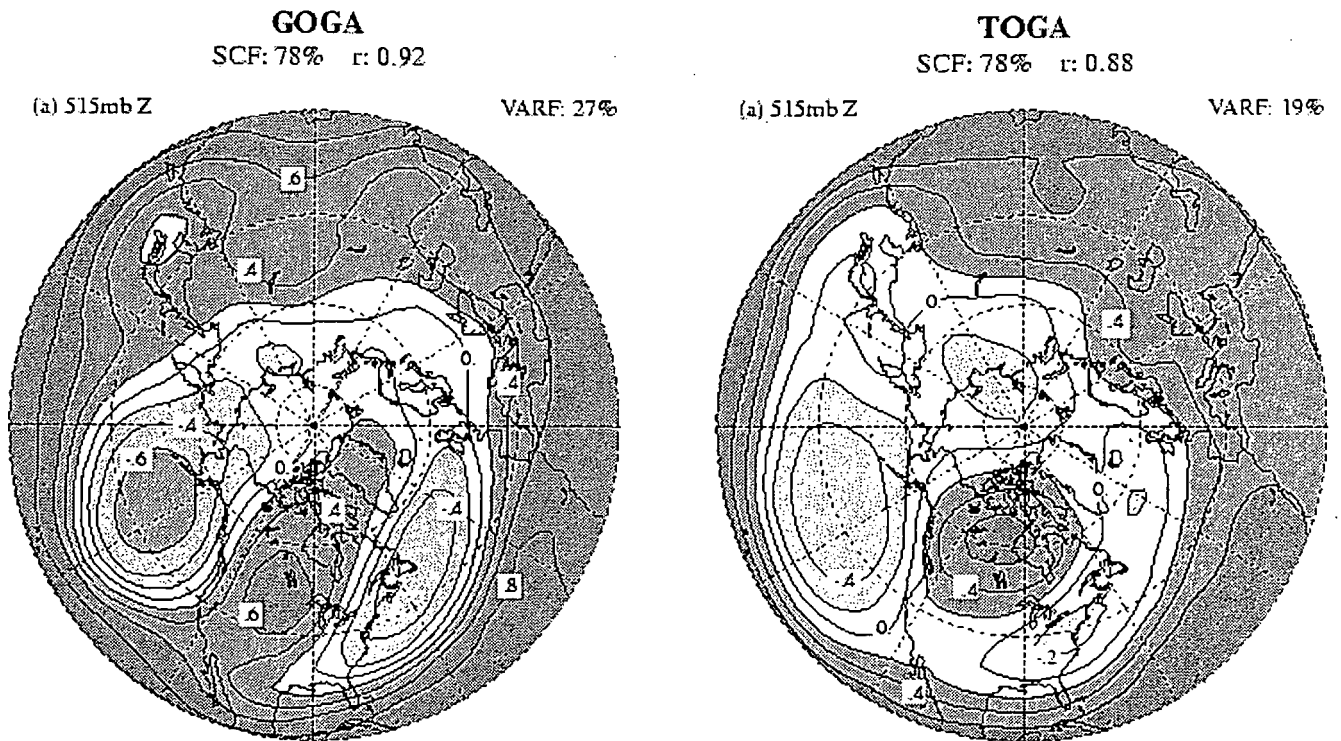


Figure I.2. Left: Spatial distribution of the 500 hPa pressure heights from an ensemble average of model runs forced by global (boreal winter) SST anomalies (GOGA). Right: Same, but for model runs forced only by SSTA in the tropical Pacific (TOGA). (Lau and Nath, 1994)

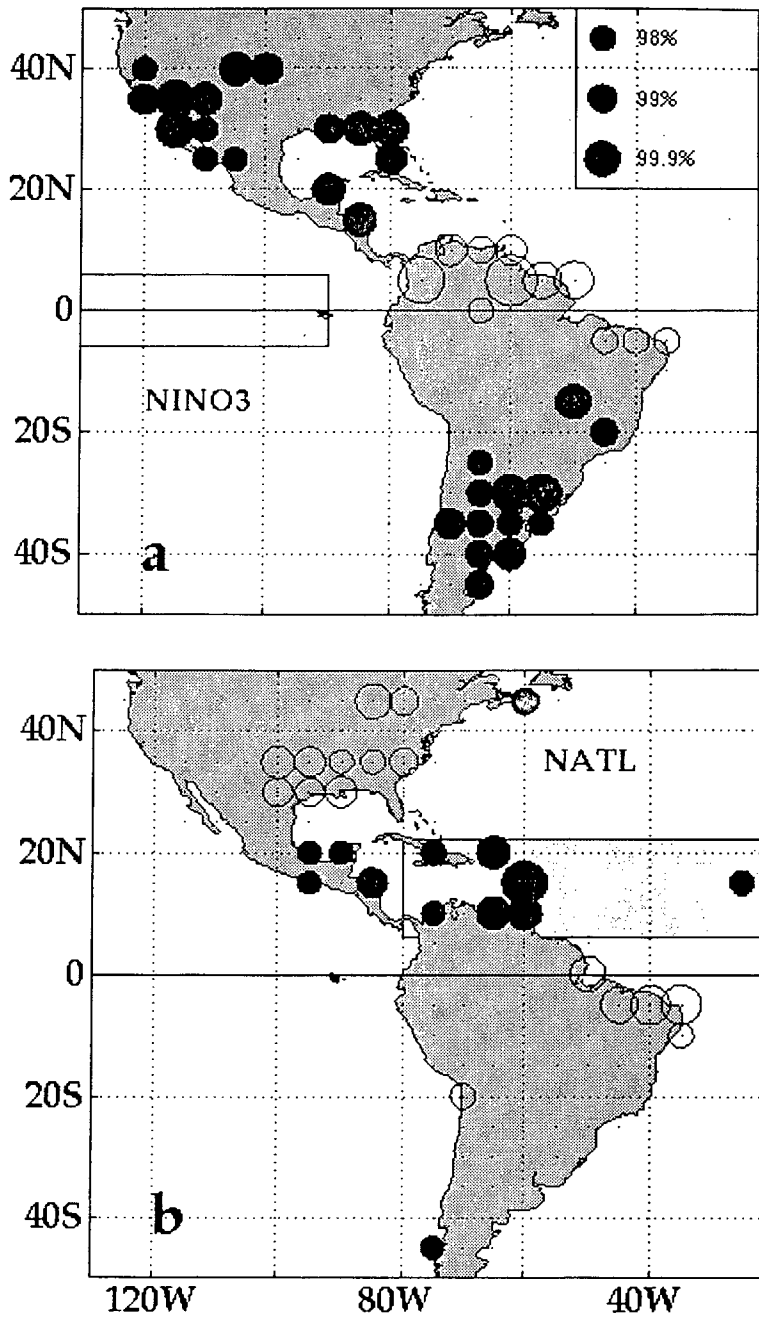


Figure I.3. Relative magnitudes (circle diameters) and sign (solid positive, unfilled negative) of maximum lagged correlations between Department of Energy 5-by-5 degree gridded rainfall departures and the NINO3 and NATL indices of SSTA variability, defined as simple averages over the regions $\pm 6^\circ, 90^\circ - 150^\circ\text{W}$ and $6^\circ - 22^\circ\text{N}, 15^\circ - 80^\circ\text{W}$, respectively. The inset legend shows the circle diameters corresponding to several significance levels (serial correlation accounted for). (Enfield, 1996)

The impact of tropical Atlantic SSTA on the surrounding land climates is amply demonstrated by studies of NW Brazil rainfall (Moura and Shukla, 1981; Nobre and Shukla, 1996) and NW African rainfall (Folland *et al.*, 1986). These studies indicate that inter-hemispheric contrasts in SSTA are strongly related to climate extremes. However, the suggestion from such studies of an SSTA dipole between the tropical North (TNA) and South Atlantic (TSA) is belied by the fact that dipole configurations are actually rare (12%-15% of the time) and occur no more often than expected by chance for the stochastically independent TNA and TSA indices (Enfield *et al.*, 1999). Nevertheless, the index formed by the SSTA difference between TNA and TSA (Servain, 1991), sometimes referred to as a dipole index, has proved to be an invaluable indicator of the meridional gradient in SSTA that is correlated with north-south displacements of the ITCZ and with strong climate anomalies over the surrounding land regions. The SSTA gradient and associated ITCZ variability appear to be governed primarily by the quasi-independent fluctuations of SSTA over the broad off-equatorial regions, TNA and TSA.

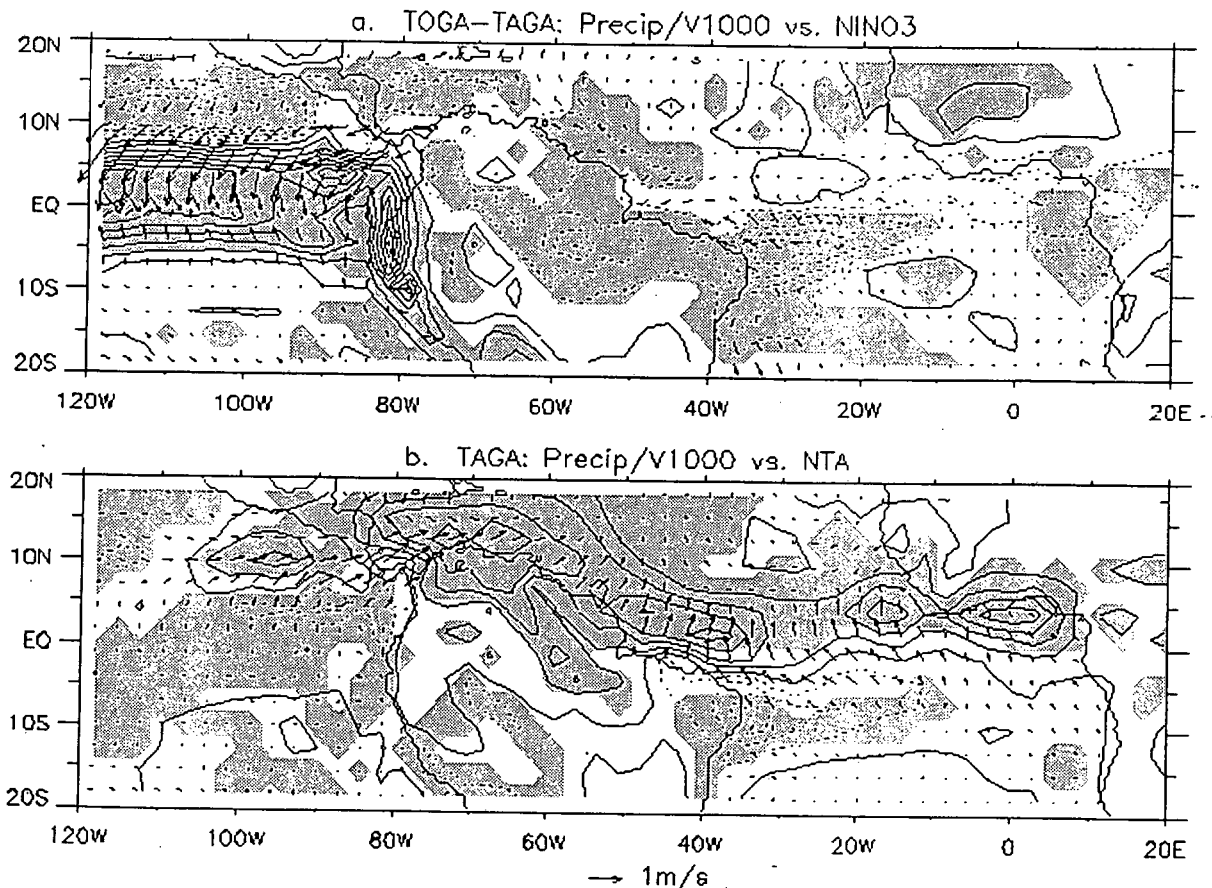


Figure I.4. Distributions of anomalous rainfall in ensemble-averaged AGCM simulations forced by subsets of global SSTA. Top: Differenced model responses to forcing by SSTA over the global tropics, and forcing only over the tropical Atlantic (TOGA-TAGA). Bottom: Model response with SSTA active only over the tropical Atlantic (TAGA). (Saravanan and Chang, 1999)

1.4 How are persistent tropical Atlantic SSTA features generated?

Having established the relevance of TAV and its probably active role in Atlantic sector climate, it remains to ask how the TAV-related features in SSTA are generated. The ways in which this might happen form the crucial working hypotheses for TAV research and, of course, must provide guidance for the design of the Atlantic observing system.

One source of TAV comes from the remote influence of ENSO through its effects on the tropical Atlantic troposphere (Hastenrath *et al.*, 1987; Hameed *et al.*, 1993; Enfield and Mayer, 1997). Approximately 25% of the total variance in the TNA index can be explained by Pacific, ENSO-related fluctuations. The tropospheric bridge for this remote forcing occurs primarily over the TNA region through the effects of altered NE trades on evaporative and sensible heat fluxes. This mechanism is indicated both by data (e.g., Enfield and Mayer, 1997) and by SSTA-forced atmospheric models (e.g., Saravanan and Chang, 1999).

The equatorial Atlantic is also capable of dynamical ocean-atmosphere interactions similar to those of the Pacific ENSO mode, and may occasionally respond to strong forcing from the Pacific. These oscillations are of smaller amplitude and period, they are usually unrelated to the Pacific, and they are not self-sustaining as they are in the Pacific (Zebiak, 1993). However, in at least one instance, trade wind forcing due to the strong 1982-83 Pacific ENSO excited the Atlantic equatorial mode, resulting in very strong, positive SSTA in the Gulf of Guinea in 1984 (Philander, 1986; Delecluse *et al.*, 1994).

Ocean-atmosphere interactions internal to the tropical Atlantic are another way in which SST gradient anomalies may occur (Carton *et al.*, 1996; Chang *et al.*, 1997). Once established in the boreal spring, positive (negative) TNA anomalies of SST are associated with northward (southward) anomalies in the cross-equatorial wind field, along with an associated northward (southward) displacement of the ITCZ and a weakening (strengthening) of the NE trades over the TNA region. The sign of the NE trades anomaly is such as to reinforce the original TNA anomaly (positive feedback). Again, as with the ENSO signal, the feedback seems to be thermodynamical, involving surface fluxes at the shorter time scales. Something similar can happen in the TSA region, though less clearly. There seems to be a tendency for the internal gradient-feedback mechanism to induce antisymmetric ('dipole') configurations of SSTA across the equator. Although other, independent sources of TNA and TSA variability seem to obscure this antisymmetric signal, there are indications that it may operate preferentially at the decadal time scale (Chang *et al.*, 1997; Enfield *et al.*, 1999; Xie and Tanimoto, 1998). The index of the meridional SSTA gradient, formed by the TNA-TSA difference, shows the decadal alternation of dipole configurations superimposed on interseasonal and interannual variations that are mainly non-dipole in character (Figure I.6). The equatorial SST variability excited by zonal wind anomalies in the western equatorial Atlantic (the "ENSO-like" mode) is an important influence on the larger TSA region within which it lies (Figure I.5). It therefore can set off a sequence of events in the meridional direction that affect the meridional gradient of SSTA and its associated ITCZ migrations and climate impacts. The latter process seems to occur through interactions of the type outlined above for an internal gradient-feedback mode. This linkage between the equatorial and meridional modes of variability has been explored by Servain *et al.* (1999). Together, these two modes of variability account for about 45 % of the total SSTA variance, and have formed the basis for the spatial distribution of the PIRATA array (Figure I.5; Servain *et al.*, 1998), which forms the nucleus about which the larger COSTA observation system is to be organized.

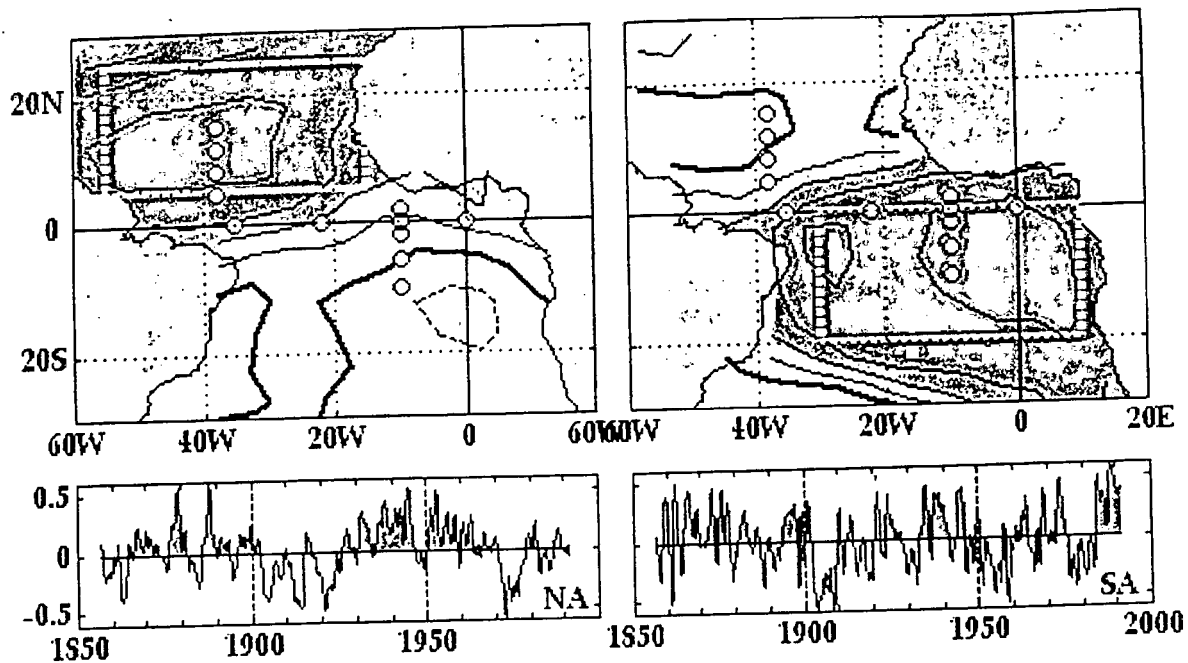


Figure I.5. Tropical Atlantic distributions of correlation between gridded SSTA (smoothed, El Niño-Southern Oscillation and trends removed) and two rotated empirical orthogonal functions (EOFs) of the data with high explained variance in the tropical North Atlantic (NA, left) and South Atlantic (SA, right). Positive values are shaded with solid contours, negative contours are dashed, the heaviest contour is zero, and the contour interval is 0.2. Dashed rectangles denote the areas over which the tropical North and South Atlantic area indices of SSTA (TNA and TSA) are calculated. Small circles show the mooring positions for the PIRATA array [Servain *et al.*, 1998]. Bottom: Temporal reconstructions of the NA, SA modal contributions to the SSTA variability within the respective TNA and TSA index areas (Enfield *et al.*, 1999).

The fact that most of the variability in the tropical Atlantic SSTA is non-dipolar, and the North and South Atlantic are to first order stochastically independent, raises a question: why is the meridional gradient-feedback mechanism, ostensibly capable of generating antisymmetric configurations of SSTA, overwhelmed by incoherence between the hemispheres? Are the TNA and TSA regions being forced predominantly by *random* atmospheric variabilities, which are themselves incoherent? Or, are they forced by spatially organized, larger scale climate oscillations that are mutually incoherent (like the NAO versus a distinct oscillation affecting TSA)? The interconnections seen between TNA, the NAO and the MOC lead us to suspect that the latter is true, although random forcings undoubtedly also occur. Whatever the importance of dipole configurations, predictive methods must aim at the meridional gradient and should account for all significant sources of gradient variability. Since dipoles tend to occur preferentially at decadal time scales and are associated with the largest gradient anomalies (Figure I.6), it will be especially important to study the physical mechanism(s) behind them. Although models may never have skill decades in advance, it is hoped that they can eventually predict decadal phase changes with lead times of seasons to a year or more.

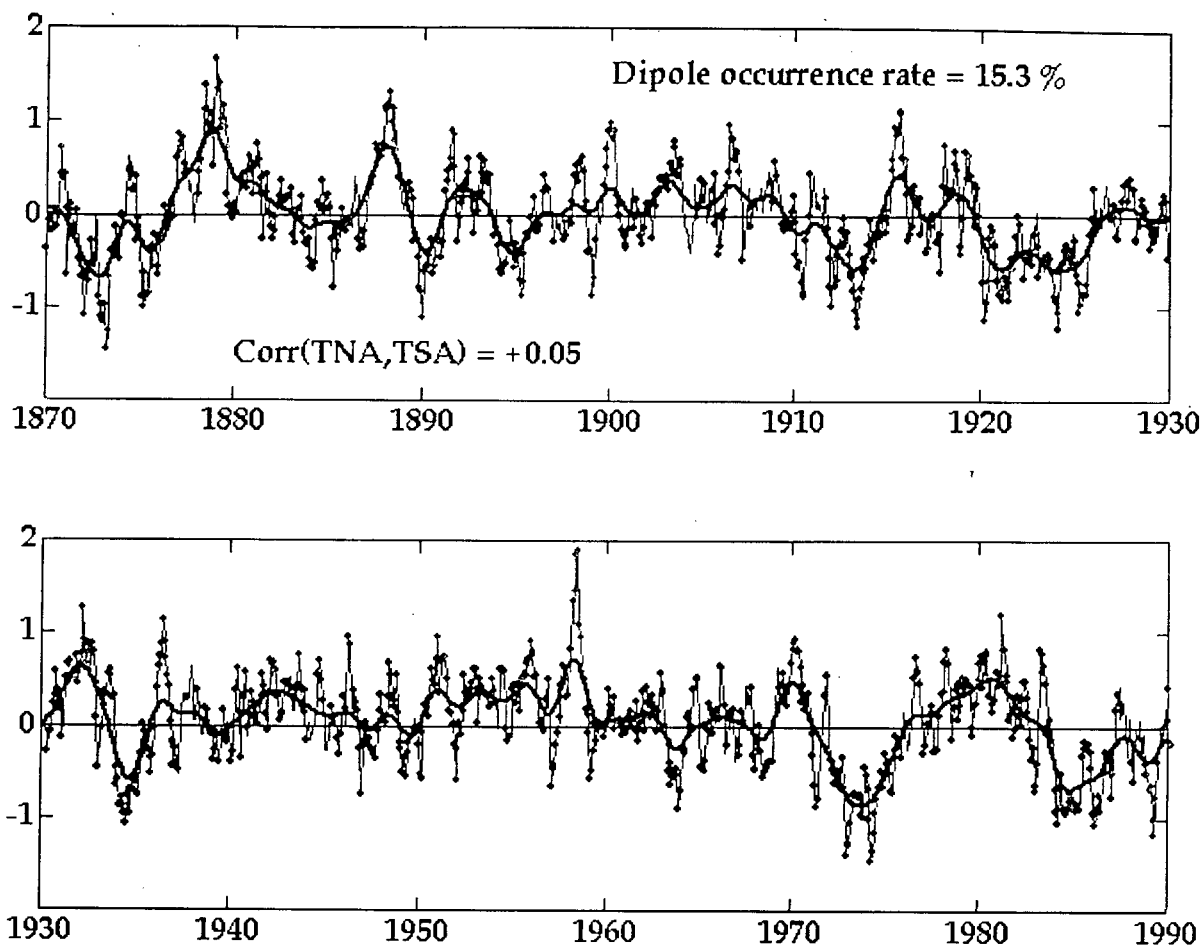


Figure I.6 Time series of the tropical Atlantic gradient index, formed by the difference between SSTA area indices for the tropical North (TNA) and South Atlantic (TSA). Colored dots are monthly averaged data and the smooth black curve is the triple 13-month running mean of the data. Red dots mark monthly averages where TNA and TSA were of opposite sign and their magnitudes exceeded $0.2\text{ }^{\circ}\text{C}$ (dipole configurations). Blue dots indicate months when the tropical Atlantic was not in a dipole configuration.

After ENSO, the NAO is the most clearly demonstrated external connection to TAV. The coupled model integration of Delworth and Mehta (1999) reproduces the large scale North Atlantic pattern of SSTA that is associated with the NAO. When the leading EOF of the model SSTA is time-differentiated (tendency) and regressed with the surface heat flux, one sees a robust pattern with large weights in the TNA region (Figure I.7). Significant but smaller weights are seen when the same is done with the advective heat flux. A conclusion is that TNA interaction with the large scale climate pattern is primarily through the air sea flux (as we also see with ENSO forcing and gradient-feedback interactions) and that gyre advection anomalies play a proportionately larger role at decadal than at interannual time scales. The coupled model experiment of Xie and Tanimoto (1998) suggests that the NAO-TAV connection works in both

directions. When forced by winds north of 20°N, the model generates a meridional, inter-hemispheric gradient of SSTA that behaves like the observed gradient. The gradient appears to respond selectively to external forcing on decadal or longer time scales.

The modeling study of Rodwell *et al.* (1999) gets us closer to understanding the possible causes and effects of TAV interactions with the NAO. A global atmospheric model, when forced by observed SSTs and global sea ice extents, produces an NAO index whose fluctuations closely adhere to those of the observed index. When observed SSTA is regressed on the simulated NAO index, a pattern is obtained that is strikingly similar to the regression on the observation-based index (Figure I.8). This is an indication that three oceanic regions actively influence the NAO: an area south of Greenland, another area in the North Atlantic bight of North America, and a third in the western tropical North Atlantic. Missing from the model-based regression, however, is the correlation of the observed NAO index with SSTA off the coast of NW Africa. This is a strong indication that the eastern tropical North Atlantic is forced by the NAO, in contrast to the region west of there. Thus the tropical North Atlantic plays a dual role of forcing and response vis-à-vis the NAO.

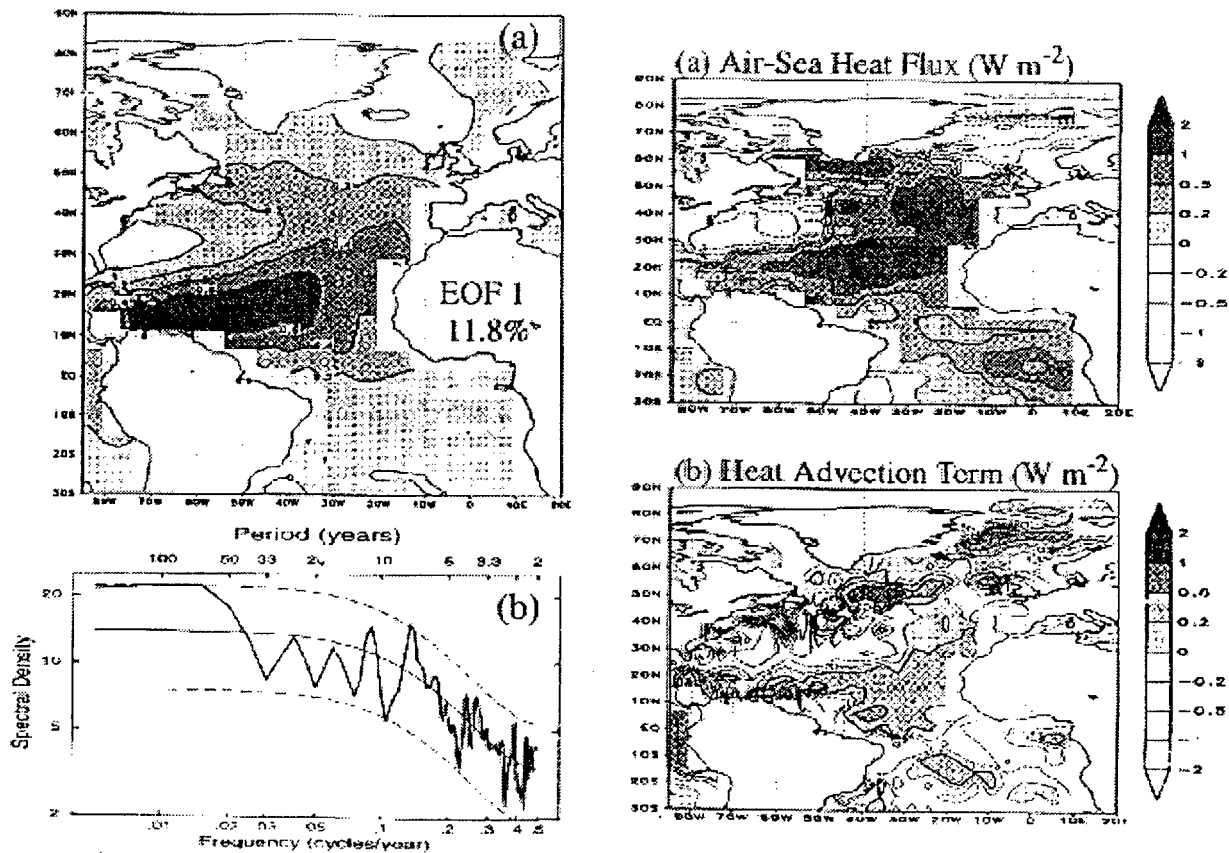


Figure I.7. Regressions of heat flux terms on the temporal derivative of leading mode of SST in the GFDL coupled ocean-atmosphere model. Top: Map of the regressions for the time series of the air-sea heat flux. Bottom: Same, but for the advective heat flux. Quantities were filtered to pass variability in the 5-30 year band. Units are W/m^2 , positive values are for flux into the ocean (Delworth and Mehta, 1998).

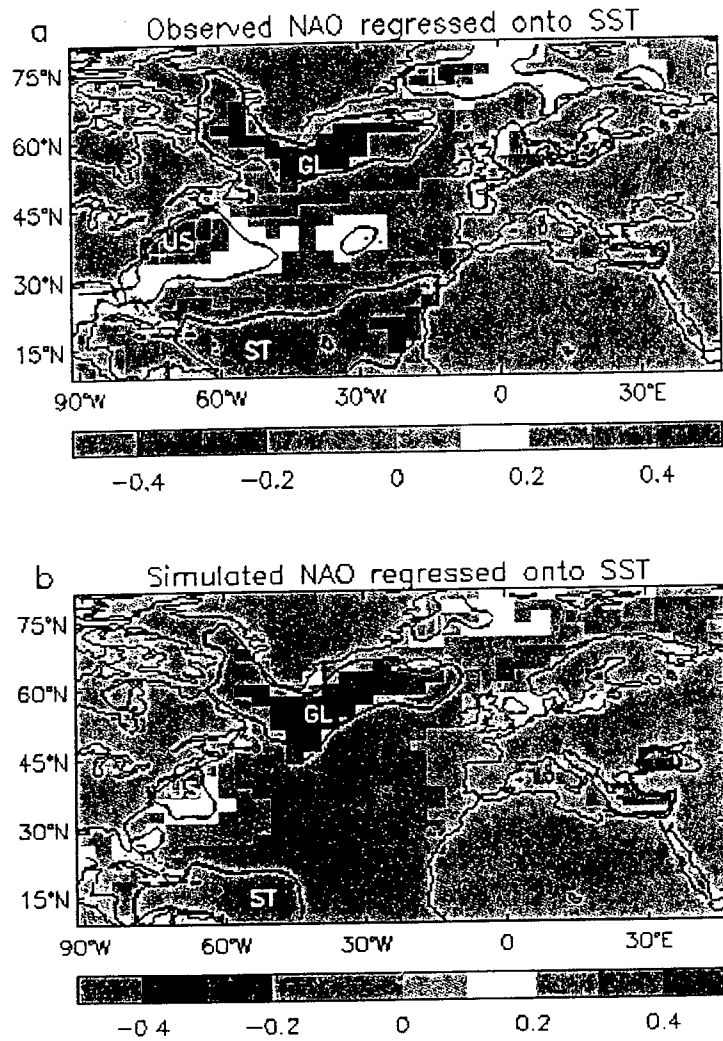


Figure I.8. NAO/SST regressions. Top: Regression of observed North Atlantic SST (annual averages) onto the 50-year time series of the observed unfiltered NAO index. Units are in °K and correspond to an NAO index anomaly of one standard deviation. Bottom: As above, but for regression of observed SST onto the ensemble-averaged NAO index of six AGCM simulations. The non-green areas within solid contours have correlation significant at the 95% level. (Rodwell *et al.*, 1999)

External forcing of the tropical South Atlantic is less obvious. The best candidate offered to date is that proposed by Robinson *et al.* (1999), based on a combination of modeling and observations. Their work shows a connection between SSTA in the TSA region, and meridional shifts in the Hadley cell formed by convection over the Amazon and subsidence over the subtropical North Atlantic.

All of the above background on Atlantic climate variability bears on the need for, and design of, an extended and more permanent observation system in the tropical Atlantic.

Workshop participants agreed that the observation 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; and
- (3) it must interact with modeling studies by providing relevant data for model-data assimilations and as verification for diagnostic and prognostic models.

In addition, it must (4) 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 four fundamental aspects: SST and surface fluxes; sea level and its related upper ocean thermal structure; the horizontal circulation; and modeling aspects. The next four sections deal with the results of the working group deliberations for those broad categories.

II. THEME 1: SST & SURFACE FLUXES

Large scale SST gradients are the key factor in driving the climate response in the tropical Atlantic sector and even over land areas as distant as the southern United States. A number of studies point to the dominance of SST fluctuations in the off-equatorial regions (± 5 to 15°) as a determinant of the meridional gradient across the equator. Thus, the processes responsible for those fluctuations must be a major target of tropical Atlantic research and its supporting observations. 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 Chang *et al.*, 1997) 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.

The equatorial region is also important for flux measurements, in two ways. One is through a dynamical zonal mode of variability not unlike the El Niño-Southern Oscillation in the Pacific, but much weaker and of shorter period (Zebiak, 1993). Fluctuations in the zonal component of the wind result in both local surface flux anomalies and in thermocline depth variations that also modify the effect of surface fluxes. On a larger scale, measurements and modeling have shown that the upper (northward) limb of the meridional overturning circulation (MOC) doubles its heat transport across the equator. The extra heat is thought to enter the upper ocean through the net surface flux over the equatorial cold tongue.

II.1 Science questions

Is the surface heat balance primarily vertical (1-D)? It is a frequently held assumption in oceanography that, away from the equator and land boundaries, SST change is governed mainly by surface fluxes (1-D). While this appears likely in the tropical Atlantic, it has not been conclusively demonstrated. Temperature advection due to Ekman transports under the trade winds could invalidate the assumption, as could advection by the mean gyre flow at decadal periods, or mixing when the upper ocean is thinly stratified. By focusing on the 1-D null hypothesis, the vertical balance will 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 change and the net surface flux (which must be accounted for by other means).

Which terms in the vertical balance control changes in SST? While we know that the evaporative heat flux (Q_e) will be larger than the sensible (Q_h) and long-wave radiative (Q_b) fluxes, the solar short-wave flux (Q_s) will likely be comparable to Q_e . 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).

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 (cloud 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 interesting question of the partition of Q_e between its components:

$$Q_e \propto \langle W \rangle \bullet \Delta q' + W' \bullet \langle \Delta q \rangle$$

where angle brackets refer to climatology and primes to nonseasonal anomalies. Modeling work (Chang *et al.*, 1999) suggests that the first term dominates in the cold water region surrounding the Cape Verde islands, while the second term dominates from the 38°W PIRATA line westward to the Caribbean. The question is relevant to how the tropical Atlantic interacts with the atmosphere because the former region appears to be one where the ocean is forced by the NAO, whereas the latter region appears to be the reverse (Rodwell *et al.*, 1999). Radiative fluxes will be comparatively more important in the cold water regions, as off NW Africa. They may account for as much as 30% of the evaporative contribution, and the cloud response to SSTA is likely such as to reinforce the temperature anomaly (positive feedback) (Tanimoto and Xie, 1999).

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

II.2 Observational requirements

Better coverage of in-situ SST - Good SST measurements will be absolutely critical in the tropical Atlantic, for several reasons. SST variability in the Atlantic greatly affects the surrounding land climates, yet it has only a fraction of the non-seasonal amplitude observed in the Pacific. In terms of the above science questions, SST is the target variable, and the SST tendency is crucial 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 (IR) estimates. The resultant 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.

Better coverage of in-situ winds - Wind speed is critical for the estimation of sensible and latent heat fluxes through bulk aerodynamic formulae. As with SST, huge disparities exist between the Atlantic wind analyses of the operational centers. Unlike the Pacific, the PIRATA array only provides reliable wind measurements at one longitude of each hemisphere, while VOS observations suffer from variations in measurement height and superstructure impedance of the airflow, among other factors. Satellite-based estimates of wind may explain some of the discrepancy, inasmuch as ECMWF now uses ERS 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.

Direct measurements of surface fluxes - At present, the net surface heat flux ($Q_n = Q_e + Q_h + Q_s + Q_b$) can only be estimated to an accuracy of about $\pm 40\text{-}50 \text{ W/m}^2$ by conventional methods (e.g., COADS plus bulk aerodynamic formulae). Similar methods applied at the Atlas moorings can probably lower this by 10 W/m^2 and another 10 W/m^2 might be gained by fine-tuning the PIRATA array. However, the coefficients used in the bulk aerodynamic formulae on which such estimates rely vary geographically due to changes in friction layer stability, mean wind speed and other factors. Only high quality, direct (turbulent) measurements of the surface fluxes can 'calibrate' the coefficients and thus allow flux uncertainty reductions to near the $\pm 10 \text{ W/m}^2$ 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.

Surface calibration of satellite flux estimators - Most of the variables in the bulk formulae can be estimated by satellites, to varying degrees of accuracy. The flux-error impacts are probably smallest for wind speed estimated from high-quality scatterometry, and largest for the specific humidity (mixing ratio) estimated from brightness temperatures. Both of these can be improved by having in-situ comparison measurements in widely differing environments such as the western off-equatorial Atlantic (warm, positive sea-air temperature difference), near the African coastal upwelling zones (cool, negative/small sea-air temperature difference), the ITCZ (warm, low wind speeds, high tropospheric water vapor content), and the equator (upwelling, highly seasonal). The single variable that cannot be estimated by satellite - air temperature - must be parameterized in a manner that almost certainly must vary from region to region. That parameterization can only be done with quality in-situ measurements

II.3 Recommendations

Increased SST coverage by surface drifters - Surface drifters appear to be the most effective and cost-efficient way to improve SST analyses based on the blending of satellite temperatures with surface ground truth, as presently done by the operational centers. The density of drifter seeding in the Atlantic should be at least equal to that of the Pacific and probably greater, given the comparative paucity of Atlas moorings, the smaller variability of SST, the greater problem of aerosols and the tendency for drifters to disperse and ground more quickly in the smaller Atlantic basin.

In a recent improvement of the drifter design, it is also possible to measure sea level pressure, wind speed, and wind direction for only double the cost of an SST-only drifter. An immediate task would be to test and evaluate the performance of these new drifters to determine if their usefulness merits an investment in them. If indeed it proves effective, it may also be a solution for improving the coverage of wind measurements. The SLP measurements would be valuable poleward of $\pm 10^\circ$, especially in the hurricane development region west of the Cape Verde Islands.

Improved measurements on key VOS routes - The instrumentation of certain vessels of opportunity should be upgraded along high priority VOS routes. Something like the IMET instrumentation suite (developed by Woods Hole) can be installed on the more reliable vessels. This is an automated and standardized package that includes replacement of ship injection temperatures with a hull-mounted SST sensor or an in-line thermosalinograph (thus adding salinity), plus improved meteorological measurements with automated correction of winds for ship motion.

Direct flux measurements from research vessels and moored buoys - The French research vessels (*Thalassa*, *Atalante*) presently have the capability for bow-mounting a specialized mast for making direct flux measurements. A French project to do this is already funded, but only for limited use. Although this method does not provide good temporal coverage at any one location, it is an excellent way of initially evaluating the scope of geographical variations in the bulk aerodynamic formulae, thus targeting sites for the deployment of moored air-sea flux buoys. It might also be feasible to adapt such measurements to the Brazilian mooring vessel, *Antares*.

The minimum requirement for improving surface flux estimates from the observing system is to deploy moored buoys that measure turbulent fluxes directly at selected, widely dispersed sites where the bulk aerodynamic coefficients are expected to vary from typical *ad hoc* values. The IMET buoy, developed in the mid-1990s by Woods Hole and deployed during the TOGA-COARE experiment, constitutes the prototypical example of such a mooring (Weller and Anderson, 1996). Another approach is to co-locate such buoys next to one or more Atlas buoys in order to evaluate the latter and improve the flux estimates obtained from them. The minimum duration of a flux mooring should be one year (to cover all seasons), with a longer period possible if adequately justified in the proposal process. During the first few years, a number of "roving" flux buoys can be successively deployed at optimal sites. The highest priority for initial deployment is located near 15°N, 51°W (⊗ symbols on map, Figure VII.1). This is at the offshore terminus of a research array which will jointly be deployed by Germany and Woods Hole for at least five years to study the northward branch of the MOC, and is also an ideal site for an operational extension (Atlas buoy) for the PIRATA array (see recommendations of the circulation group). It is an especially attractive site for flux measurements because it is in the region where the $W' \cdot \langle \Delta q \rangle$ term may dominate Q_e and be involved in oceanic forcing of the NAO. Another high priority site would be near the Cape Verde Islands where presumably the $\langle W \rangle \cdot \Delta q'$ term dominates and the NAO is thought to force the ocean. This site also lies along the important VOS track between Brazil and Europe and can be used to evaluate and calibrate an IMET-style shore station in the Cape Verde archipelago. We note, however, that an IMET-style mooring was located at 18°N, 22°W for an 18-month period in 1992-93 (Subduction Experiment, Moyer and Weller, 1997), whose measurements may suffice for this purpose. Other sites (⊗ symbols on map, Figure VII.1) are: (3) at the mean position of the ITCZ, which would move seasonally across the mooring site, and (4) in the Gulf of Guinea cold tongue where the addition of heat to the ocean may add to the meridional transport of the MOC.

Instrumentation of island shore stations - Where logistically feasible, IMET-style automatic stations at selected island shore sites are a cost-effective way to get flux-relevant measurements for the long term. We have already made initial contacts with knowledgeable present and former Cape Verde residents, to study the feasibility of such an installation in the archipelago, which is logistically distant for mooring vessels to maintain a permanent mooring. Other possible island sites are also indicated on the map (*, Figure VII.1).

III. THEME 2: SEA SURFACE HEIGHT / SUBSURFACE T-S STRUCTURE

III.1 Science questions

The discussions in this theme were organized into two categories, upper ocean variability and deep ocean variability, with the latter being defined as below 1000 m.

The scientific relevance of upper ocean variability can best be seen through the overlap with the discussions and recommendations of the working groups for SST and air-sea heat fluxes (Section II) and circulation (Section IV). To investigate the surface flux and advective processes that influence SST, observations of upper ocean temperature and salinity are also required. Hence, upper ocean T and S variability complements the other areas and directly or indirectly is relevant to the same fundamental questions of climate variability that were discussed in Section I. For example, upper ocean T and S variability are relevant to the science questions for SST and surface fluxes because subsurface measurements are required to estimate the vertical mixing and vertical advection terms in the vertical heat balance. They are relevant to the horizontal circulation because vertical integration of the upper ocean T, S structures give dynamic height, which is in turn required to estimate the geostrophic component of the circulation. In addition, the sea surface height measurements give another estimate of surface geostrophic circulation and estimates of heat content of the upper ocean.

Heat content integrated vertically to 400 m exhibits seasonal changes within 15 degrees of the equator, which have been shown to be largely dynamically forced. What are the effects on SST? On the seasonal time scale, it is well 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 true on interannual time scales as well? Does it hold true in other parts of the tropical Atlantic? These questions are difficult to address given the present observations.

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. 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. But the question remains, where is this process most important and what role does it play in the interannual variability of SST?

Salinity data are also very helpful in understanding the evolution and geographical distribution of water masses. The thermocline water near the equator is mostly of southern 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 North Equatorial Countercurrent (NECC). This boundary probably changes seasonally, in particular near northeastern South America. But what is the extent of variation of these water masses? Does the modulation of the shallow subtropical cells or of the circulation manifest itself in changes of subsurface salinity?

To obtain T and S fields, it is useful 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 the global fresh water budget and sea surface pressure). Sea surface height changes are strongly correlated in the tropics with changes in thermocline depth, although they are more directly related to the steric change integrated over

the water column (i.e., low frequency bottom pressure changes are small). 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. For example, one ring off northwestern South America was identified with peak dynamic signature in the thermocline. The annual signal, on the other hand, extends to the bottom in large parts of the equatorial Atlantic, with clear phase propagation. One should also consider dynamic height changes associated with salinity signals caused by river outflows or rainfall, which might be particularly important in the western Atlantic in the area straddled by the displacements of the ITCZ, and affected by the advection of fresh water from the Amazon. We give these examples to emphasize the complementary nature of the in situ T-S data and sea surface height observations, but questions remain. How can these two streams of information be optimally combined

Turning now to the deep ocean, investigations of this variability are necessary in order to detect possible changes in the deep water masses and in the transport of the MOC. The tropical Atlantic poses specific challenges and opportunities compared to other parts of the Atlantic. For example, the southward path of the deep waters formed in the North Atlantic (the "cold limb") is along the western boundary, but with variable paths at different depths and intense recirculations in the ocean interior, and the most intense and most complicated paths are near the equator. There are, however, a few sites where the circulation is better known and where the water mass properties can be more easily monitored, mostly away from the equator both to the north and to the south.

To study changes in the deep water masses and in the transport of the MOC, it is necessary to deploy a series of top-to-bottom moorings that are adequate to monitor the changes in water masses and baroclinic transports. In addition, hydrographic cruises to survey the large scale distribution of water masses are desirable. These hydrographic surveys should be repeated periodically (on the order of 5 years). The top-to-bottom mooring arrays proposed in the working group were to a large extent placed to monitor the transports off and in the equatorial zones (arrays at 16°N and 7.5°S), and will mostly be discussed in the Circulation sub-theme. We will therefore concentrate on the upper ocean variability, and will successively summarize recommendations for the sea surface height and subsurface components of the observing system. It should be remembered that there is a third component needing proper consideration, which concerns the optimal mix of the different sets of data. To some extent, this is one aspect of the data "assimilation" theme, although it was concluded that that estimates based only on the data would also be very valuable.

III.2 Observational Requirements

In this section and the next we break the discussion into a sea surface height section and a subsurface T-S section.

a) Sea surface height

The desired observing system should contain:

- Altimetric fields, supported by tide gauge measurements. These fields will be the base of the sea surface height component of the observing system. The altimetric fields should provide estimates of sea surface height to within 2 cm uncertainty on a monthly time scale (2 cm is equivalent to a 10 m displacement of the thermocline, or a change of 0.2 in salinity over 100 m). 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 (Mitchum, 1998). At present it is possible to constrain the altimetric drift to be less than 1 mm/yr, and the technique is continuing to improve.

- Pairs of tide gauges 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.

- The altimetric-based system is 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 interannual 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 should be the entire Atlantic basin. First of all, the amount of effort required to provide the sea level data from tide gauges is not large enough to justify splitting the tropics off. Second, just as the tide gauges provide an inexpensive way to provide historical context for the tropical variability observed by the altimeters, a basin-wide sea level dataset can also be used to make zero order estimates of relationships between the tropical variability and higher latitude variability. This is especially important if the tropical variations are thought to be possibly related to basin scale phenomena such as the MOC and NAO.

b) Subsurface T and S

The desired observing system should contain:

- An array of moorings in key positions to observe and monitor the climate modes of variability. A pilot array, PIRATA, was initially deployed in 1997 and will be maintained until the year 2000. It consists of 12 next generation ATLAS buoys deployed with the objective of describing and understanding the evolution of SST, upper ocean thermal structure, and air-sea fluxes of momentum, heat and fresh water in the tropical Atlantic. Observations are transmitted to shore via satellite by Service Argos and are available in near real-time. This array is considered the Atlantic extension of the TAO array in the Pacific.

- An integrated profiling float observing system. A float array will provide information on SST variability in regions between the moored observations.

- VOS-based observations of the temperature profiles in the upper layers to complete the description of the SST variability and to provide a description of the temperature distribution in the upper layers. The VOS system also provides an excellent means of collecting surface salinity measurements.

III.3 Recommendations

As above we will first present the recommendations concerning sea surface height, and will then turn to conclusions regarding observations of the subsurface temperature and salinity by the moored array, by profiling floats, and by the VOS system. We conclude with a brief recommendation concerning data products.

a) Sea surface height

First, we need to improve the sea level pressure fields in the tropical Atlantic. In order to be most useful for oceanographic use, the sea surface height fields provided by altimetry are adjusted for atmospheric loading in order to obtain an estimate of the oceanic surface pressure field; i.e., we need to apply the inverted barometer correction. For altimetry the required atmospheric sea level pressure (SLP) fields are obtained from model simulations that need to be improved, both regionally and globally. On a regional basis, adding SLP measurements on the PIRATA array, whenever this is feasible, would be the first priority. Adding SLP near tide gauges would also be valuable, in particular at the gauges used to monitor the flow through straits. It would also be useful to add SLP measurements to drifters, particularly in "hurricane alley".

Second, in order to make the best estimates of the altimetric drifts and to correct for such errors, it is necessary to have high frequency (i.e., hourly) data from the tide gauges in near real-time. At present the observing system for sea level is relatively weak along the equator in the Atlantic and along West Africa, in that reliable gauges do not exist or existing gauges do not report data in a timely manner. This is the case of the equatorial stations (Atoll das Rocas or Fernando de Noronha, Sao Pedro e Paolo, and Sao Tomé), and continuing these gauges and improving the data flow should be a priority. But for the most part the necessary gauges exist and the effort required is mainly to improve the reliability and the data flow.

Third, the historical tide gauge data set must be improved. At many gauges with long records only monthly mean records are available in digital form. It is difficult, if not impossible, to properly quality control a monthly mean data set. The hourly readings are required to do a thorough job of quality control, mainly because the tides provide an internal clock for checking timing (a common error in tide gauge records) as well as a scale check since the tidal amplitudes are very stable over time. Also, higher frequency data (e.g., daily data) is required to properly diagnose even interannual variability if this variability is related to the fast waves that can exist at the equator. Finally, studying the modulations of high frequency phenomena (e.g., storm surges) over interannual to decadal time scales is intrinsically interesting and requires hourly data. Obtaining these hourly readings will require a data archaeology effort. In some cases digital records may exist but have not been sent to international data centers for distribution; in some cases only paper records exist and need to be digitized. The initial areas of focus should be the coasts of Central and South America and West Africa, as this is where most of the long historical records are likely to be found.

b) Subsurface T and S from a moored array

The desired observing system should contain an array of moorings in key positions with respect to the expected modes of climate variability. The main recommendations concerning the moored array are to continue the existing PIRATA array to a transition period of 5 years and to expand the array during this period at pilot sites.

On the maintenance and expansion of the present moored PIRATA array, the following

recommendations are made (See also the PIRATA Resolution, Appendix 1). First, it is recommended that the maintenance of the present array be insured for a transition period 2000-2005, with the possible reexamination of any sites with a high failure rate, which will be assessed at the end of the pilot phase in early 2001. Second, based on the performance of the current pilot array, additional salinity sensors should be included, in particular near the surface. It should be kept in mind that if recent technological developments (profiling moorings, for example) prove to be feasible and cost-effective, then these could be used to improve the present subsurface sampling of salinity.

To expand on the recommendation to continue the array through the transition period, the different recommended sites are listed below with an assessment of how these subsurface measurements will contribute to the study of the climatic modes of variability. Note that locations are approximate, and refer more to a region than to an actual deployment site.

20°N/38°W - 15°N/42°W: along the easterly wave track. These sites will contribute to the study of the interaction between easterly waves and SST and their possible development into mature tropical hurricanes. In addition to its contribution to climate, this site is of critical importance for prediction studies.

20°N/20°W (or 15°N/20°W): within the upwelling tongue off northeast Africa. This is a major center of SST variability. It is expected that the feedback of the air-sea fluxes will be negative (i.e., will damp the anomalies), and that the anomalies will result from changes in the upwelling. Based on these considerations, 20°N would be favored over 15°N. However, 15°N is in an area of larger subsurface seasonal variability associated with the Guinea dome.

15°N/51°W: in the area of the western Atlantic where it seems that the air-sea feedback is positive. It is also at the border of a major pathway between the tropics and the subtropics and will contribute to monitoring the fluctuations of the warm water limb of the MOC.

10°N/25°W: this site will contribute to the resolution of the NECC ridge and trough in the central sector (from EuroCLIVAR plans).

10°S/10°E and 5°S/5°E: sites of negative feedback of the air-sea fluxes on SST. Both sites are strongly influenced by the seasonal equatorial and coastal upwelling. The surface layer at these sites is within the seasonal extent of the outflow of the Congo. 10°S/10°E is within the Angol Dome, which is a boundary between equatorial and tropical circulation.

15°S/30°W - 10°S/30°W moorings (and in particular the southern one) straddle the position of the seasonal South Atlantic Convergence Zone (southern hemisphere summer), where short-lived SST anomalies seem to have direct influence on climate in southeast Brazil.

c) Subsurface T and S from the profiling float array

The continuation of the 6°S-20°N sampling was strongly recommended. This array covers the equatorial and northern elements of the major patterns of the tropical Atlantic variability. The 6°N-20°N component of the array is straddled by the ITCZ seasonal and interannual variability and by the outflow of the Amazon. It also overlaps the boundary between South Atlantic and North Atlantic central waters, that is likely to manifest interannual variability. Salinity is therefore a very important component of the array and it is recommended to add this capability to the floats when feasible.

Second, it is recommended that the array be extended to 20°S as soon as possible, and that the density of deployments be increased to the one recommended by ARGO (300 km separation).

Third, past float experiments have provided an interesting data set of drifts at 1000 m. It would be most valuable that the floats in the tropical Atlantic continue to be parked at a depth of 1000 m. They should profile to 2000 m in order to provide a stable reference for the conductivity sensor.

d) Subsurface T and S from VOS observations

It is recommended that the XBT lines be maintained until ARGO has demonstrated the capability to provide adequate sampling of the T,S fields. It was also recommended to resume some of the XBT lines and to collect high resolution XBT lines in specific regions. For example, neither ARGO nor the current VOS array achieves an adequate sampling near northwestern South America. This is an important region because of the role that the rings shed at the retroflexion of the North Brazil Current play in transporting heat and mass. It has been proven that many of these rings cannot be detected by the altimeter alone, and thus the VOS observations are critical. Also, with a better sampling in this region, it might be possible to provide a census of the rings shed at the retroflexion and of their vertical structures. This could be achieved either by increasing the frequency of crossings along line AX27, or by conducting a few high-resolution sampling crossings along that line.

Second, XBT sampling in the central Atlantic (25°W) should be resumed and the data that is currently being collected should be transmitted in real or near-real time. In addition, it is recommended that the thermosalinograph measurements presently being collected by various vessels in the equatorial Atlantic be transmitted in near-real time, in particular for the four vessels of the IRD-network. It is also recommended that the data collected from the Antarctic research vessels (Polarstern, J.R. Clark) be made available to the research community.

e) Recommendation concerning data products

Products based on the data (both in situ and remotely sensed) would be a very valuable reference for more sophisticated analysis techniques involving models (e.g., assimilation, inverse modeling, etc.), and might be combined with other data sets for climate studies. We recommend that the production of such fields be encouraged, and that these products should be made available to the community via the GODAE site. We envision data products describing the T and S fields, the dynamic height field, velocity, and others.

IV. THEME 3: CIRCULATION

IV.1 Science questions

The meridional overturning circulation (MOC) was the primary focus for the COSTA Circulation Working Group discussions. Another related focus was the role of ocean dynamics in regional upper ocean temperature budgets. The MOC consists of upper (warm) and lower (cold) limbs, with the difference in internal energy transport between these limbs accounting for the net northward internal energy transport from the southern to the northern hemisphere. What remain unclear are the pathways and mechanisms by which this transport is achieved.

For the upper limb, the connections between the southern and northern hemisphere subtropical gyres include two highly time dependent intermediate gyres, a cyclonic tropical gyre to the north of the equator and a clockwise gyre that straddles the equator. Delimiting these gyres are swift, zonally oriented surface currents, the South Equatorial Current (SEC), the North Equatorial Countercurrent (NECC), and the North Equatorial Current (NEC), and subsurface currents such as the Equatorial Undercurrent (EUC) and the Tsuchiya jets. All of these currents, along with the dynamic topography gradients and surface winds that support and drive them, vary seasonally with the ITCZ such that the tropical Atlantic dynamic topography is relatively flat in boreal winter/spring and maximally corrugated in boreal summer/fall.

Along with this time dependence, the circulation is also three-dimensional. Upon approaching the equatorial region from the Southern Hemisphere, the northward internal energy transport of the upper limb currents is largely geostrophic. Upon exiting the equatorial region into the Northern Hemisphere, the internal energy transport is largely ageostrophic and contained within the near surface Ekman layer. Thus, a large vertical circulation must exist near the equator. One manifestation of this vertical circulation is the seasonally varying equatorial cold tongue where mid-thermocline waters rise to the surface. This sets the stage for air-sea interactions that drive the winds and account for the approximate factor of two increase in the annually averaged net northward internal energy flux across the equatorial region. To accomplish the annually averaged upper limb transports the ocean and atmosphere operate as a closely coupled system. SST is the basis for the ocean-atmosphere coupling, and the cold tongue provides most of the seasonally varying SST gradient both meridionally and zonally. Therefore, the cold tongue, combined with the ITCZ, is largely responsible for the surface wind field, the dynamic topography, and the circulation. It follows that the equatorial cold tongue should play an important role in Atlantic climate studies for time scales ranging from annual to interdecadal. Clockwise wind stress curl in the vicinity of the equator results in a southward basin-interior Sverdrup transport, so a net northward transport of water across the equator requires a strong western boundary current. After crossing the equator some of the western boundary current water seasonally retroreflects into the NECC and the EUC, and some is transported farther north as North Brazil Current (NBC) rings or eddies. The partitioning of the circulation pathways between the basin interior and the eddies along the western boundary remains a fundamental upper limb pathways question. Also, the mechanisms by which the waters communicate and mix between these various currents as they undergo their seasonal cycles requires elucidation. These issues of pathways and mechanisms are fully three-dimensional and time dependent problems.

The lower limb is similarly complex. Below 1000 m depth the cold limb contains two deep current cores that flow swiftly southward in the Deep Western Boundary Current (DWBC). The upper North Atlantic Deep Water (NADW) core is centered near 1600 m and the lower NADW core is near 4000 m. North of the equator the transport of the DWBC is two to three times larger

than the net interhemispheric transport of NADW. This excess transport is recirculated northward offshore of the DWBC in the Guiana Abyssal Gyre. DWBC water splits near the equator with portions feeding zonal currents and eventually recirculating in countercurrents. Like the upper limb currents, the DWBC and its related deep equatorial currents also vary seasonally. The time dependent zonal pathways within the equatorial band appear to act as temporary reservoirs for NADW on its way southward, with the seasonal pulsations providing mechanisms for mixing. At deeper depths the northward flowing Antarctic Bottom Water (AABW) splits near the equator. Part flows eastward through the Romanche Fracture Zone and part continues northward merging with the lower NADW in the Guiana Abyssal Gyre.

These basic descriptions of the upper and lower limb circulation and their three-dimensional, time dependent nature within the tropical Atlantic Ocean suggest the following science questions to be answered.

- A) What are the pathways for the MOC upper and lower limb circulations across the tropical Atlantic Ocean
- B) What are the pathways of thermocline ventilation between the subtropics and the equator
- C) What are the mechanisms by which water properties are mixed and modified as fluid transits the tropical Atlantic Ocean
- D) What are the coupled ocean-atmosphere processes responsible for the increase in northward heat flux across the equator?
- E) What is the ocean circulation's role in controlling the meridional and zonal SST gradients
- F) What are the interactions between SST and the fresh water flux within the tropical Atlantic

IV.2 Observational Requirements

Increased monitoring activities will help provide long-term descriptions, but monitoring alone will not provide information on how the actual processes work, which is required to improve model physics and parameterizations. Process experimentation is necessary. This is particularly true of the fully three-dimensional, time dependent system of the tropical Atlantic where the details of the circulation may be tied to non-isentropic processes. Under such conditions numerically modeled circulations are highly dependent on the employed parameterizations. Independent data sets are needed for diagnostic calculations, and will have the added value of helping to improve numerical models. Process experiments and improved descriptions of nature will improve the overall set of tools available to the research community.

IV.3 Recommendations

To satisfy the observational requirements, the COSTA Circulation Working Group makes the following recommendations.

- 1) Produce seasonally varying surface and upper ocean current fields by a combination of floats, drifters, altimetry, and winds.

Surface drifters, satellite altimetry, and surface wind fields may be used to map the surface

currents using Ekman and geostrophic assumptions. Thermal wind shear fields, calculated from quasi-stationary profiling floats, coupled with the surface currents will provide upper ocean circulation maps. If these existing resources are augmented by Lagrangian floats at thermocline depths then the upper limb circulation pathways, mechanisms, and water mass modifications enroute could be determined. The pathways of thermocline ventilation between the subtropics and the equator will also be refined. These observations will begin to provide a three-dimensional context to the time dependent T/S observed by the PIRATA array.

2) Monitor the MOC in the western tropical Atlantic.

A preliminary assessment of the variability of the cold limb of the MOC in the western tropical Atlantic begins in early 2000 with the deployment of the GAGE/MOVE moored arrays near 16°N (see Appendix 4, GAGE and IfM Kiel Programs). The German CLIVAR program is funding the "Meridional Overturning Variability Experiment" (MOVE) as a three-year pilot effort to monitor the baroclinic variability of the cold limb of the MOC. The technique is to use three "dynamic height moorings" combined with bottom pressure gauges to estimate the variability of the across-basin average deep baroclinic shear. These moorings will be annually renewed to yield a three year time series of baroclinic variability. The U.S. Guiana Abyssal Gyre Experiment (GAGE) array adds additional moorings with conventional current meters, so that the combined GAGE/MOVE array of 10 moorings will measure currents at several levels of the cold limb across the whole Guiana Basin for a two year period, quantifying the deep recirculation cell of the basin.

The GAGE/MOVE array could be enhanced to develop a complete cold limb and warm limb MOC monitoring array to continue after the 3-year pilot phase of MOVE, and after the two year GAGE process experiment ends (see Appendix 4, TAMOC). Enhancement could include upgrading the technological approach for dynamic height moorings to moored profiling CTD and velocity devices. The long term monitoring array could be expanded from the three German MOVE sites (which alone focus on the MOC cold limb) by adding moorings near the western boundary (for example close to Trinidad and SE of Barbados), and near the eastern boundary (for example, south of the Cape Verde Islands), adding a profiler to the 15°N/38°W PIRATA mooring, and calibration of the telephone cables between the Windward Islands to enable their use for transport monitoring. Some of these suggested mooring sites are also candidates for surface flux measurements (see section II.3 and Figure VII.1)

3) Determine deep recirculations and water mass modifications by extending the deep array at 7.5°S to the mid-Atlantic ridge.

Beginning with the northern entrance to the tropical Atlantic, and continuing across the equator to the southern region there is a need to quantify the deep water transport variability, including basin wide deep recirculation cells, temporal variations, and water mass characteristics. Basin-wide recirculation cells are anticipated on either side of the equator and swift zonal currents communicating through upwelling/downwelling cells are anticipated on and near the equator. The mixing and water mass modifications inherent with these circulations may play an important role for interhemisphere exchange of NADW and AABW. Pathways and water mass transformations of the deep water in the equatorial belt are poorly understood. Observations show an eastward salinity/tracer tongue that varies along the equator, and eastward advection is observed by current meters at upper and lower NADW depths. Both deep floats and current meter moorings show seasonal variations in the deep currents, which may play an important role in water mass transformations.

South of the equator, at 5°S , the deep water masses show sharp contrasts in their characteristics compared to observations farther north. This suggests that the equator acts as a transformation zone for NADW as it flows from the northern to the southern hemisphere. However, the mechanisms and consequences are not well understood.

A moored array will be established near 7.5°S for at least four years from year 2000 onwards to monitor the DWBC and its water mass characteristics. PALACE float deployments and shipboard, hydrographic, and current profiling observations in the western basin of the tropical Atlantic will support the moored observations. To enhance these observations, an eastward extension of the 7.5°S moored array to cover the whole western basin of the northern South Atlantic is desirable. An attractive method would be the addition of the "end-point" dynamic height moorings (see point 2, above), when their feasibility has been shown in the process study farther north at 16°N . This enhancement will help to improve our understanding of the mechanisms of the lower limb circulation.

4) Determine the relative importance between ocean dynamics and surface fluxes in the seasonal evolution of the equatorial cold tongue by implementing an equatorial divergence array for water mass, temperature, and salinity, with complete surface fluxes.

Equatorial SST evolves as a subtle trade-off between ocean dynamics, that generally tend to cool, and surface fluxes, that generally tend to warm the near surface region. Since the ocean adjusts its surface heat fluxes to dissipate anomalous SST, experiments using coupled numerical circulation models alone show difficulty in assessing the evolution of the coupled ocean-atmosphere system. An equatorial array is needed to provide an independent in-situ data set that resolves the seasonal variability in the equatorial divergences of water volume, temperature, and salinity, along with complete surface fluxes. The array should consist of separate, paired, moorings for velocity and for temperature and salinity about a central pair of moorings which also contain surface flux sensors. Imbedding this array within the PIRATA array and PALACE floats will provide a process experiment in the context of the larger scale temperature and salinity fields.

Locating the array follows from observations and equatorial ocean dynamics. Cold SST first appears in the central equatorial Atlantic in boreal spring, immediately after the trade winds intensify. Initially, cold SST on the equator is separate from cold SST along the African coast. With time the equatorial cold tongue spreads eastward and westward, and links with cold SST along Africa, but the coldest SST remains on the equator near 10°W . Equatorial upwelling results from Ekman divergence and geostrophic convergence. On an annual average Ekman divergence wins out near the surface, while geostrophic convergence wins out within the thermocline; the total convergence is strongest at the EUC core. These dynamics suggest that the array should be centered on the equator west of 20°W , where the zonal component of wind stress (Ekman divergence) and zonal pressure gradient (geostrophic convergence) are both seasonally strong. The existence of colder SST near 10°W is a consequence of processes that occur to the west as the thermocline adjusts seasonally. Maximum upwelling actually occurs west of the region of coldest SST. In addition, equatorial symmetry (important for diagnostic calculations from moorings) is best developed in the center of the basin.

The array will provide further insights into mixing rates and near equator water mass modifications, and will provide critical tests for numerical models and possible suggestions for model improvements. The observations are primarily aimed at the upper ocean (down to the base of the thermocline), however, in principle there is no reason why the measurements cannot

be extended deeper to observe the reversal in the zonal pressure gradient, poleward export into the thermocline, and the Tsuchiya jets. This would provide another layer in the overall plumbing system of the equatorial Atlantic and additional information on the ventilation pathways for the equatorial thermocline. As such it will complement the profiling and drifting floats that are planned for the region.

5) Determine the annual cycle and interannual variability in the net surface heating and ocean dynamics influences on SST in all other important upwelling regions: the NECC trough, and the NW and SW African coasts

Other upwelling regions that add to the net surface heat flux within the tropical Atlantic are the regions within the NECC trough and the coastal upwelling regions along the NW and SW coasts of Africa. Ocean-atmosphere interaction buoys are recommended for deployment within these regions to quantify the fluxes of heat and momentum. Such buoys could be used in a diagnostic mode for the purposes of determining bulk transfer parameterizations. Once these are determined, a less expensive set of monitoring instruments could be substituted.

6) Determine circulation indices by enhancing and extending the existing PIRATA array to the South American coast.

The western PIRATA line along 38°W provides the capability to monitor zonal currents north of the equator, the SEC, NECC, and the southern part of the NEC. These currents are important in the seasonal cycle of the circulation and meridional heat transport in the tropical Atlantic and may show significant interannual variability in response to changes in forcing. It is recommended that the 38°W PIRATA line be instrumented to measure dynamic heights with sufficient accuracy so that it can provide indices of the strength of these currents and their seasonal to interannual variability. Some design studies may be required to determine what additional instrumentation is needed on the moorings, if any, and whether the mooring locations along 38°W should be adjusted slightly to better bracket the latitude limits of the main zonal currents.

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. An underlying question is the partition between the northward upper limb transports along the western boundary either directly or through NBC rings or eddies, as contrasted with transports in the basin interior due to the seasonally varying Ekman layer. The dynamical linkages between the cross equatorial flow and the zonal equatorial currents are also poorly understood on interannual time scales. Having simultaneous information on the western boundary current near the equator, the interior zonal flows along 38°W , and the upstream NBC near 7.5°S would help to resolve these issues and provide an improved understanding of the role of ocean dynamics in the coupled ocean-atmosphere system.

V. THEME 4: MODELING AND DATA ASSIMILATION

One of the main objectives of COSTA is to provide a comprehensive understanding of climate variability and its fundamental predictability in the tropical Atlantic sector. We recognize that sea surface temperature (SST) is a crucial parameter in controlling seasonal-to-decadal climate variation in the tropical Atlantic. The well-known droughts of Northeast Brazil, for example, are closely related to anomalously warm/cold SST anomalies in the tropical North/South Atlantic Ocean. Droughts in Subsaharan Africa are often found to be associated with a broad band of negative/positive SST anomalies across the tropical North/South Atlantic. Rainfall variability in the Central American Caribbean region and also the growth of North Atlantic hurricanes appears to be related to tropical North Atlantic SST fluctuations. The climate of this region is also influenced by or influences the climate of other sectors such as the tropical Pacific. Thus in order to address the goals of COSTA we need to develop appropriate models and data assimilation systems capable of reproducing tropical Atlantic climate variability on seasonal-to-decadal time scales. Development of this modeling capability is crucial to enhancing the forecast capability in the tropical Atlantic sector.

Tropical Atlantic SST variability is controlled by both "local" and "remote" processes. The "local" processes involve land-atmosphere-ocean interactions within the tropical Atlantic sector. The "remote" processes involve basin-to-basin interactions (e.g., remote influence of ENSO; Enfield and Mayer, 1998) and tropical-extratropical interactions (e.g., interactions with the North Atlantic; Robertson *et al.*, 1999; Yang, 1999). Currently, the underlying physical mechanisms that determine these processes are not well understood. Neither the relative importance of "local" vs. "remote" processes in tropical Atlantic variability. Modeling studies will be extremely valuable to shed light on these fundamental questions.

V.1 Science Questions

What is the role of land-atmosphere-ocean interaction in tropical Atlantic variability?

Modeling studies suggest that air-sea interaction in the tropical Atlantic may involve both thermodynamic and dynamic feedback. 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, and the latter involves the interaction between the trade wind and SST along the equatorial wave guide (Zebiak, 1993). A 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 (Battisti, 1999, personal communication). While land-atmosphere-ocean interaction is likely to contribute significantly to tropical Atlantic variability, the underlying physical processes that dominate the interaction have not yet been determined. Detailed modeling experiments are required to further explore the regional land-atmosphere-ocean interaction.

Why is climate variability so different between the tropical Atlantic and Pacific despite the fact that the two share many common features in their climatology?

Both the eastern tropical Pacific and Atlantic ocean are marked with a well defined ITCZ/cold tongue structure and a pronounced annual cycle in meridional direction. While the Pacific ITCZ interacts with the equatorially-symmetric ENSO mode, the Atlantic ITCZ is closely coupled with the inter-hemispheric SST gradient variation. The coupling mechanisms in the two basins appear to be different: the Pacific ENSO is dominated by a dynamic feedback, whereas the Atlantic

inter-hemispheric SST gradient variability is dominated by a thermodynamic feedback. The Atlantic variability is further complicated by the existence of an ENSO-like mode (Zebiak, 1993). A recent simple coupled model study suggests that the type of dominant modes, ENSO or dipole-like, may depend upon the zonal extent of the ocean basin (Xie et al. 1999). Further modeling studies are needed to investigate how other geographical and dynamical differences between the two oceans might lead to the observed difference in their variability.

To what extent and through what physical mechanisms is tropical Atlantic variability influenced by basin-to-basin interactions?

Modeling and empirical studies (e.g. Servain, 1991; Carton and Huang, 1994; Enfield and Mayer, 1998) have shown that ENSO exerts a strong influence on seasonal-to-interannual SST variation in the tropical Atlantic Ocean. However, the atmospheric connections 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.

To what extent and through what physical mechanisms is tropical Atlantic variability influenced by extratropical-tropical interactions?

The large scale atmospheric pattern reflected in the NAO may provide a major source of forcing to tropical Atlantic variability (Xie, et al., 1998). On the other hand, tropical Atlantic SST may dictate the NAO via influencing the Hadley Circulation (Robertson et al., 1998). The dynamic processes governing this interaction between NAO and the tropical Atlantic are not clear at the moment. Furthermore, in the ocean the tropical thermocline is connected to extratropical processes via both the ventilation/subduction processes and shallow meridional circulation. Ocean modeling and data assimilation studies are needed to explore the dynamic linkage between the tropics and extratropics in the Atlantic Ocean.

How does interhemispheric exchange influence tropical Atlantic variability?

Yang (1999) presents intriguing observational evidence that 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.

V.2 Recommendations

Model development: Modeling studies must play a crucial role in developing understanding of the complex climate physics of the tropical Atlantic. Models are the primary tool by which we can address "why" questions. Yet, presently available models show many limitations in this region. Atmospheric models do not simulate surface heat flux well. This problem results in a severe climate drift in most coupled GCMs. Improved parameterization of atmospheric boundary layer and land surface processes is also badly needed. Equally important is the need for improvement in oceanic mixing parameterization that has a direct impact on subduction and

other physical processes. Because they parameterize many of these processes, simpler models are extremely useful to gain theoretical understanding of certain processes and formulate hypotheses, while complex models are required to provide a realistic simulation of climate variability and comprehensive hypothesis testing. Thus our first recommendation is to support development of a hierarchy of coupled models for tropical Atlantic climate studies.

Process experiments: There is a need for dedicated numerical modeling process experiments targeted at certain key physical processes. We encourage support for experiments of the kind listed below:

Sector land-atmosphere-ocean interaction experiments: Stand-alone atmospheric GCMs can be used to identify the atmospheric response in the tropical Atlantic sector to SST forcing and continental heating, and to identify crucial regions where the atmosphere is most sensitive to change in the lower boundary condition. Coupled ocean-atmosphere-land models can be used to identify feedback processes over the land and over the ocean.

Remote influence experiments: Stand-alone atmospheric and coupled models can be used to identify key physical processes controlling the remote influence of ENSO and connections between the NAO and the tropical Atlantic. Particular attention needs to be paid to the Pacific-Tropical Atlantic connection via Walker Circulation and PNA and the tropical-extratropical connection via Amazon heating and Hadley Circulation.

Subduction and shallow meridional cell experiments: Stand-alone, high resolution ocean models can be used to examine oceanic tropical-extratropical via thermocline ventilation/subduction and shallow meridional cells. Of particular interest are the ventilation/subduction processes in the southern subtropical/tropical Atlantic where a direct link between subduction in the subtropics and the Equatorial Undercurrent is expected.

Inter-hemispheric exchange experiments: Stand-alone ocean models can be used to identify pathways that allow inter-hemispheric exchange to occur in the tropics. Of particular interest is whether northward transport occurs exclusively in the western boundary or whether there is a significant interior route. It is also of importance to identify and understand the physical mechanisms that cause delays in the seasonal-to-decadal meridional heat transport in the tropical ocean.

Design studies and monitoring systems: Numerical studies should be used to aid the design of an observing system by identifying critical and climate sensitive regions. For example, atmospheric GCM studies suggest that the northwestern tropical Atlantic appears to be a critical region in terms of air-sea coupling and remote influence of ENSO. Similar ocean modeling studies are necessary to identify critical regions in the ocean influencing fluctuations in meridional heat transport. Modeling studies are also needed to understand the processes that control SST and surface heat flux variability in Northwest Africa to aid design of a monitoring system in the region.

Predictability and prediction studies: a key goal of this research is the development of improved prediction capability. In striving for this goal we need to know what the intrinsic predictability is of climate (particularly rainfall) in this sector. Most present climate forecasting schemes in the tropical Atlantic are statistical. These statistical models have already demonstrated skill in seasonal forecasting. Dynamical models should be expected to show even higher skill. It is already apparent that the kind of dynamical model required must include the effects of atmosphere, ocean, and land processes (even though they may be parameterized), and will

require accurate initial conditions. Further it is a requirement that such a model be able to reproduce important historical climate variations, including SST, winds, and rainfall. It is also important to know the extent to which the tropical Atlantic SST is predictable and to understand predictable dynamics in the Tropical Atlantic. In particular we should determine if there are any particular regions of the tropical Atlantic where SST is more predictable than others.

The requirement of accurate initial conditions and knowledge of historical climate fluctuations means that that ocean data assimilation will be an integral part of this effort. There is a need to perform an intercomparison of ocean reanalyses to determine the advantages and limitations of a particular assimilation technique and the extent to which it can influence climate forecasts. In summary, in order to provide a critical mass of effort directed towards predictability and prediction we recommend the formation of a few prediction groups to carry out tropical Atlantic predictability studies which could ultimately lead to routine climate forecasts in the tropical Atlantic.

VI. STATUS OF THE OBSERVING SYSTEM

Operational programs and process studies that are currently taking place in the area define the present tropical Atlantic observing system. A brief description of the elements already in place and proposed is given in what follows. Further details are given in Appendix 4.

VI.1 Present operational program

VOS and XBT

Data are collected for operational purposes to initialize seasonal forecast models and to provide verification data for the simulations. Data are also used for scientific purposes to characterize the spatial and temporal variability of the upper ocean temperature structure; to provide information for interpreting satellite altimetric data; and to study the dynamics of the upper layers of the ocean. Several lines are operational in the Tropical Atlantic and maintained by the US, France and the UK (Figure VI.1 lower panel). Along those lines, meteorological and hydrographic (XBT) observations are routinely collected (4 times a day). France operates three lines that also collect sea surface salinity (TSG).

Surface Drifters

Satellite-tracked drifting buoy data are being collected by numerous investigators and agencies in several countries. These measurements are obtained as part of an international program designed to make this data available in an effort to improve climate prediction.

A basin-scale array of drifters in the tropical Atlantic (20°S - 30°N) will be deployed and maintained for at least one cycle of the "tropical dipole". Funding is in place for the first five years of a longer-term effort. A basic array will be deployed with an average resolution of $2.5 \times 10^5 \text{ km}^2$, which is approximately equal to 2 degrees latitude by 12.5 degrees 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 in the tropical Atlantic for the hurricane season to help with the forecasts of hurricane development and hurricane tracks.

The PIRATA Array

PIRATA (Pilot Research Moored Array in the Tropical Atlantic) is a multinational 3-year (1997-2000) pilot experiment of operational oceanography with the participation of Brazil, France and the USA. PIRATA, which can be viewed as an Atlantic extension of the Pacific TAO array, consists of 12 ATLAS moorings extending along the equator and two meridional lines (Figure VI.1). This specific configuration has been chosen to provide coverage along the equator of regions of strong wind forcing in the western basin and significant seasonal-to-interannual variability in SST in the central and eastern basin. The meridional arrays cover the regions of high SST variability associated with the SST dipole mode. 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 late 1997-early 1999 years (Figure VI.1 lower panel). The final phase of deployment is scheduled for July. In addition to the ATLAS mooring measurements, 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). During the last PIRATA meeting, PIRATA-6, which was held in Miami, FL, 3-4 May 1999, just before the COSTA meeting, it was proposed that the original PIRATA array continue to be maintained during an extra period of 5 years, 2001-2006. That will guarantee a smoother transition to an operational status under the auspices of GOOS/CLIVAR. During that period of consolidation, pilot extensions of the array will come in by the participation of new partners and the development of regional scientific rationales.

VI.2 Proposed operational program

ARGO

Two proposals for profiling floats are being considered in the United States. A pre-ARGO proposal has been funded for FY99 to develop the infrastructure for the large-scale experiment. The infrastructure will be developed in the context of float deployments in the tropical Atlantic north of the equator to study subtropical cells. Float deployments will begin towards the end of calendar-year 1999. The ARGO proposal for \$4,000,000 is presently being considered in the U.S. budget process. The U.S. plans to contribute 1/2 of the resources needed to deploy the 3000 float array. Initial plans call for U.S. floats to be deployed in the North Atlantic and Pacific basins, including the tropics. However, final deployment strategies have yet to be established.

CORIOLIS

CORIOLIS is a French program conceived as the observational component of MERCATOR (the French contribution to GODAE). CORIOLIS - Atlantic is proposing to continue and improve the existing observing systems such as the VOS-XBT lines, surface drifters operated by Met-offices, and the PIRATA tropical array, and to implement a new automatic and permanent in situ network covering all the Atlantic and composed of: 500 profiling floats (such as PROVOR derived from MARVOR) as a contribution to the ARGO project, basically on a 5° x 5° grid locally reinforced in specific zones and profiling every two weeks; and 100 Eulerian expendable probes EMMA, profiling up from the bottom on a monthly basis on a 10° x 10° grid.

It is proposed to implement the CORIOLIS-Atlantic network in phase with the ARGO deployment during the 2001 -2004 period to be ready for pre-operational tests of global ocean models such as MERCATOR/GODAE.

VI.3. Current process studies

ACCE

The Atlantic Circulation and Climate Experiment (ACCE) is directed at increasing our understanding of the interaction between the Atlantic Ocean and global climate. As a contribution to ACCE an array of PALACE floats was deployed in the tropical Atlantic by NOAA/AOML and WHOI to provide current vectors at 1000 m, temperature, and in some cases, salinity profiles of the upper kilometer. AOML floats were deployed during June/July 1997 along the equator and 6°S; they will be operational until August-September 1999. A new array will be deployed in January 2000. The WHOI array consists of ten floats deployed in 1997 along

6° N and thirty floats deployed in 1998 along 11°, 13.5° and 16°N. The floats are ballasted to a pressure of 1000 db; the 1997 WHOI and AOML floats profile on the upcast, the former on a 14 day cycle and the latter on a 10 day cycle. It is proposed to maintain the current array as part of ARGO.

NBC Rings Experiment

The NBC Rings experiment is a multi-institutional effort between RSMAS/UM, WHOI, NOAA/AOML and LDEO/CU, with cooperation from scientists from the University of Sao Paulo, Brazil. The purpose of this project is to carry out a comprehensive observational study of the North Brazil Current (NBC) retroflection and the ring generation process, to study the structure and evolution of NBC rings as they propagate northwestward from the NBC retroflection, and to examine their role in the interbasin exchange of heat in the tropical Atlantic. In order to achieve these objectives, an extensive field work program is underway. During the first two cruises (November 1998 and February 1999) the following was accomplished: Deployment of an array of inverted echo sounders, one current meter mooring, one CTD mooring, and two sound sources; 26 RAFOS floats and 30 drifters were launched; and two intensive hydrographic and direct velocity profile surveys were made of the NBC retroflection and three NBC rings that were recently shed from the retroflection. Two more cruises are planned for the year 2000.

RECONOB, a numerical study of the North Brazil Current retroflection, is the modeling component of this program. It is a joint US/Brazil venture funded by NSF and CpTEC whose main objective is to study the structure and dynamics of the NBC with the use of two models: the Miami Isopycnal Coordinate Model (MICOM) and the Princeton Ocean Model (POM). The results of the two models will be compared to each other, and with the observational data being collected by the NBC RINGS Experiment.

ECLAT (Etudes Climatiques dans l'Atlantique Tropical)

ECLAT, the French component of the international CLIVAR in the tropical Atlantic, is a program whose main objective is to study the climatic variability from the seasonal to the decadal scale in the tropical Atlantic and the adjacent tropical continents, Africa and South America, and to determine its predictable components.

Different components of ECLAT field work include: (1) maintenance of the three merchant ship lines in the tropical Atlantic (XBT and TSG) to improve the description of the upper ocean variability; (2) deployment and maintenance of the PIRATA (1997-2001) moored buoys in the eastern Atlantic and a tide recorder (Sao Tomé island); (3) FLUVAP, a coordinated effort in the tropical Indo-Atlantic region to collect, validate, archive, and distribute satellite data (ATOVS) used in the reconstitution of the 4D vapor flux over the tropical African continent; and (4) EQUALANT. The EQUALANT program has as its main objective the study of the ocean circulation variability from surface to bottom, and the ocean-atmosphere interactions in the equatorial Atlantic. It consists of two cruises that will take place during 1999 and 2000. During the summer 1999 cruise, two CMM will be deployed at 10°W-Equator at a PIRATA buoy location, and two CMM moorings will be deployed at 0.5°N and 0.5°S along 10°W (Figure VII.1). One of the 10°W-Equator moorings will consist of ADCP and current meters, and the other one will include a CTD profiler in the upper 1000 m in addition to the current meters.

In collaboration with IFREMER and in the framework of the EQUEST project (MARVOR

drifter launches in the Gulf of Guinea, in the Intermediate Antarctic Water and Upper North Atlantic Deep Water layers), additional work will be performed during the PIRATA maintenance cruises. During seasonal cruises, sea surface measurements (T, S, silicate, CO₂, and chlorophyll), meteorological observations, and data from ADCP, XBT, XCTD and SVP drifters will be collected.

Guiana Abyssal Gyre Experiment

GAGE is a joint program between the US (WHOI) and Germany (IFM, Kiel). The main objective of the program is to study the Guiana Abyssal Gyre and its role in the meridional overturning circulation.

The US component of GAGE will focus on the narrow Guiana Basin near 16°N. The GAGE is principally a moored current meter and temperature sensor experiment (6 moorings instrumented at 5 levels at and below 3000 m), supported by shipboard hydrographic and acoustic Doppler current profiler measurements during the array deployment cruise in early 2000 and the array recovery cruise in early 2002. These hydrography/velocity measurements will be repeated two more times during the German cruises.

The German program enlarges the array to 10 moorings and includes augmented sampling at two additional levels besides those of GAGE: nominally 1600 m and 1300 m. Three of the German moorings will be heavily instrumented with fixed point CTDs to enable full water column hydrographic data collection and thus dynamic height for monitoring the southward transport variability of the deep thermohaline circulation limb. The German program will continue with a third year after the recovery of the GAGE equipment in early 2002, and it also is intended as a pilot program for long term monitoring activity in the German contribution to CLIVAR.

IFM-Kiel Programs in the Tropical/Subtropical Atlantic.

In addition to its coordinated cooperation with GAGE, Germany is involved in two other major projects in the tropical/subtropical Atlantic.

Tropical/Subtropical Interaction in the Atlantic is a multiyear observational program combining repeat deployments of moored stations at 7.5°S with float and shipboard observations (CTDO₂, LADCP, VMADCP, CFCs) for investigating the subtropical-tropical coupling of the warm water circulation (the shallow subtropical-tropical cell) in the western tropical South Atlantic.

Interhemispheric Exchange of Deep Water Masses is logistically linked to the above CLIVAR project; that is, cruises and mooring work at 7.5°S are combined. The scientific objectives of this program are the determination and quantification of the deep water circulation in the equatorial belt, and the role of the equator in deep water mass transformation.

The programs have long term perspectives with individual funding periods of three years, starting 1999.

Observational Programs in the Intra-Americas Sea

The "Intra-Americas Sea" (IAS) refers to the waters of the Gulf of Mexico, Caribbean Sea, and adjacent Atlantic Ocean. The IAS lies at the crossroads of the wind-driven and thermohaline circulation of the North Atlantic, with the upper ocean western boundary current essentially forming within the IAS before exiting as the Florida Current. Regional climate is affected by IAS conditions and by interactions between the IAS and the prevailing Atlantic trade winds. A large

number of observational programs are currently taking place in the region (see Appendix 4). Of immediate importance to COSTA are programs that monitor the upper ocean limb of the MOC (e.g., mass and heat transport between the IFM/WHOI zonal array at 16 N and the South American coast), and programs that monitor upper heat content within the IAS "warm pool".

VI.4 Proposed process studies

Bifurcation of the South Equatorial Current (BISEC)

BISEC is a joint US (URI, NOAA/AOML) and Brazil (Univ. of Sao Paulo, INPE) project whose main goal is to improve the understanding of the interbasin exchange of heat in the tropical Atlantic. An extensive array of instruments will be deployed to study the variability of the bifurcation of the South Equatorial Current (SEC) and the resulting formation of the North Brazil Current (NBC) and the Brazil Current (BC).

SWACE (South Western Atlantic Circulation Experiment)

The central goal of SWACE is to understand the controlling mechanisms driving the variability of the oceanic circulation in the southwestern Atlantic region and the evolution of the associated SST fields. To achieve such a goal SWACE proposes to: 1. Implement an observational array consisting of current meters, inverted echo sounders and pressure gauges to monitor the time variability and spatial coherence of the western boundary currents from Drake Passage to 25° S. The time series so obtained will span two years. 2. Analyze multiple types of satellite data to characterize the SST and SSH variations in the southwestern Atlantic and to relate them to the observed variations in oceanic circulation, atmospheric forcing and surface fluxes. 3. Analyze the output from existing global-scale numerical circulation models to identify the most robust modes captured by observational data and model simulations. 4. Develop a suite of numerical and analytical models to relate the variability of the southwestern Atlantic to the atmospheric forcing and the large-scale circulation.

Both SWACE and BISEC are projects under the South Atlantic Climate Change (SACC, see Appendix 4) umbrella. For coordination of these two projects (if they are funded), and to foster the study of tropics-extratropics connections in the South Atlantic Ocean, a 5-year international project is being funded by the Inter-American Institute (IAI), through the Cooperative Research Network (CRN) program.

VII. SUMMARY OF RECOMMENDATIONS

Based on the 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.
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.
3. Implement modeling studies, combined with data assimilation, to enhance climate forecast and to improve the design of the observing system.
4. Generate field products that combine all observations and model products.

The consensus was to continue the data collection and quality control through the existing Data Centers by platform. Recommendations included the need for making the data available in near real time for model forecast.

1. Maintenance and enhancement of present monitoring systems:

Moored Array

- Maintain the present PIRATA array for the transition period 2000-2005.
- Extend the PIRATA array with pilot sites during the transition period. Figure VII.1 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 including enhancement of observations at each side of the Caribbean straits, plus activation of cable monitoring of transport through the straits.
- 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

- Continue the current profiling floats programs in the tropical Atlantic and extend the observations to the region 20°N to 20°S. Salinity measurements should be included if possible.
- Continue and enhance the tropical Atlantic array of surface drifters in the region 20°N to 20°S.

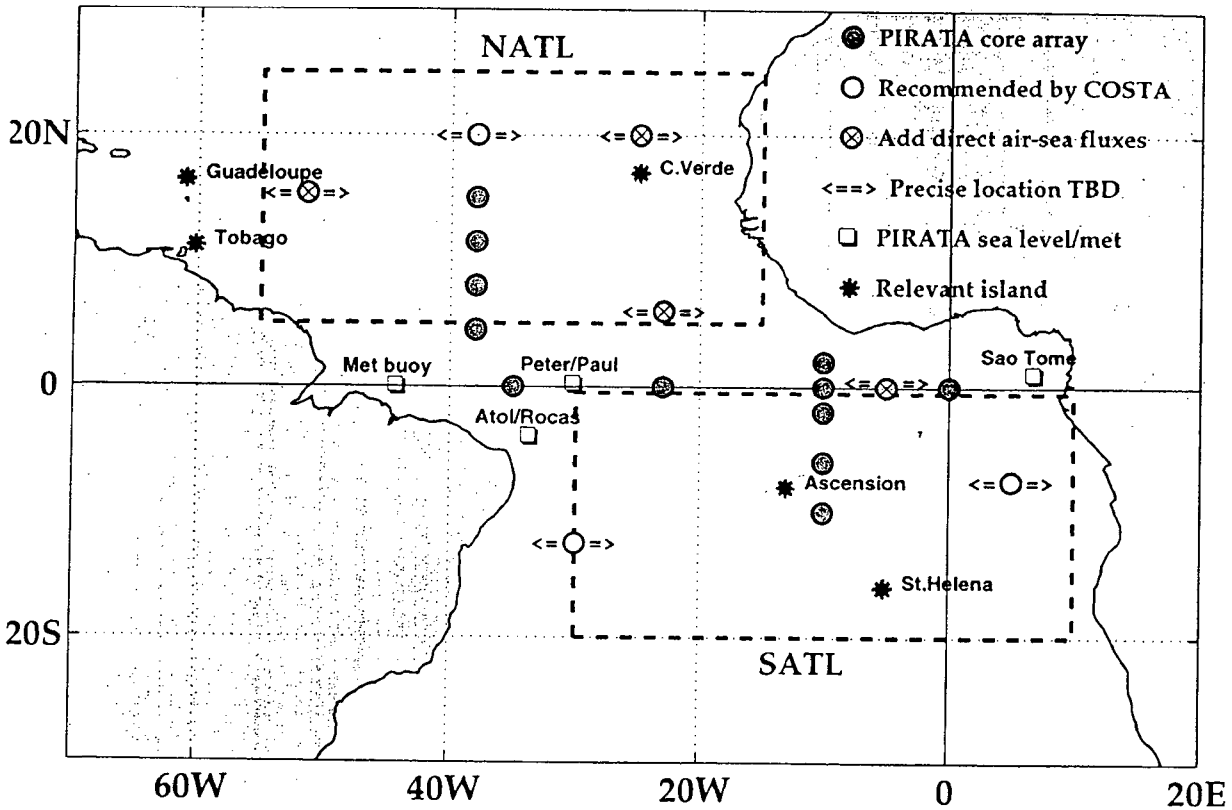


Figure VII.1. Elements of the existing PIRATA array (blue circles, squares) and of the recommended (or possible) extensions for the COSTA observing system (yellow circles, red asterisks). Left-right arrows surrounding a symbol indicates an approximate location (to be determined).

VOS / XBT

- Maintain the XBT observations from the VOS system. Increase resolution in time and space on AX-29 and other lines that cross the moored array. 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 the VOS sensors.

Implement pilot and process studies:

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.

Modeling studies combined with data assimilation.

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

Generation of Data Products

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

VIII. References

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**RESOLUTION BY THE PIRATA STEERING GROU
PIRATA-6
Miami, Florida
5 May 1999**

Progress in implementation of the Pilot Research Moored Array in the Tropical Pacific (PIRATA) was reviewed at PIRATA-6 in Miami, Florida on 2-3 May 1999. Deployment of the moored buoy array began in late 1997, and by early May 1999 nine sites were occupied and successfully transmitting data in real-time. Implementation is on schedule and nearly complete.

The full array of 12 moorings will be in place for one year before the field phase is scheduled to end in early 2001.

The first phase of PIRATA implementation coincided with a warm event in the tropical Atlantic, which contributed to one of the five worst droughts this century in NE Brazil. The buoy array captured the development of the upper ocean thermal anomalies, and the seasonal evolution of oceanic and atmospheric variability on which they were superimposed. Real-time PIRATA data available on the GTS were used in operational oceanic and atmospheric analyses and forecasts during this period. Preliminary diagnosis of the data also supports hypotheses concerning ocean-atmosphere coupling in the region.

PIRATA was originally conceived as a pilot study with a 3-year field phase in support of CLIVAR, GCOS, and GOOS objectives. It is becoming clear that a complete array for one year will provide insufficient time to evaluate whether PIRATA should be part of a permanent climate observing system. On the other hand, it is also clear that PIRATA data are already providing valuable new information for climate studies of relevance to the Americas and Africa.

Therefore, based on the initial successes of the program, the PIRATA Steering Group recommends a transitional phase towards the development of a sustained climate observing system for an additional five years, to early 2006. This extension will allow for a full demonstration of the utility of PIRATA data, and a smoother transition to operational status, if warranted.

In addition, recognizing that this extension will require a sustained level of support in terms of funding, shiptime, and equipment, the PIRATA Steering Group recommends that a PIRATA Resource Board, with terms of reference, be established to ensure that adequate resources will be available for the duration of the program. This Resource Board would initially consist of representatives from the institutions in Brazil, France and the United States that presently provide support for the array.

Finally, in recognition of the widespread interest in developing a sustained observing system in the tropical Atlantic for climate studies, as evident from the international participation at the Climate Observing System for the Tropical Atlantic (COSTA) workshop that followed the PIRATA-6 in Miami, the PIRATA Steering Group resolves to coordinate with ongoing and planned observational efforts in the region. Furthermore, building upon recommendations put forward at the COSTA workshop, the Steering Group encourages consideration of scientifically sound pilot expansion projects that build upon the original PIRATA array. Moreover, the Steering Group invites collaborations with other nations and institutions interested in implementing a sustained climate observing system in the tropical Atlantic.

AGENDA
Climate Observing System for the Tropical Atlantic
May 4 - 7, 1999

Day 1: Tuesday May 4, PM:

(Conference Room, Southeast Fisheries Center SEFC/NOAA

01:00 PM: Introduction (S. L. Garzoli)

01:30 PM: Role of the Tropical Atlantic Ocean in Climate (A. Busalacci)

02:00 PM Historical Perspective (Jaques Merle)

02:30 PM Hurricanes in the Tropical Atlantic (H. Willoughby)

03:00- 03:30 Break

03:30 PM What's important in the tropical Atlantic: Is it only regional or part of larger scale variability? (D. Enfield)

04:00 PM Sustaining a long term Observational System (Mc Phaden)

04:20 PM Observing Systems and Data Centers (Mike Johnson)

04:40 PM The Pirata Program (J. Servain)

07:00 to 9:00 PM Reception/ Dinner

Day 2: Wednesday May 5

(Conference Room, Southeast Fisheries Center SEFC/NOAA

08:30 PM to 10:00 PM

CORIOLIS (P. Marchand)

EQUALANT (B. Bourles)

ECLAT (P. Delecluse)

MERCATOR (G. Reverdin)

CPTEC atmospheric climate model (C. Nobre)

RECONOB (E. Campos)

10:00 to 10:30 Break

10:30 to 12:00 PM

Tide Gauges (M. Vianna)

German Programs (J. Fisher)

South African Program (M. Jury)

ARGO/AOML PALACE/XBT/VOS/Drifters program (Molinari)

ACCE Palace floats (R. Schmitt)

