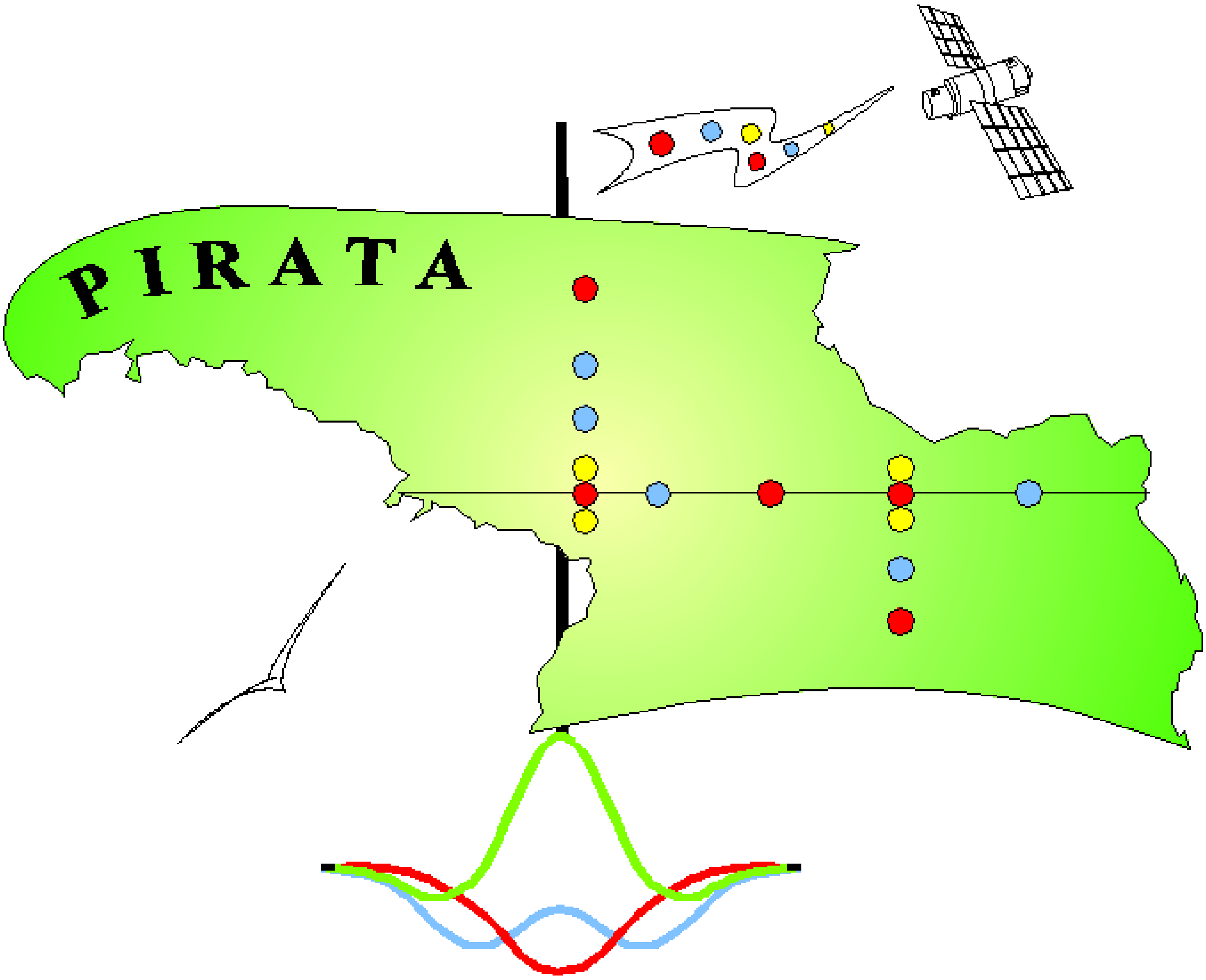
PIRATA

Pilot Research Moored Array in the Tropical Atlantic

Science and Implementation Plan for an Observing System
to support Tropical Atlantic Climate Studies
1997-2000



Final Version

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TERMS OF REFERENCE

An Organizing Committee was formed during the 4th TOGA-TAO (Tropical Ocean Global Atmosphere - Tropical Atmosphere Ocean array) Implementation Panel Session held at Fortaleza, Brazil, 12-14 September 1995. The main goal of this Organizing Committee was to produce a specific and detailed proposal for the implementation of a 3-year pilot moored array in the tropical Atlantic for climate studies. Such an observing system should be designed as the beginning of an Atlantic expansion of the TAO array which has been successfully deployed in the Pacific during the TOGA Program (1985-1994). The acronym PIRATA (Pilot Research Moored Array in the Tropical Atlantic) was chosen for a pilot experiment. PIRATA addresses the general call for further development of the tropical Atlantic Ocean observing system under auspices of CLIVAR.

The membership of the PIRATA Organizing Committee is composed of the following scientists from Brazil, France and US:

Antonio D. Moura *(co-chair),* INPE, Brazil
Jacques Servain *(co-chair),* ORSTOM/UBO, France
Antonio Busalacchi, NASA/GSFC, USA
Michael McPhaden, NOAA/PMEL, USA
Gilles Reverdin, CNRS/GRGS, France
Marcio Vianna, INPE, Brazil
Steve Zebiak, LDEO, USA

A first draft of the proposal (Version 1.0) was drawn up by the PIRATA Organizing Committee via an e-mail forum during the months of October 1995 to February 1996. The written sections were discussed during the first PIRATA meeting which was held 22-24 February 1996 at Natal (RN, Brazil). The mooring system deployment and the agenda for action were debated and defined during that meeting. A Version 2.0 was sent for comments and reviews to “ grands lecteurs ” involved in climate studies and climate program committees, especially those involved in CLIVAR. The Version 3.0 (final version) was completed during a second PIRATA meeting held at Centre ORSTOM of Brest (France) on 27-29 of August 1996. During fall 1996, this final version is sending for scientific evaluation to national (Brazil, France, USA) and international scientific committees (*e.g.* CLIVAR, GOOS, GCOS). Funding is being sought through national agencies and international cooperation. The field phase of the program is proposed to begin in 1997 and will continue until the year 2000. Deployment of 14 ATLAS moorings is envisioned as part of a multi-national effort involving Brazil, France and USA. It is expected that should PIRATA prove successful, the array will be maintained and further developed under the GOOS-GCOS auspices, and in support of international and national climate programs such as CLIVAR, ACCP, ECLAT, PACS, etc.

ACKNOWLEDGMENTS

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1. EXECUTIVE SUMMARY

The interaction of the atmosphere and the tropical oceans is a subject of both scientific interest and societal importance, as demonstrated through the accomplishments of the international TOGA program (1985-1994). The primary focus to date has been in the Pacific sector, owing to the prominence of El Nino and the Southern Oscillation in global climate. At the same time, it is well recognized that atmosphere-ocean interactions throughout the global tropics are potentially important to the earth's climate variability on the time scales of years to decades. Among the regions of particular interest, and the focus of this report, is the tropical Atlantic.

The tropical Atlantic is characterized by a strong seasonal cycle, deriving ultimately from radiative forcing and land-sea contrast, but strongly modified by atmosphere-ocean coupling. Superimposed on this seasonal cycle, there appears to be two modes of interannual and longer-term variability. The so-called “ dipole ” mode, which operates primarily at decadal and longer time scales, involves north-south interhemispheric variations in sea surface temperature. This mode has been linked to severe climate anomalies in Northeast Brazil (Nordeste) and in parts of Africa (Sahel and Sub-Sahel). A second “ equatorial ” mode, operating preferentially at seasonal and interannual time scales, has many similarities to the ENSO phenomenon in the Pacific, and involves trade wind variations and the excitation of equatorial Kelvin and Rossby waves. This mode has been associated with rainfall extremes in the Gulf of Guinea and marine ecosystem disruptions in the Benguela current area. It is not presently known whether the two modes are related. Our current understanding of these phenomena is limited, and to a great extent this is because of the lack of routine, quality controlled, oceanic and atmospheric observations in the region.

The observation system that exists relies mainly on volunteer observing ships and occasional research vessels that pass through the area. The generally infrequent oceanographic cruises in much of the region are insufficient even for monitoring interannual variability. The purpose of PIRATA (Pilot Research Moored Array in the Tropical Atlantic) is in part to remedy this crucial lack of oceanic and atmospheric data in the tropical Atlantic.

The scientific goals are:

- To provide an improved **description** of the seasonal-to-interannual variability in the upper ocean and at the air-sea interface in the tropical Atlantic;
- To **improve our understanding** of the relative contributions of the different components of the surface heat flux and ocean dynamics to the seasonal and interannual variability of SST within the tropical Atlantic basin;
- To **provide a data set** that can be used to develop and improve predictive models of the coupled Atlantic climate system.

The technical goals are:

- To design, deploy and maintain a pilot array of moored oceanic buoys, similar to the ones used during the TOGA program (the TOGA-TAO array) in the tropical Pacific;
- To collect and transmit via satellite in real-time a set of oceanic and atmospheric data to monitor and study the upper ocean and atmosphere of the tropical Atlantic.

These data will be useful for both weather and climate prediction for the region. Among those who will utilize the data in research or operational mode are: IRI, NCEP, ECMWF, GFDL, Météo-France, and other academic institutions. Such forecasts are further expected to mitigate the impacts of severe droughts over the adjoining continental regions influenced by the Atlantic.

During its experimental pilot phase in the years 1997 to 2000, PIRATA will demonstrate the feasibility of solving the engineering, logistical and maintenance problems that might arise in the implementation of such an observational system. The idea of a pilot project is to establish the appropriate technology for a meaningful and cost-effective observational system in the Atlantic in an incremental and efficient manner. After its completion, a careful evaluation of the PIRATA would determine if recommendations for a long term continuation and/or expansion of the array in the tropical Atlantic are appropriate. It is envisioned this would form a substantial contribution to GOOS and GCOS. The international research effort under the World Climate Research Program (WCRP), especially the post-TOGA activities (CLIVAR-GOALS) will greatly benefit from the additional high quality data that will be provided by PIRATA.

In addition to a better understanding of the local coupled dynamics in the tropical Atlantic, it is expected that PIRATA will help in determining the linkages between the Atlantic and ENSO. The data will also help in determining the relationships between regional climate variations and agricultural and fisheries impacts for South America and West Africa. Ultimately, it is expected that better data will facilitate the development of useful forecast models and forecast capability for the region.

This proposal follows on the scientific successes of TOGA and on the proven technology that is operative in the Pacific - in particular, the *in situ* observational system of approximately 70 buoys that form the TOGA-TAO array. PIRATA proposes to install and maintain an array of 14 moored ATLAS buoys during the years 1997 to 2000 for monitoring the surface variables and upper ocean thermal structure at key locations in the tropical Atlantic. The measurements will be transmitted via satellite (*e.g.* CLS-Argos) in real-time, and will be available to all interested users in the research or operational communities. The total number of moorings is a compromise between the need to put out a large enough array for a long enough period of time to gain fundamentally new insights into coupled ocean-atmosphere interactions in the region, while at the same time recognizing the practical constraints of resource limitations in terms of funding, shiptime, and personnel. More moorings would obviously be desirable, but not practical for a pilot study on the scale that we envision. The purpose of proposing this array then, is to demonstrate scientific success in a limited geographical region for a limited duration of time, as a guide to more serious long range planning.

PIRATA is an initiative put forward by an international group of scientists involved with TOGA and TOGA-TAO activities, and will be implemented as a collaborative multinational effort. Initial contributions will come from:

- Brazil: interest formally expressed by the Ministry of Science and Technology, the National Institute for Space Research (INPE), and the Ministry of the Navy through its Directorate of Hydrography and Navigation (DHN), as well as universities;

- France: interest formally expressed by Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM) in a collaborative effort with other French institutions, such as Centre National de la Recherche Scientifique (CNRS), Météo-France, Centre National d'études Spatiales (CS), Institut Français pour l'Exploitation de la Mer (IFREMER), and universities;

- USA: interest expressed by scientists from NOAA, NASA, and universities.

It is expected that at the end of the pilot phase of PIRATA, other nations will join in the maintenance and possible expansion of PIRATA to constitute a tropical Atlantic component of GOOS and GCOS. The program is appropriately multinational since variations in the tropical Atlantic affect many nations in the Americas and Africa. PIRATA will create a true partnership in the study of tropical oceanography and ocean-atmosphere interactions in the Atlantic by bringing key research institutions in the region to a continuing collaboration. Thereby, PIRATA addresses directly the call from several international working groups dealing with tropical ocean climate studies, including those from TOGA and the OOSDP.

Three years of measurements will only barely touch on the issues of seasonal to interannual variations in the tropical Atlantic, and will not address decadal scale variability. Yet PIRATA has the potential to establish the foundation for a longer term monitoring network that will address more completely these important scientific problems.

2. INTRODUCTION

The seasonal cycle is the largest atmosphere-ocean signal in the tropical Atlantic. The timing and characteristics of the seasonal evolution of the location of the Intertropical Convergence Zone (ITCZ) and of the sea surface temperature (SST) depend on coupled dynamics and on land-sea contrasts in ways not yet fully understood. Part of the interannual variability can be interpreted as changes of the timing or of the amplitude of the seasonal cycle, which imply an important coupling between interannual variability and the seasonal cycle. The understanding of the mechanisms involved and how it affects predictability are therefore important questions which need to be addressed.

Superimposed on the mean seasonal cycle are two modes of ocean-atmosphere variability in the tropical Atlantic with significant impacts on the regional climate of the Americas and Africa. One of these modes, which has no counterpart in the Pacific, is characterized by a north-south interhemispheric gradient in sea surface temperature, the so called “ Atlantic dipole ” (*e.g.* Moura and Shukla, 1981; Servain, 1991). This mode involves spatially coherent SST variations in either hemisphere between about 5°N-25°N and 5°N-20°S, with seasonal, interannual and decadal time scales (Fig. 1). Anomalies usually appear with opposite sign in each hemisphere, although the development is not always simultaneous, and there is debate over whether the northern and southern components of this dipole are dynamically related (Houghton and Tourre, 1992). Coupled ocean-atmosphere modeling studies of the dipole mode are in their infancy, albeit some recent results (Chang *et al*., 1996) have suggested that the physical processes responsible for interhemispheric SST variations in the Atlantic involve positive feedbacks between SST, surface winds and latent heat fluxes.

Interhemispheric SST anomalies significantly affect the position and intensity of the ITCZ, and thus exert a considerable influence on the rainfall over the Nordeste and Sahel (Moura and Shukla, 1981; Folland *et al.*, 1986; Servain, 1991; Enfield and Mayer, 1995). In particular, warm SST anomalies north of the equator and/or cold SST anomalies to the south are associated with an intensified ITCZ displaced north of its normal position, leading to drought conditions in Nordeste, and unusually high rainfall totals in the Sahel. Conversely, SST anomalies of opposite sign weaken the ITCZ and displace it southward, favoring more abundant rainfall in Nordeste and drought in the Sahel. SST variability in the northern tropical Atlantic also potentially influences rainfall over the West Indies and North America by modulating the frequency and intensity of storm activity during the hurricane season (Gray, 1990; Sheaffer, 1996).

A second mode of climate variability in the tropical Atlantic is similar to the El Nino/Southern Oscillation (ENSO) in the Pacific, with manifestations focused primarily near the equator (Zebiak, 1993; Chang *et al.*, 1996) (Fig. 2). This “ equatorial ” mode, like the interhemisphere dipole mode, varies on seasonal, and interannual time scales. During a warm phase, tradewinds in the western equatorial Atlantic are weak and SSTs near the equator are unusually high, especially in the eastern basin. During a cold phase, tradewinds in the western equatorial Atlantic are strong and SSTs near the equator are unusually low. Onset of an equatorial cold or warm event can occur rapidly on time scales of weeks to months, mediated by the excitation and propagation of wind forced equatorial Kelvin and Rossby waves. Climatic impacts of equatorial warm events includes increased rainfall in the Gulf of Guinea and disruption of the marine ecosystem in the Benguela current region (Wagner and da Silva, 1994; Crawford *et al.*, 1990). It is possible that this equatorial mode may be dynamically related to the interhemispheric dipole mode, given the similarity in time scales and the spatial overlap in patterns of variability. However, the precise physical processes that would link them have yet to be identified.

Another mode of climate variability that affects the Atlantic basin, albeit remotely, is the ENSO cycle. Examples of ENSO teleconnections include impacts on Nordeste rainfall (Ropelewski and Halpert, 1987) and modulation in the frequency and intensity of hurricanes (Gray *et al.*, 1993). It appears that for some variables, such as rainfall in Nordeste, the remote effects of ENSO SST anomalies are weaker than the effects of Atlantic SST anomalies even though the latter, with typical magnitudes of 0.5°-1°C, are significantly smaller. Clearly identifying the remote influences of ENSO on Atlantic climate variability is complicated since both the Atlantic dipole and equatorial modes also interact with the ENSO cycle. Low frequency variations in winds and SST along the equator do not appear to be self-sustaining through coupled ocean-atmosphere interactions in the Atlantic alone, and some external stimulus is required to initiate these oscillations (Zebiak, 1993). ENSO provides one possible source of external forcing (Delecluse *et al.*, 1994), given that a low SOI (characteristic of warm conditions in the Pacific) is associated with strong western Atlantic easterlies, and *vice versa* (Fig. 3). Likewise, there is a significant correlation at lags of several months between the Southern Oscillation Index (SOI) and the development of SST anomalies associated with the dipole mode in both hemispheres of the tropical Atlantic (Servain, 1991).

Recent studies suggest that seasonal rainfall variability in Nordeste is predictable a few seasons in advance using a combination of tropical Pacific ENSO SST anomalies and tropical Atlantic SST anomalies (*e.g.* Hastenrath and Greishar, 1993; Graham, 1994). However, the skill of these forecasts appears to be more strongly affected by tropical Atlantic anomalies (as in the case of Sahelian rainfall) than by those originating in the Pacific. A better documentation and understanding of the dominant modes of SST variability in the tropical Atlantic will likely lead to improvements in forecast skill and lead time for significant climate fluctuations over the Americas and Africa.

Thus, there are a number of unresolved issues concerning the genesis and evolution of ocean-atmosphere interactions in the tropical Atlantic that require further investigation. For example, what role does the mean seasonal cycle play in the development of interannual and longer time scale anomalies? What is the relative importance of the Pacific ENSO *vs.* regional scale ocean-atmosphere interactions in determining the evolution of climate variability in the Atlantic? What is the dynamical relationship (if any) between the northern and southern poles of the dipole mode? What are the oceanic and atmospheric processes that give rise to the observed SST anomalies in both the dipole mode and the equatorial mode? What sets the time scale for their development? What are the feedbacks that couple the ocean to the atmosphere on these time scales? In a general sense we expect that away from the equator air-sea heat exchanges will be important in generating SST anomalies, whereas near the equator, ocean dynamics are likely to take on greater significance. In the atmosphere, we expect that the changing pattern of SST anomalies will affect surface convergence, atmospheric deep convection and the circulation of the troposphere (*e.g.* Lindzen and Nigam, 1987; Zebiak and Cane, 1987); and that in turn these changes in atmospheric circulation will drive ocean currents and surface heat fluxes that influence the heat balance of the upper ocean. However, there have been few quantitative evaluations of these processes in the Atlantic because of the lack of appropriate data sets, particularly in the ocean. Oceanic and atmospheric numerical models of course can provide valuable insights into the working of the climate system in the tropical Atlantic (*e.g.* Carton and Huang, 1994; Zebiak, 1993). Unfortunately, models in general, and tropical ocean models in particular, are very sensitive to inaccuracies in surface forcing and parameterized model physics (Blanke and Delecluse, 1993; Bryan *et al.*, 1995; Mehta and Delworth, 1995). Hence, high quality climate data sets are needed to improve the specification of surface forcing and physical parameterizations, and to facilitate model validation. In other words, the use of models as a diagnostic tool reinforces, rather than obviates, the need for critical high quality data sets.

The FOCAL/SEQUAL programs took place in the equatorial Atlantic during 1982-84. This was a period characterized by an unusual warm event in 1984 following a period of more normal conditions in 1983 (Horel *et al.*, 1986; Philander, 1986). A large amount of moored time series data, research vessel hydrographic data, VOS/XBT data, drifter data and island wind and sea level data were collected during FOCAL/SEQUAL to characterize the ocean's response to seasonal time scale wind forcing during both a normal year and an unusually warm year (Katz, 1987a,b; Katz *et al.*, 1986; Henin and Hisard, 1987; Houghton and Colin, 1986; Richardson and Reverdin, 1987; Weisberg and Weingartner, 1986; Weingartner and Weisberg, 1991). Also, the relative importance of remote *vs.* local forcing in the accounting for thermocline depth variations both zonally along the equator and meridionally across the major zonal current systems were documented and analyzed intesively with the available data sets. Though in fact limited *in situ* wind observations were available during FOCAL/SEQUAL, the excitation and propagation of equatorial Rossby and Kelvin wave variations were identified as important agents in the adjustment of the upper ocean to wind forcing. Also, higher frequency phenomena such as instability waves and inertia-gravity waves were documented and interpreted in terms of wind-forcing and/or instabilities of the zonal current system (Weisberg, 1984; Garzoli, 1987). Conversely, virtually no measurements of surface heat and moisture fluxes were made during FOCAL/SEQUAL.

Few FOCAL/SEQUAL measurement efforts were systematically continued during the TOGA decade (unlike in the equatorial Pacific where for example, measurements begun in the 1980s as part of EPOCS now extend over a 10-15 year exist at a few locations in the TAO array). The oceanic data base in the Atlantic at present derives primarily from volunteer observing ship (VOS) programs, coastal and island tide gauge stations, and a small number of drifting buoys. However, VOS measurements of surface meteorology and subsurface temperatures are concentrated mainly along well-traveled shipping routes, in between which there are large data gaps. Moreover, time series measurements of winds, upper ocean temperatures and other data sets collected during the 1982-84 FOCAL/SEQUAL experiment (Weisberg and Weingartner, 1986; Houghton and Colin, 1986; Katz, 1987a) indicate a broad spectrum of high frequency variability that would be aliased into infrequent quasi-monthly shipboard surveys. Tide gauge stations provide highly resolved time series of sea level data, but are relatively few in number and not optimally located for climate studies. Drifting buoys, which provide estimates of SST and mixed layer velocity, are at present concentrated mainly north of 20°N and therefore provide no data in critical regions near and south of the equator. Satellite estimates of some key variables (namely surface winds, SST and sea level) are available over the whole Atlantic basin with more uniform spatial and temporal resolution. However, satellite measurements are subject to potentially significant bias errors because they rely on complicated algorithms to convert electromagnetic signals emanating from the sea surface into geophysically meaningful variables. Moreover, satellites provide no direct measurements of subsurface thermal structure in the ocean, which is essential for understanding processes affecting the evolution of SST.

A major objective of TOGA was to develop an ocean observing system to support studies of large-scale ocean-atmosphere interactions on seasonal to interannual timescales.

Under the auspices of TOGA, the TAO array was developed and finally completed in December 1994 (McPhaden, 1993; 1995). The array measures oceanographic and surface meteorological variables critical for improved detection, understanding, and prediction of seasonal to interannual climate variations originating in the tropical Pacific, most notably those related to the ENSO. The TAO array spans one-third of the circumference of the globe, from 95°W to 137°E. Moorings are deployed every 2°-3° of latitude between 8°N and 8°S along lines that are separated by 10°-15° of longitude. Data are reported in real time via CLS-Argos and retransmitted on the GTS for immediate distribution to oceanographic and meteorological centers around the world. The TAO project is a multinational effort involving the participation of the United States, Japan, Korea, Taiwan, and France. Maintenance of the TAO array, as well as other components of the TOGA observing system, is crucial to the success of the climate research programs. An expansion of the TAO array to the two other tropical oceans was recommended by the CLIVAR Scientific Steering Group (Anonymous, 1995).

Therefore, in view of present limitations in the existing data base for tropical Atlantic climate studies, we propose to develop in the Atlantic a program of moored measurements similar to the TAO Array used to study ENSO variability in the equatorial Pacific. This program is designed to improve our understanding of the processes by which the ocean and atmosphere couple in key regions of the tropical Atlantic. The program, called **PIRATA (Pilot Research Moored Array in the Tropical Atlantic)** will provide finely resolved time series measurements of surface heat and moisture fluxes, sea surface temperature and salinity, and subsurface temperature and salinity in the upper 500 m.

Data from PIRATA moorings can be assimilated into operational numerical models for improved “ nowcasts ” of oceanic and surface meteorological conditions. These nowcasts can in turn serve as initial conditions for coupled ocean-atmosphere models used in climate forecasting. The most commonly used data sets at present for experimental ENSO prediction in the Pacific are surface winds, SST and upper ocean thermal structure (*e.g.* Ji et *al.*, 1995; Chen *et al.*, 1995; McPhaden *et al.*, 1996). We can expect that development of dynamical coupled models for accurate predictions of Atlantic SST anomalies and their regional climatic impacts will depend on the availability of comparable oceanic data sets for initialization.

The field phase of the program is proposed to begin in 1997 and to last for 3 years. Deployment of 14 moorings is envisioned as part of a multi-national effort involving Brazil, France and the US. All data will be available in real-time via CLS-Argos, with a subset of the measurements (winds, air temperature, SST and subsurface temperature) retransmitted on the GTS to operational weather and climate prediction centers around the world, being also available through the Internet.

PIRATA addresses the general call for further development of the tropical Atlantic Ocean observing system under the auspices of CLIVAR. It also responds to specific recommendations that consideration be given to expanding the TAO Array into the Atlantic basin for climate studies (USA National Research Council, 1994; Ocean Observing System Development Panel, 1995). PIRATA is being coordinated with the WOCE/Atlantic Climate Change Experiment (ACCE) field program scheduled for 1997-98. It is now considered as part of the Brazilian contribution to GOOS, while its relation to GCOS will be defined in the near future. PIRATA is viewed as one of the major components of Etudes Climatiques dans l’Atlantique Tropical (ECLAT) which will be the French contribution to CLIVAR in the tropical Atlantic. It can also be viewed as a pilot study for NOAA's Pan American Climate Studies (PACS) program which intends to develop a tropical Atlantic focus for field work after the year 2000. Hence, PIRATA will be well-integrated with ongoing and planned international climate research programs, as well as with efforts to improve dynamical short-term climate prediction of variability originating in the tropics.

The remainder of this document is outlined as follows. In Section 3, we present a general background on coupled ocean-atmosphere variability in the tropical Atlantic. This is followed in Section 4 with a description of the existing ocean observing system in the tropical Atlantic, together with details of the proposed PIRATA moored array. After a summary (Section 5), Appendix A provides information about programs related to PIRATA in order to identify those efforts with which PIRATA will be coordinated.

3. THE TROPICAL ATLANTIC OCEAN-ATMOSPHERE-LAND SYSTEM.

3.1 Mean Climate and Seasonal Cycle

The tropical Atlantic Ocean and atmosphere present many similarities in their mean structure and seasonal cycle with the equatorial Pacific. This suggests that some of the same air-sea coupling processes are at work in the two oceans, and not surprisingly warm events similar to El Nino also occur in the tropical Atlantic. However there are important differences. The Atlantic ocean is narrower, and the continental influences of both South America and Africa are more readily felt. The asymmetry of the continental mass distribution between the northern and southern hemisphere induces a monsoon regime near Africa.

3.1.1 Mean Climate

Over the equatorial Atlantic ocean, deep convection and high cloudiness are often confined to a narrow band that spans the entire ocean with a slight northward tilt towards Africa. This region defines the intertropical convergence zone (ITCZ), usually located north of the equator and associated with surface wind and moisture flux convergences (Hastenrath, 1985). The maximum latent heat release occurs in the lower troposphere, which produces heavy rainfall. The ITCZ continues over the neighboring continents, where it contributes a large portion of the precipitation. Over the ocean, rainfall in the ITCZ is highly variable with some of the most intense events associated with the propagation of 5-day easterly waves, in particular during boreal summer.

A confluence zone is located not far from the ITCZ, usually to its north in the eastern Atlantic, in particular during boreal summer. It separates at the surface air flowing from the north in the northeasterly trade winds from air flowing from the south in the southeasterly trade winds. Winds there are weak and variable (Hastenrath and Lamb, 1977). The confluence zone corresponds to a pressure trough and is located over warm water, close to the latitude of maximum SST in the central Atlantic (Fig. 4). The atmospheric circulation at basin scale is strongly influenced by the intensity and position of the ITCZ, and is quite steady away from the ITCZ. The link between the position of the ITCZ and the SST distribution therefore reveals a coupling between the atmosphere and the ocean. South of the equator, over the ocean, the winds usually flow from the south-east and are quite steady. In the western Atlantic, the direction does not change until the close vicinity of the confluence zone. In the eastern Atlantic, where the convergence zone is often located over the continent, the winds are more meridionally oriented near the equator and rotate clockwise towards Africa, due to the influence of the African continental land mass.

Near the equator, surface temperatures are lowest in the central Atlantic (0-20°W). The presence of this cold water has an effect on the atmospheric boundary layer. Because the SST is locally lower than further south, the atmospheric boundary layer is cooled near the equator by the interaction with the ocean, a process which stratifies the lower atmospheric layer and inhibits vertical mixing in the atmosphere. This results in a very low latent heat loss of the ocean. The stratus decks over the southern regions of cold water probably also contribute to maintaining the hemispheric asymmetry of SST by reducing the amount of solar insolation reaching the surface in the southern hemisphere.

The upper ocean dynamically responds both to the curl of the wind stress and the wind stress near the equator (Philander and Pacanowski, 1986). The slope of the sea surface results from the tilt of the thermocline. The thermocline depth and the sea surface elevation exhibit extensive zonal and meridional structure (Fig. 5). Along the equator, the thermocline deepens towards the west. The associated slope of sea surface elevation nearly balances the force exerted by the zonal wind stress to the upper layer of the ocean (Weisberg and Weingartner, 1986). The average wind pattern therefore results in a deeper thermocline near the equator in the western Atlantic than in the eastern Atlantic, and north of the equator than south of it (Philander and Pacanowski, 1986). Thermocline depth is deeper north of the equator than south of it, which probably results from the winds blowing to the north across the equator. The thermocline is deepest near 5°N and is shallowest north of 10°N. The curl of the wind stress at these latitudes is such as to lift the thermocline north of the confluence zone and depress it between the equator and the confluence zone (Katz, 1981). In the Gulf of Guinea, the curl of the wind stress also contributes to lift the thermocline south of the equator. The reservoir of warm water is therefore less voluminous close to Africa, in particular, south of the equator than in the western Atlantic.

To understand the distribution of surface temperature (Fig. 4), it is interesting to analyze the heat budget of the upper layer of the ocean. This is controlled by oceanic processes, vertical mixing, upwelling of colder subsurface waters, horizontal advection, as well as by the heat exchange with the atmosphere. The wind direction favors coastal upwelling along most of the African coast south of the equator, as well as along part of the coast of the Gulf of Guinea north of the equator. The major source of upwelling is along the equator in the central Atlantic, where the southeasterly winds are favorable for an Ekman divergence. In the eastern Atlantic, where the wind is meridional at the equator, the main Ekman divergence and upwelling are located slightly south of the equator. The near-equatorial Ekman divergence, by far the largest, entrains to the surface 10×10^6 $m^3 s^{-1}$ of thermocline water (Gouriou and Reverdin, 1993). It results in a doming of isotherms in the upper thermocline on the equator in the central Atlantic, and a little south of the equator in the eastern Atlantic (Merle, 1980a). This upwelling lowers SST near the equator in comparison to neighboring northern and southern latitudes.

The water brought to the surface by the equatorial divergence originates mainly from the southern subtropical gyre, from which it flows in the thermocline towards South America and from there into the eastward Equatorial Undercurrent. The surface water near the equator flows westward toward South America and meridionally poleward due to Ekman divergence (Fig. 6) (Richardson and Walsh, 1986; Richardson and Reverdin, 1987). Part of the water flowing from the equator is then entrained north of 5°N in the eastward flowing North Equatorial Countercurrent, and part of the water (mainly the branch of the current south of the equator) reaches South America.

Most of the equatorial Atlantic gains heat through the air-sea interface (Fig. 7), because the radiative heat gain is larger than the latent heat loss as a result of the low cloud amont near the equator and of low latent heat losses (Hastenrath and Lamb, 1978). The gain is largest near the equator and along Africa where the upwelling occurs and is near zero at 10°N and 10°S. During the surface water transit away from the eastern Atlantic, the water is therefore warmed up by surface heat exchanges. This surface heating in part explains the SST distribution with warmer waters in the west. The equatorial Atlantic gains heat, which is exported by a meridional circulation (warmer surface water outflow and colder subsurface inflow). The surface water ultimately flows mainly to the northern hemisphere where it contributes at least 10 Sv to the northward upper limb of the thermohaline circulation (Schmitz and McCartney, 1993). This meridional heat flux is significantly different than that in the equatorial Pacific, where the surface waters flow meridionally away from the equator in both hemispheres.

There is little rainfall south of the equator and therefore a large deficit of fresh water flux in the southern hemisphere (Fig. 8). Hence, the salinity of surface water is very high when it reaches the vicinity of South America and is entrained northward in the intense North Brazil Current (Fig. 9). This warm and salty water is mixed with a significant flow of fresh water from the Amazon and other South American rivers (close to 0.2 Sv) and freshened by the rainfall at the latitude of the ITCZ. A significant portion of the surface water in the North Brazil Current is actually first entrained offshore between 5°N and 8°N towards the east north-east in the North Equatorial Countercurrent (Richardson and Reverdin, 1987). However, part of the water also flows towards the northwest closer to the south American continental shelves becoming entrained into large anticyclonic eddies near Guyana (Richardson *et al.*, 1994). Because of the meridional circulation, the fresh water does not stagnate in the equatorial western Atlantic, another difference with the western equatorial Pacific where strong barrier layers formed by local precipitations are often found.

3.1.2 Seasonal variability

The ITCZ experiences a very large seasonal migration coincident with the migration of the warmest surface water in the western Atlantic. Its position is farthest north in August-September where it reaches 14°N in the eastern Atlantic and 8°N at 30°W. Its position is farthest south in April when it straddles the equator in the western Atlantic (Hastenrath and Lamb, 1977). The timing of the cycle is different than over the continent where the monsoonal changes are closer to the course of the sun. Part of the difference is attributed to the maintenance of the tongue of cold water along the equator until September in the eastern Atlantic (Fig. 10a) and October-November in the central Atlantic (Fig. 10b).

The seasonal excursion of the ITCZ is associated with a large change in both wind stress curl and wind stress intensity (Mayer and Weisberg, 1993). North of the equator, the curl of the wind changes sign seasonally which modulates the Ekman pumping/downwelling and results in a seasonal change of the meridional topography of the thermocline (Katz, 1981, 1987a). These vertical displacements of the thermocline propagate westwards as Rossby waves, and the associated vertical displacements of the thermocline are largest in the western Atlantic north of the equator (Carton and Katz, 1990) (Fig. 11). The currents associated with the dynamic topography have the largest seasonal cycle in the western Atlantic (Richardson and Walsh, 1986). In particular, the North Equatorial Countercurrent found between 5°N and 8°N, reaches its peak intensity in August-September, when it is associated with large meanders near South America, and merges with the permanent Guinea current. In the Gulf of Guinea, the currents which are more shallow, have large variations, both at the annual and the semi-annual period. Away from the equator, the net heat flux at the air-sea interface is strongly modulated by the changes in the wind intensity (which are weakest near the ITCZ) and by the seasonal march of the sun (Hastenrath and Lamb, 1978) (Fig. 12).

Near the equator, the seasonal cycle of the wind is strongest in the western Atlantic, where the ITCZ crosses the equator in January-April (Fig. 10c). The intensification of the westward wind stress first begins in April between 0° and 10°W, and then moves westward. In the western Atlantic, there is a long period of established southeasterlies, which are strongest in August-September, and a short period of variable winds, in February-April near 30°W and in May near 45°W. The transition between the two periods can be quite sudden, in particular, in

May when the ITCZ moves northward (Weisberg and Tang, 1990). In the eastern Atlantic, the seasonal cycle of winds is largest in the meridional component, and is more regularly modulated at the annual period. The strongest meridional winds are associated with the peak of the African monsoon when the ITCZ is farthest north. This is also the time when the cold tongue is most developed (Philander and Pacanowski, 1981; Houghton, 1989), and the equatorial Atlantic heat gain from the atmosphere is largest (Fig. 12).

The seasonal changes in the wind, in particular, in the western Atlantic induce a response in the equatorial wave guide (Cane, 1979) which results in changes of the slopes of the thermocline (Figure 11) and the sea surface. According to Houghton (1983) and Verstraete (1992), the vertical displacement field of the isotherms is trapped within 250 km of the equator, which is consistent with a second baroclinic mode. The fast changes in the wind in April-May resulting in changes of the zonal pressure force that are not in equilibrium with the zonal wind stress, at least on a monthly time scale. Kelvin waves have been observed at subseasonal frequencies, which propagate eastward towards the eastern Atlantic (Katz, 1987b) (Fig. 13). Comparison between the zonal pressure gradient observed during FOCAL/SEQUAL and that modeled using a forced linear equatorial long wave model shows (Fig. 14) that the zonally and temporally integrated response to the zonal wind stress determines the thermocline adjustment along the equator (Weisberg and Tang, 1990). Kelvin and Rossby waves are excited which together with their boundary reflections account for the seasonal evolution of the thermocline along the equator. They are in particular responsible for the semi-annual component of the thermocline depth, current and sea level fluctuations in the eastern equatorial Atlantic, which are quite prominent there despite a fairly regular annual cycle of the wind forcing in the eastern Atlantic.

An equatorial cold tongue develops usually in May. The onset coincides with the intensification of the equatorial easterly wind stress. The zonal wind stress intensification in the equatorial Atlantic is responsible for the shoaling of the thermocline and the appearance of the cold tongue in the eastern Atlantic (Servain *et al*., 1982; Houghton, 1989). The wind intensification in the central and eastern equatorial Atlantic results in an increase of Ekman divergence, vertical mixing, and a meridional asymmetry in mixed layer depth (Philander and Pacanowski, 1981). The seasonal evolution and the maintenance of the cold tongue also depend on other processes, such as vertical and horizontal advection, vertical mixing, and fluxes associated with instability waves (Weingartner and Weisberg, 1990, 1991).

The northern edge of the cold tongue is often bounded by an abrupt temperature front. Immediately to the north of this front is a region of strong air mass modification, where northward-moving air which has just crossed the equatorial cold tongue flows over warmer surface waters. This transition is marked by an increase in surface wind (Fig. 10a). As the boundary layer becomes unstable, drier, faster-moving air is mixed downward toward the surface.

The current structure associated with the Equatorial Undercurrent close to the surface at the equator and the intense westward South Equatorial Current near the thermal front north of the equator is prone to instabilities, at least in the early phase of the upwelling season (Weisberg and Weingartner, 1988; Steger and Carton, 1991; Legeckis and Reverdin, 1987). On satellite imagery, this corresponds to the development of undulations and cusps in the thermal front with wavelengths of the order of 1000 km. These are often associated with eddies of warmer and fresher water to the north of the front, which propagate to the west at a speed close to 0.5 ms^{-1}. The development of the instabilities results in a meridional convergence of heat which is only partially compensated by a vertical eddy loss, and therefore contributes to a seasonal warming of the cold tongue (Weingartner and Weisberg, 1991).

3.2 Interannual Variability

The interannual variability of the tropical Atlantic region is considerably weaker than that of the tropical Pacific, and has been much less intensely studied. Interannual variability in the tropical Atlantic is often regarded as being dwarfed by the powerful influence of the annual cycle. Indeed, analyses of selected time series (*e.g.*, Horel *et al.*,1986; Servain, 1991) do show a dominance of the annual component in the variability, perhaps the result of the entire oceanic domain being “ close ” to the surrounding continents, and impacted by monsoonal dynamics. Yet the year-to-year and longer-term fluctuations are by no means negligible. Figure 15 shows the amplitude of interannual variability in zonal and meridional pseudo stress and SST for the tropical Atlantic region, together with the ratio of seasonal to interannual variability. Particularly near the equator (and in the outer tropics for winds), the relative contributions of interannual variability are seen to be significant. A prominent case of interannual variability is the 1983-1984 time period, during which an extensive oceanic field program was conducted by France and the US (FOCAL/SEQUAL) - ironically, to study the seasonal cycle. In fact, the evolution of the seasonal cycle during these two years was very different, with the latter year showing major perturbations of SST, winds, convection, and ocean circulation that resembled in many ways an El Nino occurrence in the Pacific (Philander, 1986; Lamb *et al.,* 1986; Weisberg and Colin, 1986; Hisard *et al.,* 1986; Katz *et al.,* 1986; Horel *et al.,* 1986; Verstraete, 1992). Along with the other anomalies, both the Nordeste and the Sahel regions experienced significant anomalies in precipitation during these years (Servain and Séva, 1987). These effects have not been unprecedented, as the studies of Merle (1980b) and Shannon *et al.,* (1986) indicate. More recent studies of the North Equatorial Countercurrent in the western equatorial Atlantic reveal very high interannual variance relative to the annual cycle (Katz, 1993), a result consistent with studies of thermocline depth variability (Houghton, 1991). Figure 16 shows the variability in near-equatorial 20°C isotherm as derived from XBT's over the period 1980-1993. Interannual fluctuations of order 10 m are clear, and at least as energetic as seasonal fluctuations. Regarding upper ocean currents, observations in the tropical South Atlantic suggest quite minor seasonal changes (Molinari, 1982). Further study of the role of interannual *vs.* seasonal variability in subsurface fields, and the connections to surface variables, is needed.

Empirical studies have attempted to look at the associations between regional climate (precipitation) anomalies and other ocean/atmosphere variables. For , composites of extreme precipitation events (Hastenrath and Heller, 1977; Moura and Shukla, 1981) have revealed a basin-scale meridional dipole structure in SST. The structure is coherent throughout the entire tropics, to the north and south of about 5°N. A very similar SST structure emerges from similar studies based on precipitation extremes in the Sahel region (Lamb 1978a,b; Lough 1986; Folland *et al.,* 1986; Wolter 1989). Servain (1991) introduced a simple index of the difference in SST anomaly over the northern tropics and southern tropics, and was able to show significant correlations of this index with precipitation in both the Sahel and Nordeste over a roughly 25 year period. Figure 17 shows the anomalies of SST and pseudo stress between November 1984 and April 1985, a particularly wet period for the Nordeste. The large-scale meridional gradient of SST trends, and strengthening (weakening) trend of the Northeast (Southeast) trades is clearly evident. Extreme years in Nordeste precipitation nearly always feature such patterns in wind and SST. The immediate cause of the precipitation anomalies in the Nordeste appears to be displacements in the position of the ITCZ and associated rain band, which are closely linked to changes in the near-equatorial gradient of SST (Hastenrath and Heller 1977; Hastenrath 1978). Moura and Shukla (1981) demonstrated this linkage in an atmospheric GCM simulation; many more recent modeling studies have confirmed the result. For eastern Nordeste (that is, a roughly 300 km-wide zone along the eastern coast of Brazil between 3°S and 15°S), interannual variability in precipitation is largely dependent on other less studied processes, being strongly correlated to surface wind and SST variability in the southeastern Atlantic (Rao *et al.,* 1993). The mechanisms also appear complicated for the Sahel, involving not only displacements of the oceanic ITCZ, but also the stability of low level air and associated precipitation in the Guinea coastal region to the south of the Sahel (Fontaine *et al.,* 1995). On interannual time scales these two regions exhibit out-of-phase fluctuations in precipitation (Wagner and da Silva, 1994). Palmer (1986) and others have had some success in simulating Sahel precipitation by prescribing Atlantic, and more generally global, SST. Similar statistical studies performed to predict the rainfall anomaly over the Nordeste have had the same success (*e.g.* Hastenrath and Greishar, 1993).

Attempts to characterize modes of SST variability alone have been less conclusive, and have led to considerable debate. Traditional EOF (or principal component) analyses as done by Weare (1977), Hastenrath (1978), Lough (1986), and others, reveal a mode of variability much as described above, with opposite signs in the tropics to the north and south of about 5°N. The time series for these modes show a dominance of low frequencies - decadal or longer - but with notable seasonal and interannual fluctuations as well. A recent analysis by Nobre and Shukla (1996), based on combined SST and surface wind stress, depicts essentially the same pattern, with cooler SST associated with stronger winds, and warmer SST associated with weaker winds in each hemisphere (Fig. 1). Another mode appears in many analyses, featuring anomalies of one sign throughout nearly the entire tropics, but with accentuated variance on or slightly south of the equator. The time series for this pattern is more predominantly interannual. Houghton and Tourre (1992) showed that the dipole pattern in particular is not stable with respect to “ Varimax ” rotation, and that the rotated principal components separate into independent northern and southern tropical monopoles. More recently, Mehta and Delworth (1995) have performed analyses of 100-year SST time series from the GOSTA data set, and find evidence for both quasi-independent (tropical) hemispheric variability and dipole-like variability at slightly different frequencies in the decadal range. Thus, it seems that the coherence between northern and southern tropical SST (relative to about 5°N) is variable, but that the coherence within each hemisphere is high, on interannual and longer time scales. To date there is very little information on the relationship between these hemispheric scale SST patterns and other oceanic variables, including subsurface temperature and currents. It is therefore not yet possible to determine the connections between the Atlantic thermohaline circulation or upper ocean wave processes and these low frequency SST patterns, although North Atlantic Gyre and basin-scale variability in subsurface yearly mean temperatures (with a peak around 13 years) have been found by Levitus *et al.* (1994) using data from the latitude range of 20°N to 70°N. Established somewhat more clearly is the importance of surface heat flux anomalies - particularly those associated with variations in wind speed - in forcing the hemispheric-scale SST patterns. Carton *et al.* (1996) found, using ocean GCM simulations, that the dipole-like pattern could be simulated quite well over a 30 year period when forced only by the wind speed related component of surface heat flux. There is to date no explanation for the decadal and longer term fluctuations of the tradewinds, and associated subtropical anticyclones of either hemisphere. There is no known mechanism by which internal atmospheric dynamics could generate such time scales, and thus the most plausible explanations could involve coupling to either the land surface or the ocean(s). As such mechanisms have not been identified, it is fair to say that there is no theory for the low-frequency hemispheric scale variability that is both prevalent and influential on regional climate in the tropical Atlantic. At least one coupled GCM experiment has produced arguably realistic variability of this type (Mehta and Delworth, 1995), but the results have not to date yielded a dynamical explanation. Clearly, more information and more study is needed.

As mentioned above, the year 1984 presented a scenario very reminiscent of El Nino, with near equatorial westerly wind anomalies and central and eastern basin SST anomalies. A somewhat similar evolution, from June to August 1968, is shown in Figure 18. There are more general indications of such equatorial patterns. Wagner and da Silva (1993) correlated precipitation in the Guinea coastal region with Atlantic SST over a nearly 40 year period, finding a clear El Nino-like, equatorial SST pattern. Zebiak (1993) identified a similar pattern, and further showed that the wind/SST structures associated with the mode were consistent with local coupled dynamics analogous to ENSO. Earlier studies had already demonstrated the importance of equatorial waves and remote wind forcing to the eastern Atlantic ocean variability, demonstrating a general dynamical similarity with the Pacific (McCreary *et al.,* 1984; Servain *et al.,* 1982; Hirst and Hastenrath, 1983a,b).

The equatorial mode variability is well captured by area-averaged winds and SST in the western and central portions of the basin (respectively), between about 3°N and 3°S. Such indices show that the variability associated with this mode is primarily seasonal to interannual, with relatively stronger seasonal modulation of interannual anomalies than is apparent in the Pacific. The modulation is such that significant anomalies are generally confined to the northern summer and fall season (Zebiak, 1993), helping to explain the particularly strong associations with Guinea coastal and Sahel precipitation, also focused on the summer season. The equatorial variability, in its predominantly seasonal to interannual character, contrasts particularly with the longer time scale variability of the northern basin-scale mode. On the other hand, distinctions between the equatorial and southern basin-scale mode have not been clearly established; indeed the geographical overlap guarantees some degree of interrelationship. More precise characterization awaits further research.

Coupled model experiments have suggested that the equatorial mode is dynamically akin to ENSO, despite some systematic differences in the spatial patterns dictated by differences in the climatological mean atmosphere-ocean state in the two tropical basins (Zebiak, 1993). Perhaps the most important difference involves the zonal positioning of the coupled anomalies. In the Atlantic setting, strong anomaly coupling occurs in the western portion of the basin, owing to the presence of strong easterlies and upwelling there in the climatological mean state. In contrast, the strongest anomaly coupling for the Pacific is situated close to the center of the basin. This difference in positioning has interesting consequences on the near-equatorial oceanic heat budgets for the two basins. This notwithstanding, the results suggest that interannual oscillations in the Atlantic are partially regulated by a “ delayed-oscillator ” mechanism involving upper ocean wave dynamics and equatorial upwelling. If this proves correct, then in analogy with the Pacific, a degree of determinism and predictability is implied. However, the problem is complicated by at least two factors. Present results suggest that local interactions within the Atlantic alone are unable to support the observed variability levels, even at the equator. This means that perturbations of separate origin are also important. The most obvious source on interannual time scales is ENSO. Indeed, there is evidence of a relationship between Pacific SST and Atlantic SST and winds. Uvo *et al.* (1996) find a relation between Pacific SST and northern tropical Atlantic SST, in particular. Significant correlations between eastern Atlantic wind stress and the Southern Oscillation Index (which is of course tightly tied to Pacific SST) have also been found (Fig. 3). Strong negative (positive) values of the SOI during November-March are often followed by a strengthening (weakening) of the eastern equatorial winds during subsequent months.

A recent study by Tourre and White (1995) and model experiments carried out by Delecluse *et al.* (1994) indicate that the ENSO-tropical Atlantic connection is the result of a globally perturbed atmosphere. The ENSO-induced wind anomalies modify the western equatorial Atlantic subsurface structure, sometimes triggering an Atlantic warm (cool) event. These authors note that Pacific SST's are not sufficient to explain the equatorial Atlantic SST variance, implying that regional ocean/climate anomalies cannot be considered as simply ENSO-driven. It is also known that the Nordeste rainfall has an ENSO connection (Hastenrath, 1990; Ropelewski and Halpert, 1987). The extent to which, and manner in which such ENSO-related perturbations interact with the annual cycle, basin-scale, and equatorial coupled variability in the Atlantic are important topics for further work. Other sources of perturbations, related to quasi-biennial variability (Servain, 1991), potential influences of land-atmosphere interactions and extratropical variability also remain to be examined.

3.3 Scientific Questions

Sections 3.1 and 3.2 have served to highlight the seasonal and interannual variability of the oceanic and atmospheric circulation that is particular to the tropical Atlantic Ocean basin. Coming out of the TOGA program and into research programs such as CLIVAR and GOALS, the scientific community is expanding its focus out from the tropical Pacific and toward the other tropical oceans and higher latitudes. The overarching scientific question for the tropical Atlantic sector pertains to the role of the tropical Atlantic Ocean in influencing (*i.e.*, initiating, regulating, and modulating) seasonal, interannual, and longer time scale climate anomalies both regionally and hemispherically. Although the tropical Atlantic basin is characterized by a fairly regular seasonal cycle, it is not without significant anomalous perturbations. While the frequency and amplitude of such deviations from climatology may be smaller than for the Pacific, their socio-economic ramifications can be nonetheless quite severe. This holds true for countries that border the Atlantic on both ends of the basin where societies have come to rely on a regular and unbroken repetition of the seasonal cycle. A timely example of such departures from normal occurred in 1995. During this year, the increased hurricane activity in the Atlantic Ocean attracted considerable attention. However, less widely known is that the oceanographic conditions in the tropical Atlantic Ocean, possibly not unrelated to the hurricane incidence, were also extremely anomalous. For several months SST was 1-2°C above normal across the entire tropical Atlantic Ocean, sea level as measured *in situ* and from radar altimeters was of the order of 10 cm above normal. In the open ocean, the tuna fishery experienced important abnormal changes both in space and time. Furthermore, alongshore pelagic fisheries were dramatically reduced in 1995. Previous interannual events of this magnitude occurred in 1968 and 1984. At the present time, little is known of the causal mechanisms of this recent anomalous warm event in 1995.

The key to improving our understanding of the climatic influence of the tropical Atlantic Ocean is a better appreciation for the processes that determine the space-time variability in SST within the basin. An initial focus on SST is necessary because this is the key quantity responsible for atmosphere-ocean coupling as inferred by many empirical studies linking SST with anomalous rainfall. This raises a number of scientific questions that are not mutually exclusive but rather interrelated. Among the most pertinent and pressing issues for PIRATA are the questions:

⁎ *What processes are responsible for changes in the off-equatorial meridional or so-called dipole gradient in the tropical Atlantic SST vs. those changes in SST along the equator?*

Obviously, SST variability is a manifestation of, and intrinsic to, complicated ocean-atmosphere coupling. This question seeks elaboration on those processes, both oceanic and atmospheric, that induce changes in SST. Our ability to obtain a better appreciation for this coupling will require enhanced information on the upper ocean thermal structure, the three-dimensional transports of mass and heat, and changes in response to forcing by surface fluxes. It is likely that different processes are responsible for anomalous SST variability on and off the equator. However, it is important that they be considered together as there may be important interactions of these two modes of SST variability on climatologically relevant time scales.

Under this general question there arises a number of more specific questions:

- What is the regional distribution of the processes that control SST evolution, ranging from one-dimensional heat flux/entrainment balances to fully three-dimensional processes?

- What controls the seasonal evolution of the ocean-atmosphere fluxes that result in a distinctive hemispheric asymmetry in winds, convection and SST? How does the meridional SST gradient influence the ITCZ displacements relative to the continental effects of South America and Africa?

- What mechanisms are responsible for interannual variations in ocean-atmosphere fluxes, convection and SST? How are these related to the seasonal cycle? Do they represent an inherently coupled ocean-atmosphere-land feedback loop that determines off-equatorial SST variability? If so, are they the same north and south of the equator?

- What are the non-local tropical influences on Atlantic SST variability? Specifically, what are the effects of changes induced by Pacific Ocean warm events (Delécluse *et al.*, 1994; Curtis and Hastenrath, 1995)? More generally; what are the Pacific Ocean, Indian Ocean and continental heat source influences on the tropical Atlantic?

- What are the extra-tropical influences on the tropical Atlantic, *e.g.* exchanges or influences from higher latitudes as noted by Déqué and Servain (1989) and Hansen and Bezdek (1996)?

- What are the physical mechanisms that link anomalous SST variability with anomalous rainfall over the land masses that border the tropical Atlantic?

- What are the effects of a marine boundary layer not in equilibrium with local SST as demonstrated by Murtugudde *et al.* (1996) off the coast of West Africa where warm dry air is advected over the cooler waters of the coastal upwelling zone?

⁎ *To what degree does the tropical Atlantic SST variability affect the coupled ocean-atmosphere-land system of the region and its predictability?*

When considered in isolation, an improved understanding of the factors that determine anomalous SST variability in the tropical Atlantic may be an interesting research problem from a climate perspective, but the practical benefits of such research depend on how our understanding of the coupled system is advanced as a result. In view of the geographic distribution of land and ocean within the region, the influence of tropical SST variability may not be as dominant as it is for the air-sea coupling over the Pacific Ocean.

- To what extent is the predictability of the equatorial coupled mode affected by the meridional or dipole coupled mode? Is there decadal or interdecadal scale modulation of the equatorial coupling?

- To what degree is the predictability of the coupled system within the tropical Atlantic basin determined by local interactions *vs.* external influences such as connections with ENSO?

Similarly, in programs such as ACCE, and when considering decadal scale ocean-atmosphere variability, a pertinent question to be confronted is:

* *How do anomalous changes in the oceanic transports of mass and heat affect SST, and hence the coupled system, within the tropical Atlantic basin and via exchanges to higher latitudes?*

In contrast to the Pacific Ocean, the zonally averaged circulation in the tropical Atlantic is characterized by a net northward transport of mass and heat. The significance and range of influence for anomalous changes in the tropical Atlantic Ocean circulation remains an open question. For example, Bjerknes (1964) recognized the possible importance of advection in determining regional SST patterns. He described the path of an SST anomaly originating in the South Atlantic, subsequently being advected into the subtropics of the North Atlantic (*i.e.,* cross equatorial and cross gyre exchanges), and the associated atmospheric response. It is recognized that anomalous changes to the tropical Atlantic Ocean circulation can and do exist. However, what is less well known are the implications of such changes for regional and hemispheric climate variability.

Determining the controlling mechanisms for inter-gyre and inter-hemisphere heat transport in the Atlantic Ocean is an underlying issue. Mayer and Weisberg (1993) suggest a rectification of the annual cycle wherein both western boundary currents and interior Ekman transports are important, with fluid being heated and stored within an equatorial gyre prior to being transported farther northward. If this hypothesis is correct then an interannual modulation of the seasonal cycle should impact northward heat transport.

- What, then, are the magnitude and time scales for variability in the net transport of heat from the tropical to the northern hemisphere sub-tropical Atlantic Ocean?

- Do these transport variations have origin in the southern hemisphere subtropics as indicated, for example, by anomalous warming within the Benguela current in relation to ENSO (Shannon *et al.*, 1986).

- Do coastal trapped Kelvin waves emanating from the tropics play an important role at mid-latitudes in the Atlantic as suggested in the Pacific ? Is there an associated excitation of Rossby waves and a related long-time scale, westward propagating response as is conjectured for the Pacific (Jacobs *et al*, 1994)?

- What and where are the key indices for monitoring the anomalous mass and heat transport into, within, and out of the tropical Atlantic Ocean?

To adequately address the full range of questions highlighted in this section will require in situ observations, satellite observations and dynamical models of the ocean-atmosphere-land system. As envisioned, the PIRATA array will contribute directly to several of these questions, and indirectly to others through interaction with satellite measurement and modeling efforts. In the following section we describe the PIRATA array in detail, and how it will enhance observational capabilities within the framework of existing tropical Atlantic programs. In the final section, we summarize the unique contributions of PIRATA to improved description, understanding, modeling and prediction of climate variations in this region of the world ocean.

4. A MONITORING SYSTEM IN THE TROPICAL ATLANTIC

The present Tropical Pacific Ocean Observing System developed as a result of an outgrowth of one or more process oriented experiments such as the EPOCS, TIWE, Tropic Heat, and COARE initiatives. These process oriented experiments helped to identify those oceanic and atmospheric variables that needed to be measured on a continuous basis in support of ENSO monitoring and prediction. Within the past 10-15 years, the French-American FOCAL/SEQUAL experiment was the most comprehensive process experiment in the tropical Atlantic. Surface winds, subsurface thermal structure, subsurface currents were monitored along the equator together with observations across the surface topography trough-ridge structure north of the equator in order to advance our understanding of the seasonal response of the tropical Atlantic Ocean to surface forcing. As fate would have it, this experiment took place during the very anomalous period of 1982-1984. Since then, smaller process studies were initiated covering limited areas (*e.g.*, STACS, WESTRAX, AmasSeds); some of which have served as national contributions to the TOGA, WOCE or other major international projects. All in all however, the major observational emphasis of the international community during the TOGA decade has been focused towards the development of an observing system and prediction models for the Pacific ENSO. The effort made to design and implement an observing system specific to the tropical Atlantic basin has received less attention.

4.1 The Present Status

The present status of the operational surface and subsurface data collection within the Tropical Atlantic is briefly described below.

4.1.1 Volunteer Observing Ship (VOS) System

(a) Surface Observations (SST and Pseudo Wind Stress, Salinity)

Most of the raw data of SST and wind are in the form of observations from ships of opportunity (Fig. 19) transmitted over the GTS and recorded in real time by NCEP. At the very beginning of each month, the raw data covering the previous month are provided to Centre ORSTOM-Brest by COAPS (formerly MASIG) at FSU. Between 6,000 to 8,000 records are then immediately processed for the study region (from 60°W to the African coast and from 30°N to 20°S). The method used to calculate SST and pseudo wind stress monthly fields is based on a combination of objective and subjective analysis (Servain *et al.*, 1985). The final products are 2°x2° gridded monthly fields. This data base is available from January 1964 upon request (soon on Internet) and is currently updated on a monthly basis. It is the access to these data sets that allowed, for instance, the recent 1995 warm event to be monitored on a delayed mode basis. The ORSTOM Atlantic data set for 1985-1994 pseudo wind stress (Servain *et al.*, 1996) was officially labeled as a “ TOGA product ” (the same manner as the FSU 1985-1994 Pacific and Indian Ocean wind products), and is available on the TOGA-CD-ROMs.

Two ORSTOM XBT lines (Le Havre - Cayenne and Le Havre - Rio de Janeiro) have been equipped with hull thermosalinographs in 1994-95. The records of temperature and salinity at about 10 meters depth (according to the burden of the ship) are continuous, and recorded with the ship position every 5 mn when the ship is moving. These data are processed at Centre ORSTOM-Brest (WOCE salinity DAC). A study for a real-time transmission via the

INMARSAT system is underway. The possibility exists that other XBT lines will be outfitted with a thermosalinograph system in the near future

(b) Subsurface Temperature Observations (XBT)

In terms of the establishment of operational data acquisition systems within the tropical Atlantic, *in situ* measurements during TOGA, based on a VOS expendable bathythermograph (XBT) program, have been conducted by several agencies from different nations. In the tropical Atlantic they were mostly achieved by ORSTOM (France) (5 XBT lines), NOAA (USA) (5 XBT lines), BSH (Germany) (1 XBT line) and a few other countries/institutes with lower periodicity. Three of these lines (40°N-30°S), occupied during TOGA, are still maintained by ORSTOM (AX-11, AX-15, AX-20). NOAA is currently maintaining its five lines (AX-8, AX-10, AX-12, AX-14, AX-29), and BSH its line (AX-11) (Fig. 20). Most of the observations are transmitted in real-time over the GTS, the others are only transmitted in delayed mode. Under normal conditions, about one crossing a month is achieved on each line, with a probe released every 6-hours (= about 100 miles) from 0 to 500 meters. The data profiles are processed, validated and archived at the Global Subsurface Data Center (IFREMER/ORSTOM-Brest) and NODC within the framework of the WOCE UOT-DAC data management scheme, where they are available upon request. The historical TOGA-WOCE data base covers the period 1985-present, but the Centre ORSTOM has a complete archive of data beginning in 1979. A comprehensive summary of yearly observations on each of these lines since 1990, including the number of transects and the number of observations achieved, is maintained on the WOCE DIU Web server at the University of Delaware.

A monthly climatology (temperature at standard levels) is being processed and will be available soon on the ORSTOM-Brest Web server. As discussed below, these data have been used by ORSTOM in an operational ocean model to offer the international community a regular monthly diagnosis of the upper layers of the tropical Atlantic.

At the conclusion of TOGA, the management of the global VOS XBT network has been transferred to an international body of IGOSS, the SOOP Management Committee (SMC). Concerning national commitments with regard to probes supply and line maintenance, the situation stands as follows: subject to scientific guidance from the CLIVAR Upper Ocean Panel and the GOOS/GCOS Ocean Observation Panel for Climate (OOPC), NOAA plans with annual review, to continue these tropical Atlantic XBT lines. ORSTOM plans to maintain the XBT monitoring on the three above-mentioned lines, provided an adequate supply of probes (around 1,500 by year) is maintained by NOAA. In any case it should cover at least the PIRATA Program period.

4.1.2 Operational In Situ Sea Level Data Acquisition (Tide Gauges with Satellite Transmission Capability in the Tropical Atlantic)

Although production of mean sea-level data products has traditionally been a priority within several international projects (TOGA, WOCE, GLOSS), very few of the planned sea-level stations within these projects obtained the status of long-term operational satellite transmitting capability in the Tropical Atlantic (Fig. 21). During the intense monitoring of FOCAL/SEQUAL (1982-84 and a few years afterward), there were about 8-10 tide gauges implemented by ORSTOM in the Tropical Atlantic (Dakar, Cabo Verde, Abidjan, Lomé, Sao Tomé, Fernando de Noronha, Natal, St. Peter and St. Paul Rock, Cayenne, ...). The data were recorded *in situ* and picked up once a year (at times maybe more). Progressively some of the

FOCAL tide-gauges were equipped with the CLS-Argos system (see below). However, due to many problems (human and financial), this network is now almost deserted, especially along the Africa continent. It is noteworthy that the tide gauge at Sao Tomé, which is still in operation, permitted the detection of elevated sea levels in the Gulf of Guinea during the 1995 warm event. At the present time there is an ongoing effort to send quality-controlled data from some tropical stations to the TOGA Sea Level Center, or to the Fast-WOCE Data Bank, by the organizations responsible for the tide gauges in operation. WOCE and TOGA tide gauge stations constitute only a subset of stations in the tropical Atlantic of potential value to PIRATA though. Additional sites are operated through the following projects:

(a) The French TOGAMA and WAT-BEE Projects:

The implementation at Cayenne, Praia, Dakar, Lomé and Sao Tomé of five pressure tide-gauge stations with the CLS-Argos telemetry link was supported by ORSTOM through the TOGAMA Program during 1989-92. The tide gauges in Cayenne, Praia, Dakar and Lomé were dismantled in 1993. In 1994, the Sao Tomé station was inoperational from March to October. The Sao Tomé station was refurbished late October 1994 by ORSTOM, with the help of CS through the WAT-BEE project. Furthermore, a new pressure gauge was installed back at Ile Royale (Cayenne) in October 1994. These pressure tide gauges are maintained until now by ORSTOM and the support of CS as part of the French WOCE-related TOPEX/Poseidon (T/P) verification effort in the equatorial Atlantic. The data issued from the Sao Tomé tide gauge were regularly dispatched to the TOGA Sea Level Center in Hawaii, and intercomparisons with altimetry from T/P were performed (Mitchum, 1994; Verstraete and Park, 1995).

(b) The British ACCLAIM Project:

This project, initiated in 1985, maintains satellite-transmitting pressure tide gauge systems which relay hourly data from sites at Ascension and Sta. Helena Islands by Meteosat to the Proudman Oceanographic Laboratory in Bidston, UK. This system is able to automatically control the benchmarks, and to be referenced to geocentric coordinates. Hourly data have been reported to the Fast-WOCE data Bank in the University of Hawaii since 1993.

(c) The Brazilian INPE REMARSAT Project:

This project, initiated in 1993, presently maintains four CLS-Argos transmitting pressure tide gauges located at Fernando de Noronha, Termisa, Fortaleza and Tamandaré, around the Brazilian northeastern coast. The project objective was to deploy, maintain and evaluate the possible applicability of the polar orbiting Brazilian satellite system SCD-1, against the results obtained from the CLS-Argos service. Also the feasibility of maintaining a high-precision tide-gauge monitoring coastal and island network that would meet the requirements of several other Brazilian projects, especially those related to coastal dynamics, has been assessed. The usefulness of this project for PIRATA is manifest, and can be augmented with the deployment of one station at the St. Peter and St. Paul Rocks, and the general monitoring of the residues between the *in situ* data from the gauges and the altimeter data from T/P and ERS1-2 satellites. Hourly data from 1993-96 are being forwarded to Fast-WOCE and TSLC in the end of June. Monthly distribution of sea-level products from this network is planned to be started by the end of 1996.

4.1.3 Operational Ocean Modeling

(a) A French Experiment Project (OPERA):

As a contribution to TOGA-France-Atlantic, a 2-year test (1990-1991) of an operational ocean model of the Tropical Atlantic was performed by ORSTOM and CNRS (LODYC-Paris, ORSTOM-Brest), and sustained by PDC. During that period, a monthly bulletin (BOAT = Bulletin Ocean Atlantique Tropical) was edited and delivered to the TOGA scientific community. At that time, an OGCM (OPA4 developed by LODYC) was forced by observed winds (*cf.* 4.1.1a above) and climatological heat fluxes. XBT data (*cf.* 4.1.1b above) were assimilated. In 1991, this project was revived by Météo-France, using the new version of the OGCM (OPA7) and forced (wind and “ heat ”) by the AGCM Emeraude, then AGCM ARPEGE (from November 1992), developed at Météo-France. The OGCM is run a month at a time. Most recently, the model output was used to analyze the evolution of the 1995 warm event.

(b) An USA Experiment:

At the NCEP (formerly NMC) an Atlantic Ocean assimilation system is running in a quasi-operational mode. At present it assimilates XBTs and SSTs. It extends from 50°S to 65°N and at the northern and southern boundaries it is relaxed to the Levitus’ climatology. The surface stress and heat flux are weekly averages from the NCEP mid-range forecast model. The model itself is the GFDL MOM GCM and its nominal resolution is 1x1 degrees with higher meridional resolution (1/3 degree) in the tropics. The system is kept up to date to within a few weeks of the current date. Weekly averaged fields from this system for the most recent few months are available on the NCEP FTP server. The same system has been used in a retrospective analysis of the years 1980-89. XBTs and the Reynolds analysis of SST were assimilated and the wind stress and heat flux came from the da Silva analysis of COADS. Monthly averaged fields from his run were saved and are also available on the FTP server. Future plans to upgrade the Atlantic system will include improvements to the model and a new, extended assimilation system, which will allow the assimilation of satellite altimetry data.

4.1.4 Satellite Data Products

Satellite data products for the tropical Atlantic include SST retrievals from NOAA/AVHRR, Meteosat, and ERS/ATSR. Sea topography information is available going back to the mid 1980’s from the GEOSAT radar altimeter and more recently from TOPEX/Poseidon and ERS1-2 altimeters. Sea surface wind speed measurements have been available since 1987 from the passive microwave SSM/I sensor. Active microwave sensors, *i.e.* scatterometer, measurements of surface wind velocity are available from the AMI on board ERS1-2 and from the NSCAT instrument launched on board ADEOS in August 1996. The ERS1-2 wind is processed in Centre IFREMER at Brest.

Remotely sensed measurements of ocean color are expected to resume with the launch of the SeaWiFS sensor during early 1997 and should prove useful for monitoring regions of oceanic primary production for delineating ocean circulation features such as the instability waves and the retroflection of the North Brazil Current.

Direct read-out real time access to IR and visible Meteosat data are processed by ORSTOM in various locations (Dakar, Lannion, Montpellier, Toulouse) to monitor daily the ITCZ, and to construct a 5-day SST map (with a combination of SST ship). The western limit is 40°W. FUNCEME at Fortaleza is also a station for satellite imagery.

For more than 30 years INPE has maintained a campus located at Natal, at the tip of the northeastern Brazilian region. A competent and dedicated group of engineers have been testing, developing and maintaining Data Collection Platforms (DCP) and sensors for using the CLS-Argos communication system. This group is interested in helping with the development and maintenance of DCPs connected to the buoys that PIRATA will be implementing in the tropical Atlantic. An enhancement of activities related to physical oceanography is planned to take place at Natal in support of satellite oceanography. It is expected that a collaborative work will take place between the INPE Group at Natal and the NOAA-PMEL Group. That collaboration could be enhanced by the participation of the Oceanography Group at INPE in Sao José dos Campos. PIRATA can therefore count on logistical support for some engineering and technical work from INPE at Natal, as needed.

4.2. An Agenda for Action: a 3-Year Moored Array Pilot Study in the Tropical Atlantic (PIRATA)

In this section we outline a plan for a pilot moored array designed to address some of the outstanding scientific issues related to climate variability in the tropical Atlantic. This array will consist primarily of 14 moorings spanning a region from 10°S-15°N, 0°-35°W (Fig. 22). The array design is based on our present understanding of relevant physical processes at work in the coupled ocean-atmosphere system, and the time and space scale on which they operate. Design has also been facilitated by an observing system simulation experiment (OSSE) to determine the impact of different array configurations on analyses of sea surface height variations (Hackert *et al.,* 1996).

The field program will last three years (1997-2000), with the array being built up in stages over the first two years, and maintained at full strength for the third and final year. The moorings will measure variables considered critical for understanding coupled ocean-atmosphere interactions in the region, including surface meteorological measurements and subsurface temperature, salinity and currents. These data will lead to an improved definition of surface boundary layer processes in both the ocean and the atmosphere, as well as a better understanding of the role that ocean dynamics plays the evolution of climate signals in the region.

We note at the outset that the proposed mooring array configuration is a compromise between the need to sample a range of climatic regimes over a wide geographical extent, but at the same time provide data with some degree of coherence both within and across these regimes. For the same number of moorings, broader latitudinal or longitudinal coverage would have to come at the expense of spatial coherence. The total number of moorings in the array is a compromise between the need to put out a large enough array for a long enough period of time to gain fundamentally new insights into coupled ocean-atmosphere interactions in the region, while at the same time recognizing the practical constraints of resource limitations in terms of funding, shiptime, and personnel. More moorings would obviously be desirable, but not practical for a pilot study on the scale that we envision. We fully expect though that the scientific value of the data for a wide spectrum of research and operational activities will become manifest during the course of our pilot study, and that this success will engender discussion of possible expansions and extensions of the array for climate studies in the tropical Atlantic on a longer term basis. The purpose of proposing this array then, is to demonstrate scientific success in a limited geographical region for a limited duration of time, as a guide to more serious long range planning.

The details of mooring design, array design, deployment schedule, logistics support and data distribution are presented in the following subsections. It should be borne in mind that the proposed array is designed to complement rather than supplant existing measurement systems described in the previous section. Indeed, the most meaningful analyses of ocean-atmosphere variability in the region will be based on the synergistic utilization of all available data sources.

4.2.1 Mooring Design

The moorings used in this array will be primary ATLAS moorings like those used in the equatorial Pacific as part of the TAO Array. ATLAS mooring design is presently being upgraded, with several “ next generation ” systems already deployed in the Pacific in 1996. We expect that the next generation system will be fully operational by the beginning of the PIRATA field phase, and therefore describe its instrumentation and sampling characteristics in this section. In general, the next generation ATLAS retains many of the characteristics of the original ATLAS design (multivariate measurements, relatively low cost, real-time data stream), but with improved accuracy, temporal resolution, flexibility in vertical sensor array design, and increased number of variables measured.

Measurements below the surface will be transmitted to a processor on the surface buoy from sensors inductively coupled to the mooring line, as compared to the older style ATLAS that has an electro-mechanical conducting cable separate from the mooring line. Both the original and the next generation ATLAS mooring systems have a design lifetime of one year. Features of the next generation mooring design relevant to PIRATA are described below. For brevity, we will refer to the moorings as ATLAS moorings, with the understanding that they are the next generation type systems.

The variables measured will be 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 180 m, 300 m and 500 m). The latter measurements are made to determine mooring line shape which can be used to correct for any significant mooring in the vertical sensor arrays. Placement of the subsurface temperature and conductivity sensors on the mooring line will be location dependent, and determined by the details of the local underlying mean thermohaline structure. Specifically, sensors will be positioned to favor finer vertical resolution in the surface layer and upper thermocline.

Winds, air temperature, and relative humidity will be measured using sensors deployed previously on ATLAS moorings, namely RM Young wind assemblies and Rotronic air/humidity sensors. Rainfall will be measured with an RM Young Siphon gauge similar in design to that deployed during TOGA COARE on the Woods Hole Oceanographic Institution IMET mooring (Weller and Anderson, 1996). Incoming short-wave radiation will be measured with an Eppley PSP pyranometer. All ocean temperature measurements will be made with the PMEL mini-temperature recorders. Salinity will be determined from either a Falmouth Scientific Inc. conductivity sensor or a SeaBird SeaCat type electro-mechanical sensor. Based on laboratory calibrations and field tests, we expect accuracies of about 0.2-0.3 ms^{-1} for wind speed, 0.1°C for air temperature, 2% for relative humidity, 0.03°C for ocean temperatures, 0.02 psu for salinity, 2-3% relative accuracy for short-wave radiation (McCarty and McPhaden, 1993; Mangum *et al.*, 1994; Freitag *et al.*, 1995; Cronin and McPhaden, 1996). Measurements of rainfall in the open ocean are problematical regardless of what type of sensor or platform is used; we expect that siphon gauges mounted on the ATLAS moorings will provide measurements of rainrate accurate to within ∓10%, which would be better than the ∓30% accuracies obtained from optical rain gauges on TAO buoys during COARE (Cronin and McPhaden, 1996).

All data will be collected and internally recorded at 10 minute intervals. Daily averages and some spot 10-minute samples will be telemetered to shore via CLS-Argos. A subset of the data will be retransmitted via the GTS for distribution to support operational weather and climate forecasting at national meteorological and oceanographic centers around the world.

4.2.2 Array Design

The PIRATA moored array consists of 14 ATLAS moorings spanning 10°S-15°N, 0°-35°W (Fig. 22). 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 spacing of moorings near the equator (5°-10° zonally and 2° meridionally) has been chosen to resolve the rapid Kelvin wave responses to abrupt wind changes in the western Atlantic. The 10° zonal separation of moorings along the equator is comparable to that of the FOCAL/SEQUAL moored array deployed in 1982-84.

Meridional mooring sections extend northward along 35°W from 2°S to 15°N, and southward along 10°W from 2°N to 10°S. These meridional arrays cover the regions of high SST variability associated with the SST dipole mode. The meridional spacing of moorings (2°-5°) is chosen to provide a minimal definition of coherent structures in the surface boundary layers of the ocean and the atmosphere on seasonal time scales across the range of latitudes on each of the two lines (35°W and 10°W). The zonal offset of the lines is dictated by the zonal offset of maximum SST variability in the northern and southern hemispheres.

This proposed ATLAS array cuts across a wide range of climatic regimes in terms of air-sea interaction. Along the equator, it extends from the cold tongue in the east where the oceanic thermocline is shallow, where equatorial upwelling is strong and where oceanic heat gain is large; to the western Atlantic warm pool where the oceanic thermocline is deep and net oceanic heat gain is small (Fig. 7). Meridionally, the array traverses the ITCZ, a region of high SST, weak winds, high cloudiness and precipitation, low solar irradiance and low evaporation (*cf.* Section 3.1). In contrast, in the northeast tradewind region north of the ITCZ along 35°W, conditions are drier, less cloudy, the winds are stronger and the SSTs are lower. The region south of the equator along 10°W is in the southeast tradewind regime. The relatively low SSTs off the equator in this region may be related in part to offshore influence of coastal upwelling in the Benguela Current region, and to the presence of the low level marine stratus decks.

Horizontal heat advection is likely to be of secondary importance in the surface layer heat balance on seasonal and interannual time scales away from the equator and coastal boundaries. Thus, in general, moored current measurements are a second priority in PIRATA. However, direct estimates of currents along the equator are important because of the role of ocean dynamics in creating SST anomalies there. An acoustic Doppler current profiler mooring is therefore proposed for 0°, 20°W to monitor current variations in the central Atlantic. This location is one of high zonal current variability in a region where interannual SST anomalies are also of significant amplitude, indicating a potentially significant role for zonal advection in creating thermal anomalies. Also, fluctuations in zonal mass transport in the Equatorial Undercurrent, which can be monitored at this mooring site, may be related to variations in upwelling intensity in the equatorial cold tongue.

In addition to direct measurements of velocity on the equator, the array will provide indices of zonal geostrophic mass transport along 35°W and 10°W. Temperature and salinity time series data can be used to compute dynamic heights relative to 500 m, from which geostrophic flow between mooring locations can be estimated. Thus, for example, we will be able to examine both seasonal and interannual velocity transport variations in the South Equatorial Current, the North Equatorial Current and the North Equatorial Countercurrent. Furthermore, we can examine the relationship of these current variations to wind forcing and SST variability.

The importance of wind forcing, and its response in terms of wave dynamical processes argue strongly for the incorporation into the array of wind and sea level measurements at a few strategically located islands (Fig. 22). St. Peter and St. Paul’s Rocks (0.7°N, 29.2°W), previously instrumented during FOCAL/SEQUAL, is a small island with little topographic relief, so that winds measured there are representative of those over the open ocean. The island lies in a key region of strong wind forcing where interannual variations in the zonal wind component are highly correlated with the Southern Oscillation Index (as discussed in Section 3). Wind measurements at this site can serve as backup should winds on the nearby 0°, 30°W mooring fail. Conversely, in combination with these nearby moored wind measurements, those from St. Peter and St. Paul’s Rocks will provide valuable information on the small scale structure of the wind field in the western Atlantic.

Wind and sea level measurements at Atol das Rocas (3.9°S, 33.5°W) would extend the measurement array along the westernmost mooring line into the southern hemisphere. This extension is particularly important for tracking seasonal migrations of the ITCZ, and for defining the meridional structure of surface height variations between 4°S and 15°N. Continued maintenance of the tide gauge station at Sao Tomé (0.5°N, 6.5°E) will allow detection of thermally and dynamically forced sea level variations in the eastern equatorial Atlantic. Existing sea level and wind measurements from Ascension Island (7.9°S, 14.4°W) will provide valuable *in situ* data in the central basin south of the equator. This is a region of strong southeast tradewind forcing poorly sampled by VOS measurements.

Finally, Brazil plans to implement a network of meteorological buoys on its continental shelf as a contribution to GOOS (see 4.3.2). High priority should be given to implementing one of these buoys during PIRATA to extend the definition of wind forcing along the equator to the west of the 35°W meridian. It is anticipated that some of these coastal buoys will measure subsurface temperature as well. Such measurements, initiated at 0°, 44°W during PIRATA would provide a description of wind and temperature variability along the equator with 5°-10° zonal resolution over nearly 5000 km (between 0° and 44°W).

4.2.3 Deployment Schedule

The schedule for development of the moored array is show in the following Table:

Date (MON/YR)	8/97	8/98	2/99	8/99	2/00	8/00
Moorings Deployed	5	5	10	14	14	14

The dates in this table are approximate and should be viewed as indicative of the preferred phasing of the implementation plan. Actual dates may shift due to availability of ship time, funding, etc. However, implementation is expected to begin in late 1997 and continue through late 2000, spanning three full calendar years. Detailed discussion of the implementation timetable for the moored array follows.

The first phase of five buoys (shown by solid circles in Figure 22) will be deployed in August 1997. These buoys will be recovered and a second set of five buoys deployed one year later in August 1998. After that, cruises are planned at six month intervals to build up the array to full strength by August 1999 (Fig. 23). The array of 14 moorings will then be maintained for a full year, until August 2000. Thus, we will have accumulated three years of data at the original five sites in the array, and a full year of higher spatial resolution data at all 14 sites.

The total number of new moorings required to implement this plan is 24, which acconts for the one year design lifetime of the ATLAS mooring system and the staggering of cruises at six month intervals to turn around recovered systems for later redeployment. It also takes into account losses of mooring systems due to catastrophic mechanical failure or, more commonly, due to vandalism associated with tuna fisheries. These losses have historically been about 10% in the Pacific, and they are factored into our plan for the Atlantic at that level.

Approximately nine months lead time is required to acquire mooring materials, construct the moorings, and ship them to the field of operations prior to deployment. This means that funding must be secured for the program in late 1996 for a field phase beginning in August 1997.

Regarding the island wind and sea level measurements, instrumentation of St. Peter and St. Paul Rocks and of Atol das Rocas should be done in the first year of the program, and maintained throughout the three year experiment. Similarly, priority should be given to installing Brazilian meteorological buoy at 0°, 44°W in the first year of PIRATA.

4.2.4 Logistic Support

Logistic support in terms of shiptime for developing and maintaining the PIRATA moored array will be mainly the responsibility of Brazil and France. Rough estimates of the number of days of shiptime support to build up and maintain the moored array shown in Figure 22 have been developed based on a preliminary assumption that a Brazilian research vessel (RV) would service the western half of the array, and a French RV would service the eastern half of the array (the central part of the basin being maintened by both nations at least until end 1999). Servicing the entire 14 mooring array once would probably require about 50 days of shiptime, depending on ship’s speeds (assumed to be 10-12 knots), ports of call, and carrying capacity. It is assumed in this calculation that CTD stations would be occupied every 1° along latitude and longitude transects. Thus, in the first year of the program during which five moorings will be deployed, it would be reasonable to assume that at most 50 days of shiptime would be required. Shiptime to service mooring sites in the array in 1999 and 2000, when cruises are staggered at six month intervals, could double this amount, or 100 days. The actual numbers will need to be refined based on more specific information concerning ship availability, but these estimates establish reasonable upper bounds for shiptime usage.

For the duration of PIRATA, the Brazilian Directorate of Hydrography and Navigation (DHN) has pledged a maximum of 40 days of shiptime per year of the Brazilian RV Antares to support mooring operations from Natal (RN). The newly commissioned French RV Antéa, a 35 m catamaran homeported at present in Abidjan (CRO-ORSTOM), Ivory Coast, will be also involved in the PIRATA mooring deployments. The carrying capacity of this ship for ATLAS moorings systems being limited (2), it is intended that a larger French RV will be used in 1999 to complete the PIRATA mooring deployment along the equator.

4.2.5 Data Distribution

In addition to the real-time GTS data stream described in Section 4.2.1, PMEL will also maintain a data base of real-time and research quality delayed mode data for all variables. Duplicate archives will be maintained at the Centre ORSTOM (Brest) and INPE (Sao Jose dos Campos and/or Natal). Data processing, error checking, archiving and dissemination will be based on well established procedures developed over the past 20 years of Pacific based mooring research at PMEL.

All data will be available via anonymous FTP and via the World Wide Web (Fig. 24). A special PIRATA home page (analogous to the TAO COARE home page at http://www.pmel.noaa.gov/toga-tao/coare.html) will be developed for access to the real-time and delayed mode PIRATA data sets. Thanks to an electronic link between PMEL (Seattle) and Centre ORSTOM (Brest), this information will be also available directly on the ORSTOM-Brest home page at http://www.ifremer.orstom.fr.

4.2.6. Institutional Arrangements

By prior agreement within the PIRATA steering group, the responsibility for purchasing ATLAS mooring systems will be shared by Brazil (6 systems), France (6 systems) and the USA (12 systems). All moorings during the pilot study will be built by PMEL, under contract with the institutions involved in the program. PMEL will coordinate shipping to and from the theater of operations, as well recovery and deployment of mooring systems at sea. PMEL will also be responsible for all calibration, laboratory check outs, instrument refurbishments. Brazil and France will be responsible for logistic support as described in Section 4.2.4.

PMEL will train technical personnel from participating institutions in France and Brazil in the techniques of ATLAS mooring hardware, instrumentation and data processing. This training will be conducted as part of the pilot study to build up the technical infrastructure and expertise for climate mooring programs in France and Brazil. A program of technical exchange will be established similar to that which has been underway for several years among the multi-national partners involved in maintaining the Pacific TAO array (USA, France, Japan, Korea and Taiwan). France, through its ORSTOM laboratory in Nouméa, New Caledonia, was an early major participant in developing the Pacific TAO Array. Technical expertise for TAO mooring operations already established in ORSTOM will be expanded upon for PIRATA.

4.3 Interactions with Other Programs

As for the TAO program in the Pacific, the PIRATA program is not conceived here as a completely self-sufficient program. The main role of PIRATA is to complete the existing and future status of the observing system in the tropical Atlantic, and to give adjustable and truth elements to future model experiments. Consequently, many scientific interactions will take place between PIRATA and other climatic programs which will develop in the tropical Atlantic region. Such interactions will be of mutual benefit to PIRATA and the other programs. These other programs are described in the Appendix A (“ Interactions with other programs ”). Here, we only list the programs, giving for each one its main objective.

4.3.1 International Programs

- CLIVAR-GOALS (Climate Variability and Predictability Program - Global Ocean-Atmosphere-Land Systems) is to study the seasonal to interannual variability of the coupled ocean-atmosphere-land system. PIRATA is designed to become a component of CLIVAR-GOALS. Outside PIRATA, the main activity of CLIVAR in the tropical Atlantic will be the maintenance of the XBT network and model applications.

- GCOS (Global Climate Observing System) is to ensure the collection and distribution of data sets critical to monitor and predict the climate variability and climate change.

- GOOS (Global Ocean Observing System) is to provide data sets for monitoring and prediction of global oceanic variability. It is expected that GCOS and GOOS will maintain the PIRATA network after the formal end of PIRATA (year 2000).

- IAI (Inter-American Institute for Global Change Research) is established by sixteen countries in the Americas to focus their effort on increasing understanding of global change phenomena and their societal implications.

- LBA (Large Scale Biosphere-Atmosphere Experiment in Amazonia) is an international research program designed to create the new knowledge needed to understand the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia, the impact of land use change on these functions, and the interactions between Amazonia and the Earth system.

4.3.2 Brazilian Programs

The Brazilian GOOS Program (GOOS/Brazil) is being conceived in such a way that its proposed tropical array of moored systems will occupy the sites planned by PIRATA west of 20°W, and will upgrade the presently operating satellite-transmitting coastal tide gauge network to the whole coast. The national buoy program (PNBOIA), part of GOOS/Brazil, includes low cost drifters deployed monthly in the Southern Atlantic as well as moored arrays of ATLAS type buoys in the continental shelf area and in the PIRATA domain.

- The REVIZEE program (Avaliaçao do Potencial Sustentavel de Recursos Vivos na Zona Economica Exclusiva) is a large ship-time consuming ongoing effort to obtain fisheries and physical data from CTD and XBT stations made during the cruises. Although conceived to survey the Brazilian ZEE (Zona Economica Exclusiva), the cruises are covering a good portion of the southwestern tropical Atlantic.

4.3.3 French Programs

- Through the SAMBA (Sub-Antarctic Motions in the Brazil Basin) Program, 16 Marvor floats will be launched along 35°W and between 2°N and 4°45S in early March 1997. These floats are thought to reveal Antarctic Intermediate Water motion in the equatorial band and how this water mass crosses the equator.

- The PICOLO (Production Induite en Zone de Convergence par les Ondes Longues Océaniques) Program is to understand a heavy catch of tuna that occurs in a region considered biologically poor, but prone to tropical instability waves. Because both PIRATA and PICOLO programs will use the same French RV (Antéa), the coordination between these two programs will be especially high.

- ECLAT (Etudes Climatiques dans l'Atlantique Tropical) is a multidisciplinary program designed to become the French contribution of CLIVAR in the tropical Atlantic. PIRATA and Satellite & Climat (see below) will belong to ECLAT.

- Satellite & Climat is a coordinated effort in the Indo-Atlantic equatorial region to collect, validate, archive, distribute satellite data used in the reconstitution of the 4D vapor flux over the Equatorial African continent. The PIRATA data set will be used here to validate the satellite data at the surface over the ocean.

- Clipper-Mercator Programs concern the development of Atlantic high resolution (Clipper) and Global operational (Mercator) oceanic numerical experiments.

4.3.4 USA Programs

- PACS (Pan American Climate Studies) is to understand and more realistically model the climate of the Americas and the adjacent regions. The PACS activity are now essentially oriented in the Pacific Ocean. Beginning in 1999, the PACS activity will expend into the Atlantic region.

- ACCE (Atlantic Climate and Circulation Experiment) is planned to study the role of the Atlantic's thermohaline circulation in global atmospheric climate. It works mainly in the North Atlantic region, including the equatorial basin where drifters will be deployed.

- SeaWiFS (Sea-viewing Wide Field of view Sensor), MODIS (Moderate Resolution Imaging Spectrometer) and SIMBIOS (Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies) are NASA satellite ocean color programs designed to provide routine high-resolution global fields of surface chlorophyll-a, diffuse attenuation, primary productivity and other products related to marine biogeochemistry. The PIRATA program and its mooring platforms could provide a focus for collaborations between these various programs (satellite and field) to address related physical, biological and observational problems.

5. SUMMARY

5.1 Expected contributions of PIRATA to climate studies in the Atlantic

The tropical Atlantic includes on both adjoining continents, semi-arid climate regions where the interannual and longer-term fluctuations of precipitation are of enormous economic and social significance, in particular the Nordeste and sub-Saharan regions. Of great societal significance are the interannual and decadal changes in the intensity and frequency of hurricanes spawned in the tropical Atlantic. Oceanic variability on these time scales is also of key importance to many countries of the region, due to impacts on fisheries and related industries. A concentrated research effort, including the establishment of a baseline of more comprehensive observations in support of modeling and empirical studies, is needed to improve our ability to monitor and predict these climate and climate-related variations.

Several studies have identified strong relationships between tropical Atlantic SST, upper ocean variability, and regional climates, that are indicative of important atmosphere-ocean coupling in the region. Such coupling, in concert with radiative forcing and land-sea contrasts, results in a strong seasonal cycle. The mechanisms involved are at present only partially understood. Superimposed on this seasonal cycle are two modes of ocean-atmosphere variability. One of these modes, which has no known counterpart in the Pacific, is characterized by a north-south interhemispheric gradient in SST, the so called “ Atlantic dipole ”. This mode involves spatially coherent SST variations in either hemisphere between about 5°N-25°N and 5°N-20°S, with seasonal, interannual and decadal time scales. A second mode of climate variability is similar to the ENSO in the Pacific, with manifestations focused primarily near the equator. This “ equatorial ” mode, like the interhemisphere mode, varies on seasonal and interannual time scales. Yet, it is not known if the two modes are interrelated or if they are independent. Our current understanding of these phenomena is limited to a great extent because of the lack of high quality, systematic oceanic and meteorological measurements over the region.

The *in situ* observational system that exists in the tropical Atlantic relies mainly on volunteer observing ships and occasional research vessels that pass through the area. One purpose of PIRATA is to augment the existing data base with comprehensive oceanic and meteorological measurements in the tropical Atlantic, and to address some of the scientific questions that have been posed concerning the climate variability of the region.

The scientific goals are:

- To provide an improved **description** of the seasonal-to-interannual variability in the upper ocean and at the air-sea interface in the tropical Atlantic;
- To **improve our understanding** of the relative contributions of the different components of the surface heat flux and ocean dynamics to the seasonal and interannual variability of SST within the tropical Atlantic basin;
- To **provide a data set** that can be used to develop and improve predictive models of the coupled Atlantic climate system.

The technical goals are:

- To design, deploy and maintain a pilot array of moored oceanic buoys, similar to the ones used during the TOGA program (the TOGA-TAO array) in the tropical Pacific;

- To collect and transmit via satellite in real-time a set of oceanic and meteorological data for the study of the upper oceanic circulation in the tropical Atlantic and its overlying atmosphere.

The PIRATA field program will last three years (1997-2000), with the array being built up in stages over the first two years, and maintained at full strength for the third and final year. The array will provide high temporal resolution and high accuracy measurements of key oceanic and atmospheric variables. Moderate meridional resolution (2°-5° latitude) will be achieved along 10°W and 35°W; zonal resolution of 5°-10° will be achieved along the equator. The measurements will provide an improved description of SST, air temperature, winds, humidity, precipitation, and short wave radiative fluxes for the region, which in turn will allow for improved description of air-sea fluxes of momentum, heat and moisture. The data will also provide an improved description of salinity and temperature in the upper ocean. In addition, observations of upper ocean velocity will be made at one key location. These measurements will be valuable as ground truth for satellite missions, and in some cases in the development of blended satellite/*in situ* analyses (such as the NCEP SST product).

PIRATA salinity and precipitation measurements will be the first systematically collected from moorings in the tropical Atlantic. These data will help to chararcterize seasonal and interannual variations in surface moisture fluxes as, for example, associated with variations in the position and intensity of the ITCZ (*e.g.* Schmitt *et al.*, 1989; Yoo and Carton, 1990). The salinity data will be valuable for gauging the local response of the ocean to evaporation minus precipitation, for detecting the possible influence of Amazon runoff advected into the interior basin, and for estimating the effects of the salinity on density stratification in the surface layer. The potential for rain-induced salt-stratified “ barrier layers ” to inhibit vertical turbulent mixing to shallow depths in regions of high precipitation in the equatorial Atlantic may be of possible climatic significance, as has been hypothesized for the equatorial Pacific (Lukas and Lindstrom, 1991; Ando and McPhaden, 1996). Simultaneous collection of surface heat and moisture flux data, together with upper ocean data, will provide the opportunity to examine the extent to which the heat and salt balances may be coupled in the tropical Atlantic, and the effect of that coupling on SST variability.

By providing for improved estimates of air-sea fluxes, PIRATA measurements will allow a better understanding of the relative contributions of the different components of surface heat flux to observed SST variability on seasonal to interannual time scales in the tropical Atlantic. PIRATA will also contribute to the identification of ocean dynamical processes (*e.g.* equatorial Kelvin wave excitation and propagation) in the development of climatic variability, and help further stimulate advances in our conceptual understanding of the climate dynamics in the region. Although decadal or longer-term variability cannot be addressed over the time period of PIRATA, the foundation for long time series measurements which could be used to study such variability will be set in place. Satellite and/or operational atmospheric analyses that will be augmented by PIRATA observations will be helpful in understanding better the variations in atmospheric heating and its relation to SST.

PIRATA will be extremely useful for validation of regional ocean, atmosphere and coupled models. It will also provide high quality data to allow for quantitative assessment of model physical parameterizations. In addition, the PIRATA data in conjunction with other observations and observational products will provide improved forcing fields for uncoupled model simulation studies of both oceanic and atmospheric variability. Finally PIRATA data will serve as important input into model assimilation systems applicable both to diagnostic analyses and for initialization of regional climate predictions. Such predictions may help to mitigate the impacts of severe droughts over the adjoining continental regions influenced by the Atlantic.

5.2 A Role for Additional Process-oriented Field Work

In the context of a large spatial scale, long time scale monitoring array, PIRATA provides an opportunity for additional process experiments to address the numerous scientific questions that extend beyond PIRATA capabilities alone. For example, a quantitative determination of the physical factors controlling SST is a critical factor for climate predictions. Models can estimate this, but an independent data set is necessary to validate and improve upon the models. Similarly, cross-equatorial and inter-gyre transport of heat may affect large scale ocean-atmosphere interaction. Model and data-based analyses exist, leading to hypotheses on how northward upper ocean heat transport occurs; however, specific measurements are required to better define the pathways and mechanisms of cross-equator and inter-gyre heat exchange. Paralleling such questions within the upper ocean are those pertaining to the atmospheric boundary layer, specifically in relation to moisture flux convergence, cloudiness and deep convection.

Recent examples of process experiments embedded in a basin scale observing system include the TIWE and COARE programs in the central and western equatorial Pacific, respectively, and the emerging PACS program with its initial focus on the eastern tropical Pacific. The basin scale TOGA observing system provided a long term, large scale context in which to interpret the results of these shorter term, more geographically limited field studies. In turn, the process-oriented field work provided new information on important physical mechanisms at work in the ocean-atmosphere system, and the time and space scales on which they operate. This new information has in some cases been valuable for refining or expanding the measurement capabilities of the TOGA observing system in the Pacific.

5.3 A Basis for Monitoring

The idea of PIRATA as a pilot project is to gradually and firmly establish the ATLAS moored technology as appropriate a meaningful and cost-effective observational system in the Atlantic. During the three years of the PIRATA program we will adapt the technology to the science problems, and solve maintenance and logistical problems that might arise. It is expected that at the end of the pilot phase of PIRATA and the demonstration of the success of the observational system and the science performed, other nations will join in the maintenance and possible expansion of the array in order to make PIRATA a routine basic observational system in the tropical Atlantic as part of GOOS and GCOS.

In addition to a better understanding of the dynamical processes in the tropical Atlantic, it is expected that PIRATA will help explain the linkages between the Atlantic and the ENSO phenomenon in the Pacific, during El Nino years. The data will also help in better establishment of climate variations and agricultural and fisheries impacts alongshore South America and West Africa (small pelagics, lobsters, etc.) and open ocean (tuna, etc.). Moreover, improved data, both in terms of quantity and quality, will prove invaluable in identifying the dominant physical mechanisms of the coupled climate system, and thereby aid in evaluating and improving skill of coupled forecast models.

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Appendix A

INTERACTIONS WITH OTHER PROGRAMS

Several programs are now underway or planned that can provide important data to PIRATA. A summary of these programs follows:

A1 International Programs

A1.1 Climate Variability and Predictability Program - Global Ocean-Atmosphere-Land Systems (CLIVAR-GOALS)

As a follow-on to the TOGA program, the Global Ocean-Atmosphere-Land Systems (GOALS) program continues the study of seasonal to interannual variability of the coupled climate system. The central hypothesis of CLIVAR-GOALS is that variations at the ocean-atmosphere-land interface, *e.g.*, the upper ocean (including SST), soil moisture, sea ice, and snow, exert a significant boundary condition influence on seasonal to interannual variations of the overlying atmospheric circulation and its predictability. As such, the understanding and prediction of the climate variability on these time scales will require accurate measurements of the global surface and upper-ocean conditions together with improved models to simulate the evolution of the system. The scientific objectives of this program are: (*i*) to observe, describe, and model the variability of the coupled global upper-ocean-atmosphere-land system on seasonal-to-interannual time scales, and to understand the mechanisms and processes underlying this variability and its predictability, (*ii*) to improve the skill of predicting seasonal-to-interannual variation using coupled models of the global upper ocean-atmosphere-land system and to improve the requisite observing systems, and (*iii*) to design and implement observing, computing, and data collection systems needed for describing and predicting the state of the global upper ocean-atmosphere-land system.

It is expected that CLIVAR-GOALS would accomplish some of these objectives by extending the observational domain of interest from the tropical Pacific to the entire global tropics to understand seasonal-to-interannual tropical variability and to advance tropical predictive capability on time scales of months to a year or more. This would involve expanding the observing system to the tropical Atlantic and Indian oceans, using other programs to provide data for the land areas bounding these oceans, and using the combined data for better predictions over the global tropics. This envisioned expansion of the observing network has been identified as a priority of the CLIVAR-GOALS program. Many of the same dynamical and sampling arguments regarding the importance of surface-wind forcing that were used to advocate the TAO array in the Pacific, also apply in the Atlantic and Indian Oceans. Thus the extension of TAO measurements into the equatorial zones of these oceans is an important part of CLIVAR-GOALS.

A1.2 Global Climate Observing System (GCOS)

The Global Climate Observing System (GCOS) has recently been established to ensure the collection and distribution of data sets critical to monitoring and prediction of climate variability and climate change. GCOS will address measurement requirements in all components of climate system, including the ocean, atmosphere, land, cryosphere and biosphere. The observing system will be comprised of both *in situ* and satellite components providing high quality measurements necessary for meeting the requirements of climate scientists, forecasters, and policy makers. Specific goals of GCOS (Spence and Townsend, 1995) are to provide data for:

- Climate system monitoring, climate change and detection, and response monitoring especially in terrestrial ecosystems and mean sea level
- Application to national economic development
- Research toward improved understanding, modeling and prediction of the climate system

GCOS will not directly make measurements, but rather facilitate, encourage and coordinate long term commitments from individual nations involved in climate monitoring and prediction. Implementation will build on existing capabilities, augmented by enhancements which are both scientifically justifiable and technically feasible. System design will be evolutionary, adapting to advances in scientific understanding and technological developments. However, an initial priority for the ocean component of GCOS is continuation and expansion of the observing system established under auspices of the TOGA Program (1985-94). The ocean component of GCOS is similar in scope and purpose to the climate module of the Global Ocean Observing System (GOOS; see following section); implementation of these programs is being coordinated to ensure maximum scientific and societal benefits. GCOS is sponsored by the International Oceanographic Commission (IOC), the World Meteorological Organization (WMO), the United Nations Environmental Program (UP) and the International Council of Scientific Unions (ICSU).

A1.3 Global Ocean Observing System (GOOS)

The Global Ocean Observing System (GOOS) is an internationally coordinated effort to provide data sets for monitoring and prediction of regional and global oceanic variability. The system will include the measurement of major physical, chemical and biological properties of the ocean from a combination of satellite and *in situ* platforms. System design will be based on sound scientific principals and will encompass data collection, distribution and management to support five major program subsystems or modules:

- Analysis and prediction of climate variability and climate change;
- Coastal zone protection, management and development;
- Monitoring and assessment of living marine resources;
- Assessment and prediction of the health of the ocean;
- Improved ocean services for various national applications (especially weather forecasting).

GOOS is sponsored by the International Oceanographic Commission (IOC), the World Meteorological Organization (WMO) and the United Nations Environmental Program (UP). It will be implemented by national organizations in coordination with these sponsoring bodies, taking full advantage of the results of global research programs. An initial priority for GOOS is the climate module, and it is envisioned that early progress can be made on establishing an operational observing system for climate in the tropical regions based on the successes of the recently completed TOGA Program and follow-on programs such as the World Climate Research Program's (WCRP) study of Climate Variability and Predictability (CLIVAR). The climate module of GOOS is similar in scope and purpose to the ocean component of Global

Climate Observing System (GCOS); implementation of these programs is being coordinated to ensure maximum scientific and societal benefits.

A1.4 Inter-American Institute for Global Change Research (IAI)

Recognizing the importance of regional approach to the study of global change, the Inter-American Institute for Global Change (IAI) was established by sixteen countries in the Americas and a formal agreement was signed on May 13 1992 in Montevideo, Uruguay. The IAI will focus its efforts on increasing understanding of global change phenomena and their societal implications while augmenting scientific capacity in the region and for this it has a strong educational and training program. The scientific agenda includes seven initial themes: (*i*) Tropical Ecosystems and Biological Cycles, (*ii*) Impacts of Climate Change on Biodiversity, (*iii*) El Nino-Southern Oscillation and Inter-Annual Climate Variability, (*iv*) Ocean-Atmosphere-Land Interactions in the Inter-Tropical Americas, (*v*) Comparative Studies of Oceanic, Coastal and Estuarine Processes in Temperate Zones, (*vi*) Comparative Studies of Temperate Terrestrial Ecosystems, (*vii*) High Latitude Processes.

IAI is functioning as a regional entity and conducts research which no one nation in the regional can undertake on its own. It consists of a distributed network of research institutions, working in collaboration to implement the science agenda of the Institute. A recent grant from the Global Environmental Facility (GEF) is helping building an infrastructure for research in a dozen of countries in South and Central Americas. Another grant from National Science Fundation (NSF) was announced and soon will be implement to start initial research activities as part of a regional collaboration (funds are not directed for individual country proposals). This grant is being preceded by regional workshops to further detail the proposals and get additional collaboration from other scientists and institutions originally not included. IAI has a Directorate located at the National Institute for Space Research (INPE), at Sao José dos Campos, SP, Brazil.

From a PIRATA perspective, there are clear interfaces for collaborative work with the two science agenda, namely (*iii*) El Nino-Southern Oscillation and Interannual Climate Variability, and (*iv*) Ocean-Atmosphere-Land Interactions in the Inter-Tropical Americas.

A1.5 Large Scale Biosphere-Atmosphere Experiment (LBA)

The Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) is an international research program designed to create the new knowledge needed to understand the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia, the impact of land use change on these functions, and the interactions between Amazonia and the Earth system. LBA research will be scientifically organized into six themes: (*i*) Physical Climate, (*ii*) Carbon Storage and Exchange, (*iii*) Biogeochemistry, (*iv*) Atmospheric Chemistry, (*v*) Land Surface Hydrology and Water Chemistry, and (*vi*) Land Use and Land Cover.

A data management system will be created to act as repository for all the LBA data. It will be include already existing data and all the new satellite, aircraft, and ground-based data from the individual science teams. Like PIRATA and “ Satellite & Climat ” (see A3.4), PIRATAand LBA will be mutually supportive in terms of data gathering and both can be seen as contributions to PACS (see A4.1). Continental data obtained by LBA and oceanographic/meteorological data measured by PIRATA will form an extended data base for climate research over the Amazon and adjoining Atlantic Ocean, including the water vapor flux and balance over the region.

A2 Brazilian Program

A2.1 The Brazilian GOOS Program

The Brazilian GOOS Program (GOOS/Brazil) is being conceived in such a way that its proposed tropical array of moored systems will occupy the sites planed by PIRATA west of 20°W, and will upgrade the presently operating satellite-transmitting coastal tide gauge network to the whole coast. The national buoy program (PNBOIA), part of GOOS/Brazil, includes low cost drifters deployed monthly in the Southern Atlantic as well as moored arrays of ATLAS type buoys in the continental shelf area and in the PIRATA domain.

A2.2 The REVIZEE Program

The program Avaliacao do Potencial Sustentavel de Recursos Vivos na Zona Economica Exclusiva (REVIZEE), which refers to the Assessment of the sustainable potential of the living resources of Brazil’s exclusive economic zone, is an initiative resulting from one of the major goals defined by the IV sector Plan for Brazil’s Marine Resources (IV PSRM). That reflects the Brazilian government’s concern with respect to its responsibilities undertaken when joining the UN convention on the Law of the Sea.

The purpose of REVIZEE is to quantify the sustainable potential of recruitment of living resources in the Exclusive Economic Zone (EEZ; ZEE in Portuguese) with the following objectives: (*i*) identify the living resources of the Brazilian ZEE and its environmental characteristics of its occurrence, (*ii*) determine its biomass, (*iii*) establish the potentials for recruitment. Activities are foreseen for the 1994-1998 period.

The REVIZEE program is a large ship-time consuming ongoing effort to obtain fisheries and physical data from CTD and XBT stations made during the cruises covering a good portion of the southwestern tropical Atlantic. Thus, there will be a coordination between the Brazilian participation of PIRATA and the REVIZEE program, especially in the availability of the Brazilian RV shiptime.

A3 French Programs

A3.1 Sub-Antarctic Motions in the Brazil Basin (SAMBA)

As the final stage of the French WOCE float program in the South-West and Equatorial Atlantic, 16 Marvor floats will be launched along 35°W and between 2°N and 4°45S in early March 1997. These acoustic floats will drift at 800 db and surface every 3-month to transmit their data via CLS-Argos. They will complement the 9 Marvors already launched in November 1994 along 25°W between 2°N and 2°S. These floats are thought to reveal Antarctic Intermediate Water motion in the equatorial band and how this water mass crosses the equator. The acoustic coverage is provided with 4 sound sources from IFREMER/LPO and 9 sound sources from WHOI (these latter are mainly in the Brazil basin) and should be available until the year 2000. A nominal 3-year lifetime is expected for the Marvor (10.5 float-year-data have been recovered yet with the 9 Marvors launched in November 1994) (Ollitraut *et al.*, 1995). Data will be analyzed then provided within the WOCE policy.

A3.2 Production Induite en Zone de Convergence par les Ondes Longues Océaniques (PICOLO)

An ORSTOM multidisciplinary program is underway in the tropical Atlantic: the PICOLO program 1996-1998 (Production Induite en Zone de Convergence par les Ondes Longues Océaniques). It aims at understanding a heavy catch of tuna (25,000 t/year) that occurs seasonally in a region considered biologically poor (2°N-4°N ; 10°W-20°W) (Voituriez and Herbland, 1982). This region is prone to tropical instability waves which are at maximum when the shear between the South Equatorial Current and the North Equatorial Countercurrent is well developed during boreal summer-fall (Weisberg and Weingartner, 1988; Morlière *et al.*, 1994). Tropical instability waves and their associated anticyclonic eddies (Legeckis and Reverdin, 1987) are highly energetic phenomena, that are particularly pronounced in the PICOLO region (Richardson and McKee, 1984). They involve intense meridional velocities (+/- 1 m/s) and vertical velocities (+/- 20 m/day) from the surface to the thermocline depth (Morlière *et al.*, 1994). Therefore it is likely that this particular physics be a major process for bringing nutrients (nitrate) from the nutricline to the surface layer, hence enhancing biological processes (Murray *et al.*, 1994). This enrichment may lead in turn to the tuna concentration.

In order to study this special physics and ecosystem, a series of oceanic cruises are planned in 1996-1998 with the ORSTOM RV. Antéa based in Abidjan (Ivory Coast). During these cruises tropical instability fronts and eddies will be finely sampled with physical, bio-optical and biological measurements. Since these oceanic campaigns are of limited duration and can only provide a snapshot of the studied phenomenon, it is of crucial importance for the PICOLO program to be completed by a continuous *in situ* survey. Consequently, a northward extension of the PIRATA mooring array at about 20°W would greatly reinforce the success of the PICOLO program. At the same time the PICOLO measurements would complement the PIRATA observations. Furthermore, some joint PICOLO and PIRATA experiments could be simultaneously planned using the RV Antéa.

A3.3 Etudes Climatiques dans l'Atlantique tropical (ECLAT)

ECLAT (Etudes Climatiques dans l'Atlantique Tropical) is a multidisciplinary and multi-institute program which is now being prepared and discussed in France. ECLAT is designed to become the French participation of CLIVAR in the tropical Atlantic (the scientific objectives are the same). ECLAT is intended to be underway until the end of CLIVAR (2010), but the present proposal is only related to the period 1997-2000. ORSTOM has initiated this program, where researchers of other French institutes (CNRS, CNES, French Universities, Météo-France, IFREMER, etc.) are invited to join. Foreign research institutes (African and Brazilian institutes) will be also invited to collaborate thanks to the cooperation duty of ORSTOM.

Physical oceanography, physics of atmosphere, ocean and atmosphere modeling, satellite data processing, continental hydrology, fisheries statistics, etc., will be the main activities in ECLAT. Two components will be essential and complementary: the component “ observation ” and the component “ modeling ”. For the component “ observation ”, some sub-programs are already underway, and must only be developed (*i.e.* XBT network, altimetry, ...). Some other sub-programs have to be created. This will be the case for PIRATA. PIRATA and Satellite & Climat (see A.3.4) are intended to become two pièces maîtresses in the component observation of ECLAT.

A3.4 Satellite & Climat

The potential water vapor sources for the West African monsoon are the Gulf of Guinea, the great African equatorial rainforest, and the Indian Ocean via high altitude flows. Using (*i*) the synoptic fields of meteorological parameters (SST, wind, humidity...) deduced from *in situ* (VOSs, PIRATA, ...), and (*ii*) satellite measurements (Meteosat, ERS1-2, SSM/I, NOAA/TOVS,...), the atmospheric variables can be (potentially) reached in the four dimensions. The satellite alternative to classic observations finds here more than elsewhere a justification which has convinced funding agencies (PNUD, FAO) to progressively develop a network of receiving stations for Meteosat and NOAA in Nairobi (KMD), Niamey (AGRHYMET, ACMAD), Dakar (ASECNA, CSE, UTIS), Fortaleza (FUNCEME).

The aim of the program Satellite & Climat is to coordinate such satellite activity between the previous cited stations, in order to monitor the monsoon water fluxes in the tropical Atlantic and western Indian Ocean region. Implementation and validation of satellite updated softwares will improve the use of the regional models. Climatic variables (*e.g.* latent and sensible heat fluxes) at the air-sea interface will particularly take benefit of the PIRATA data set which will be of first importance for the program Satellite & Climat, like for the LBA program (see A1.5).

A3.5 Clipper-Mercator Programs

The French numerical modeling community is involved in developing “ Clipper ”, a very high resolution model of the Atlantic Ocean. This numerical model will be forced with realistic forcing and validated by comparison with existing data. Its objectives are scientific: understanding the effect of small- and meso-scale eddies on the circulation. Efforts to assimilate data will be carried both for this project and for Mercator, its offshoot.

Mercator is a French proposed project which aims to forecast the ocean by assimilating data in a high resolution model. A preliminary test-phase is proposed which should last until the year 2000, and during which the system will be developed and tested against independent observations. The project is also viewed as contributing to experimental design and the development of an ocean-observing system.

A4 USA Programs

A4.1 NOAA Pan American Climate Studies (PACS) Program

The Pan American Climate Studies Program (PACS) began in 1995 with scientific objectives to understand and more realistically model: (*i*) the seasonally varying mean climate of the Americas and adjacent ocean regions, (*ii*) the role of boundary processes in forcing seasonal-to-interannual climate variability over the Americas, (*iii*) the coupling between the oceanic mixed layer and the atmospheric boundary layer in the tropical Atlantic and eastern Pacific, and (*iv*) the processes that determine the structure and evolution of the tropical sea-surface temperature field. At present, PACS supports modeling studies, historical data analysis, and climate diagnostics work. In addition, PACS has provided funding for pilot field studies in the eastern equatorial Pacific for the period 1995-98.

A PACS Implementation Plan is presently under development for the period 1998 and beyond. The period 1998-2000 will include a major observational program focused on the ITCZ/Cold Tongue complex in the extreme eastern Pacific, and will utilize *in situ* observations provided by the TAO Array, supplemented by shipboard and aircraft observations. Included within this study is the region of extreme deep convection centered over the Panama Basin, southern Central America, and northwest South America. Possible augmentation of the existing radiosonde network in these areas is under consideration. Longer range plans include oceanic and atmospheric observations in the tropical Atlantic after the year 2000.

PACS scientific interests in the region are similar to those of PIRATA. Hence, results from the PIRATA program could help motivate and focus PACS planning for work in the Atlantic. In turn, PACS could provide potential framework in the US for continued contributions to PIRATA after the year 2000. PACS has been endorsed as a contribution to the US Global Ocean Atmosphere Land System (GOALS) program, which in turn is an important element of the international CLIVAR-GOALS program (see A1.1).

A4.2 Atlantic Climate and Circulation Experiment (ACCE)

As the final observational stage of the US World Ocean Circulation Experiment (US WOCE) and as a component of the ongoing Atlantic Climate Change Program (ACCP), the Atlantic Circulation and Climate experiment (ACCE) experiment has been planned to study the role of the Atlantic's thermohaline circulation in global atmospheric climate. ACCE science and implementation plans were reviewed in the US by NSF and NOAA and the approved field work will begin in 1996 and 1997.

One of the programs supported is the “ Subsurface Float Observations in the Upper Layers of the Tropical and Subtropical North Atlantic Ocean ”. This program calls for the deployment of an array of PALACE, S-PALACE and RAFOS floats in the North Atlantic from 6°S to 60°N on a basin-wide 600 km grid. PALACE floats drift at a prescribed depth for a pre-set time, rise to the surface obtaining temperature profiles and transmit the floats surface position and temperature profiles via CLS-Argos. The float sinks to its assigned depth to repeat the cycle. Newer PALACE floats can also provide salinity profiles (S-PALACE floats). A 10-day cycle is envisioned with a resulting float lifetime of over a year expected. The low-density component of the experiment is directed at determining the factors for SST variability over the basin. Float deployments will provide a uniform grid over the tropics of the upper 1000 m temperature field. Two high-density components are directed at studying Subtropical Underwater and the salinity budget of the tropical Atlantic and 18°C water in the subtropical Atlantic. As part of this program, an array of 19 PALACE floats will be deployed between the equator and 6°S to address questions on water mass distribution and properties, as well as circulation. In conjunction with surface drifters and the NOAA VOS XBT data, the floats will provide information on the relative roles of advection and surface fluxes. In particular on the establishing of the near-equatorial cold water tongue, and to provide information on how much of the heat transport towards the North Atlantic is carried by the North Brazil Current. The quasi-Lagrangian trajectories of the floats launched along 6°S will provide information on the cross-gyre exchange of mass and heat. In order to do that, the PALACE data will be analyzed in the framework of the results to be obtained from an array of RAFOS float to be deployed simultaneously (fall 1997) at the Benguela Current and its extension. Floats will be programmed to surface approximately every 2 weeks, with deployment scheduled for the summer of 1997. Data will be collected for at least two years. In addition, as part of ACCE, COAPS at FSU will provide surface wind and surface flux fields for the Atlantic during the ACCE time-field. Both the float and surface field data will provide important information to PIRATA and close coordination with ACCE investigators is warranted.

A4.3 Sea-viewing Wide Field of view Sensor (SeaWiFS), Moderate Resolution Imaging Spectrometer (MODIS) and Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS)

SeaWiFS and MODIS are two instruments designed for ocean color observations. SeaWiFS is now scheduled for launch in early 1997. MODIS is on the EOS-AM and -PM platforms which are to be launched in 1998 and 2001, respectively. All three missions will collect global data sets every two days with resolutions of 4 km (SeaWiFS) and 1 km (MODIS). In addition, there are currently three other foreign platforms (ADEOS-I, ENVISAT and ADEOS-II) scheduled for launch between 1996 and 2002 which carry instrument capable of generating global marine biological products, *e.g.* chlorophyll-a and primary productivity. SIMBIOS is an initiative designed to take data from this international constellation of ocean color sensors and merge the products into more complete global geophysical fields. SIMBIOS will require a great deal of international cooperation and a variety of in-situ data for sensor cross-calibration and product validation.

The tropical Atlantic is of great interest for a number of reasons. First, the eastern equatorial Atlantic supports a prolonged phytoplankton bloom from July through January even though the equatorial upwelling only persists for July and August. The physical dynamics that keep nutrients within the euphotic zone have not been clearly delineated. This being the case, it is not known how much of the primary production associated with the bloom is regenerated production based on recycled nutrients (NH4) and how much represents new production (NO3 based). New production is related to carbon sequestration and export to deeper layers below the euphotic zone. Quantifying the partition between regenerated and new production is key to understanding the role of Atlantic in the global carbon cycle.

The bio-optical algorithms used to relate satellite estimates of water-leaving radiances to surface pigment concentrations have been shown to underestimate observed concentrations in the tropical Atlantic, especially during periods of upwelling. If the concentrations are underestimated, so will be the estimates of primary production. One proposed reason for the failure of the bio-optical algorithms is that most algorithms have been developed in waters where the background concentration of dissolved organic matter is higher than in the freshly upwelled waters of the tropics. Thus, the algorithms may have an implicit bias. More complete bio-optical data sets from this region must be obtained to verify the bias and the cause. If a bias exists, then a regional bio-optical algorithm must be developed. Finally, Saharan dust common in the tropical Atlantic is not adequately handled by the atmospheric correction algorithms applied to satellite data. The errors in the correction usually result in over-estimation of pigment concentration. SeaWiFS, MODIS and SIMBIOS projects will collaborate to address these algorithm deficiencies. However, logistical support for field observations in the tropics will limit these programs’ success unless opportunities to share ship and mooring resources can be arranged.

Thus, there are a variety of issues that must be addressed if the biological processes in the tropical Atlantic are to be understood and adequately monitored. The PIRATA program and its mooring platforms could provide a focus for collaborations between various programs (satellite and field) to address related physical, biological and observational problems.

Appendix B

LIST OF ACRONYMS

ACCE	Atlantic Circulation and Climate Experiment
ACCLAIM	Antartic Circumpolar Current Levels by Altimetry and Island Measurements
ACCP	Atlantic Climate Change Program
ACMAD	African Center for Meteorology Applied to Developpement
ADCP	Acoustic Doppler Current Profiler
ADEOS	Advanced Earth Observing Satellite
AGCM	Atmospheric General Circulation Model
AGRHYMET	Agronomie-Hydrologie-Météorologie
AmasSeds	Amazone Shelf Sediment Study
AMI	Advanced Microvawe Instrument
ARPEGE	Action de Recherche Petite Echelle Grande Echelle
ASECNA	Agence pour la Sécurité de la Navigation Aérienne en Afrique et à Madagascar
ATLAS	Autonomous Temperature Line Acquisition System
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very-High-Resolution Radiometer
AX	Atlantic Ocean XBT Line
BOAT	Bulletin Océan Atlantique Tropical
BSH	Bundesamt fuer Seeschiffahrt und Hydrographie
CD-ROM	Compact Disk - Read Only Memory
CLIVAR	Climate Variability and Predictability of WCRP
CLS-Argos	Collecte, Localisation, Satellites, Service Argos
CS	Centre National d’Etudes Spatiales
CNRS	Centre National de Recherche Scientifique
COADS	Comprehensive Ocean-Atmosphere Data Set
COAPS	Center of Ocean-Atmospheric Predictive Studies
COARE	Coupled Ocean-Atmosphere Response Experiment
CRO	Centre de Recherche Océanographique
CSE	Centre de Suivi Ecologique
CTD	Conductivity-Temperature-Depth profiler
DAC	Data Assembly Center
DCP	Data Collection Platform
DHN	Diretoria de Hidrografia e Navegação (of the Brazilian Navy)
DIU	Data Information Unit
ECLAT	Etudes Climatiques dans l’Atlantique Tropical
ECMWF	European Centre for Medium Range Weather Forecast
EEZ	Exclusive Economic Zone
ENSO	El Nino-Southern Oscillation
ENVISAT	Environmental Satellite
EOF	Empirical Orthogonal Function
EOS-AM	Earth Observing System AM platform
EOS-PM	Earth Observing System PM platform
EPOCS	Equatorial Pacific Ocean Climate Studies
ERS	Earth Remote Sensing Satellite

FAO	Food and Agriculture Organization
FOCAL	Français Océan Climat Atlantique Tropical
FSU	Florida State University
FTP	File Transfer Protocol
FUNCEME	Fundaçao Cearense de Meteorologia e Recursos Hidricos
GCM	Global Circulation Model
GCOS	Global Climate Observing System
GEF	Global Environmental Facility
GEOSAT	Geodetic Satellite
GFDL	Geophysical Fluid Dynamics Laboratory
GLOSS	Global Sea-Level Observing System
GOALS	Global Ocean-Atmosphere-Land System
GOOS	Global Ocean Observing System
GOSTA	Global Ocean Surface Temperature Atlas
GRGS	Groupe de Recherche de Géodésie Spatiale
GSDC	Global Subsurface Data Center
GSFC	Goddard Space Flight Center
GTS	Global Telecommunication System
IAI	Inter-American Institute for Global Change Research
ICSU	International Council of Scientific Unions
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer
IGOSS	Integrated Global Ocean Services System
IMET	Improved Meteorological Sensors
INMARSAT	International Maritime Satellite
INPE	Instituto Nacional de Pesquisas Espaciais
IOC	International Oceanographic Commission
IR	Infrared
IRI	International Research Institute for seasonal to interannual climate prediction
ITCZ	Intertropical Convergence Zone
KMD	Kenyan Meteorological Department
LDEO	Lamont-Doherty Earth Observatory
LODYC	Laboratoire d'Océanographie Dynamique et de Climatologie
LPO	Laboratoire de Physique des Océans
MASIG	Mesoscale Air-Sea Interaction Group
MODIS	Moderate Resolution Imaging Spectrometer
MOM	Modular Ocean Mode
MON	Month
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NH4	ammonia
NMC	National Meteorology Center
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanic Data Center
NO3	nitrate
NSCAT	NASA Advanced Scatterometer
NSF	National Science Foundation
OGCM	Ocean General Circulation Model
OPA	LODYC's OGCM
OPERA	Observatoire Permanent de l'Atlantique Tropical

ORSTOM	Institut Français de Recherche Scientifique pour le Développement en Coopération
OOPC	Ocean Observation Panel for Climate
OOSDP	Ocean Observing System Development Panel
OSSE	Observing System Simulation Experiment
PACS	Pan American Climate Studies program
PALACE	Profiling ALACE float
PICOLO	Production Induite en Zone de Convergence par les Ondes Longues
PIRATA	Pilot Research Moored Array in the Tropical Atlantic
PMEL	Pacific Marine Environmental Laboratory
PNBOIA	Plano Nacional de Boias
PDC	Plan National d'Etude du Climat
PNUD	Programme des Nations Unis pour le Développement
PSP	Precision Spectral Pyranometer
PSRM	Brazilian Marine Resources Program
QBO	Quasi Biennal Oscillation
RAFOS	SOFAR spelled backwards
REMARSAT	Rede Maregrafica com Telemetria por Satelite
REVIZEE	Avaliaçao do Potencial Sustentavel de Recursos Vivos na Zona Economica Exclusiva
RN	Rio Grande do Norte
RV	Research Vessel
SCD	Satelite de Coleta de Dados
SAMBA	Sub-Antarctic Motions in the Brazil Basin
SeaWiFS	Sea-viewing Wide Field of view Sensor Sea-Viewing
SEQUAL	The Seasonal Response of the Equatorial Atlantic
SIMBIOS	Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies
SMC	SOOP Management Committee
SOFAR	Sound Fixing and Ranging Float
SOI	Southern Oscillation Index
SOOP	Ship of Opportunity Program
SP	Sao Paulo
S-PALACE	Salinity-Profiling ALACE float
SSM/I	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
STACS	Sub-Tropical Atlantic Climate Studies
Sv	Sverdrup (= 10^6 m^3s^{-1})
TAO	Tropical Atmosphere-Ocean array
TIWE	Tropical Instability Waves Experiment
TOGA	Tropical Ocean-Global Atmosphere
TOGAMA	TOGA Marégraphes Atlantique
TOPEX/Poseidon	Ocean Surface Topography satellite mission
TOVS	Tiros Operational Vertical Sounder
T/P	see TOPEX/Poseidon
TPOOS	Tropical Pacific Ocean Observing System
TSLC	TOGA Sea Level Center
UBO	Université de Bretagne Occidentale
UK	United Kingdom
UN	United Nations

UP	United Nations Environmental Program
UOT	Upper Ocean Thermal
US	see USA
USA	United States of America
UTIS	Unité de Traitement d'Images Satellites
UWM	University of Wisconsin-Milwaukee
VOS	Volunteer Observing Ship
WAT-BEE	WOCE/Atlantic/Tropical-Boundary Eastern Equatorial
WCRP	World Climate Research Program
WESTRAX	Western Tropical Atlantic Experiment
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
XBT	Expendable Bathythermography
YR	Year
ZEE	Zona Economica Exclusiva
4D	Four Dimensions

This final version of of PIRATA (Version 3.0) is available without the cover and the figures in RTF format compressed (**pirata30.rtf.Z)**

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FIGURE CAPTIONS

Figure 1: The first joint EOF of SST, τ^x and τ^y monthly anomalies over the tropical Atlantic from September 1963 to August 1987 according to Nobre and Shukla (1996). **(a)** The spatial pattern and **(b)** the associated coefficient time series. The contours represent the SST loadings; contour interval is 0.1; negative contours are dashed; values greater than 0.4 or lower than -0.5 are shaded; the zero-contour is not drawn. The arrows represent the vectorial sum of τ^x and τ^y loadings; the vectors are scaled accordingly to the arrow plotted at the lower right side of the upper panel.

Figure 2: Upper panel: correlations between the SST anomaly index ATL3 (the area-averaged SSTA in the outlined region) and SST anomalies at all points in the tropical Atlantic basin, based on the Servain *et al.* (1987) analyses for the period 1964-1988 according to Zebiak (1993). Lower panel: correlations between ATL3 and the zonal and meridional pseudo-stress anomalies (plotted in vector format) based on the same analyses and observation period.

Figure 3: (a) Complex correlation coefficient of the 1964-1995 SOI anomaly time series, 5-month averaged centered on January, with observed wind stress anomaly in May in the total tropical Atlantic. Coefficients are multiplied by 100; only values greater than or equal to 50 (95% confidence level) are represented. **(b)** The full line is the time series of 1945-1995 SOI anomaly, 3-month averaged centered on February; the dashed line is the time series of 1945-1993 zonal wind stress anomaly in May at 35°W-Equator. All anomalies (a, b) are standardized. SOI data are from Climate Diagnostic Data Base, (a) wind data are from Servain *et al.* (1996), (b) wind data are from UWM/COADS (da Silva *et al.*, 1995). (Servain, 1996, unpublished).
Note positive/negative values of SOI ("La Nina/El Nino " events) were mostly related, with a few months delay, to a relaxation/strenghtening of the wind stress in the west equatorial Atlantic, especially from the 1970's.

Figure 4: 1964-1995 SST and pseudo wind stress total average. Data from Servain *et al.* (1996).

Figure 5: (a) Mean vertical section of temperature along the equator according to Merle (1980). (b) Mean dynamic height 5/500 m according to Merle (1978) (about 16,000 hydrocasts are included and between 10°N and 10°S the data was averaged in square of 4° of longitude, 1° of latitude).

Figure 6: Average ship drift velocity according to Richardson and Walsh (1986).

Figure 7: Annual fluxes at the air sea interface from COADS data, according to Oberhuber (1988) 2°x2° gridded climatology. The incoming short wave flux, long wave flux and latent flux are indicated as well as the net heat flux at the air-sea interface.

Figure 8: Annual fresh water flux at the air sea interface (positive if a loss for the ocean), according to Yoo and Carton (1990) (cm.month^{-1}).

Figure 9: Sea surface salinity averaged during 1977-1995 from an ORSTOM-NODC data set (A. Dessier, pers. comm., 1996).

Figure 10: (a) SST (°C) and wind stress vectors (dynes.cm^{-2}) time-latitude (t-y) seasonal climatology (1945-1989) along 10°W, from 5°N to 15°S. **(b)** Same as (a) but along 30°W, from 25°N to 15°S. **(c)** Same as (a) but time-longitude (t-x) along the equator, coast to coast. The data are from UWM/COADS (da Silva *et al.*, 1995), the processing was done by I. Wainer.

Figure 11: **(a)** seasonal position of the 23°C isotherm on a vertical section along the equator according to Merle (1980). **(b)** Dynamic height records from inverted echosounders at 28°W (light line) and 38°W (heavy line) in 1983 and 1984 according to Katz (1987a).

Figure 12: Monthly net heat fluxes at the air sea interface from COADS data, according to Oberhuber (1988) 2°x2° gridded climatology.

Figure 13: Band passed (10 days to 3 months) dynamic heights from inverted echosounder records along the equator according to Katz (1987b). Upper panel: the time series at 28°W (upper curve) and 4°W (lower curve). Lower panel: linear regression of lag times for maximum cross correlation from the equatorial inverted echosounders. The phase lag from west to east is indicative of Kelvin wave propagation.

Figure 14: A comparison between the vertically integrated temperature observed on the equator at 4°W and 28°W overlayed by the model simulated thermocline (smooth curve) according to Weisberg and Tang (1990). The time series have been normalized by their standard deviations.

Figure 15: (a) Interannual variability and **(b)** ratio of seasonal *vs.* interannual variabilities for the zonal pseudo wind stress. **(c)** and **(d)** same as (a) and (b) but for the meridional pseudo wind stress. **(e)** and **(f)** same as (a) and (b) but for SST. A composite figure from Servain *et al.*, 1985. Units are m^2.s^{-2} for the pseudo wind stress and °C for SST.

Figure 16: (a) 1980-1993 XBT measurements along the ship track AX15 (see also Fig. 20). **(b)** 1980-1993 monthly time series of the 20°C isotherm depth anomaly (m) averaged in the shaded losange in (a) close to 10°W-Equator. The dashed line is a 6-month moving average.
Note positive/negative values are related to upward/downward abnormal movements of the 20°C thermocline depth (Servain, 1996, unpublished).

Figure 17: (a) SST (°C) and pseudo wind stress (m^2.s^{-2}) anomalies averaged from November 1984 to April 1985. Note a cooling at 15°N and a warming at 10°S, respectively related with a strengthening in the Northeast trades and a relaxing in the SE trades. **(b)** The full line is the Servain's SST dipole index (Servain, 1991) averaged during November-December (*year 0*) of each year (1964-1993); the dashed line, shifted from one year to the left *vs.* the x-labels, corresponds to a Nordeste rainy season (February to May; *year 1*) anomaly index (C. A. Repelli, pers. comm., 1994). Note the wettest years (such as 1985) are related to strong negative values for the Servain's index, as shown in (a) (Servain, 1996, unpublished).

Figure 18: SST (°C) and pseudo wind stress ($m^2.s^{-2}$) anomalies averaged during June to August 1968. Note the equatorial warming close to 10°W which is related with a convergence of the anomaly stress in the same area. Data from Servain *et al.*, 1987, (Servain, 1996, unpublished).

Figure 19: Location of SST measurements received in real time via the GTS during January 1996 from VOSs and drifting buoys.

Figure 20: The Atlantic TOGA/WOCE-XBT network.

Figure 21: Existing tide gauge network in some tropical Atlantic islands (Sao Tomé, Ascension, Sta. Helena, Sao Pedro e Sao Paulo, Fernando de Noronha) and in some coastal stations (Cayenne, Fortaleza, Termisa, Tamandaré).

Figure 22: The PIRATA array, 1997-2000. The first phase of five buoys (shown by four solid circles and one solid losange) will be deployed in August 1997.

Figure 23: The 3-phase deployment of the PIRATA array.

Figure 24: Schematic of the PIRATA data flow.