A Pilot Research Moored Array in the Tropical Atlantic (PIRATA)

Jacques Servain,* Antonio J. Busalacchi,+ Michael J. McPhaden,# Antonio D. Moura,@ Gilles Reverdin,& Marcio Vianna,** and Stephen E. Zebiak++

ABSTRACT

The tropical Atlantic Ocean is characterized by a large seasonal cycle around which there are climatically significant interannual and decadal timescale variations. The most pronounced of these interannual variations are equatorial warm events, somewhat similar to the El Niño events for the Pacific, and the so-called Atlantic sea surface temperature dipole. Both of these phenomena in turn may be related to El Niño–Southern Oscillation variability in the tropical Pacific and other modes of regional climatic variability in ways that are not yet fully understood. PIRATA (Pilot Research Moored Array in the Tropical Atlantic) will address the lack of oceanic and atmospheric data in the tropical Atlantic, which limits our ability to make progress on these important climate issues. The PIRATA array consists of 12 moored Autonomous Temperature Line Acquisition System buoy sites to be occupied during the years 1997–2000 for monitoring the surface variables and upper-ocean thermal structure at key locations in the tropical Atlantic. Meteorological and oceanographical measurements are transmitted via satellite in real time and are 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, ship time, and personnel. Seen as a pilot Global Ocean Observing System/Global Climate Observing System experiment, PIRATA contributes to monitoring the tropical Atlantic in real time and anticipates a comprehensive observing system that could be operational in the region for the 2000s.

1. A scientific rationale

The seasonal cycle is the largest ocean–atmosphere signal in the tropical Atlantic. The timing and characteristics of the seasonal evolution of the location of the intertropical convergence zone (ITCZ) and of 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 amplitude of the seasonal cycle, which imply an important coupling between interannual variability and the seasonal cycle. Understanding the mechanisms involved, and their impact on predictability, are important questions that 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. A first mode of climate variability in the tropical Atlantic is similar to the El Niño–Southern Oscillation (ENSO) in the Pacific, with manifestations focused primarily near the equator (Zebiak 1993; Chang et al. 1997) (Fig. 1). This equatorial mode varies on seasonal and interannual timescales. During a warm phase, trade winds in the

*Centre ORSTOM, Brest, France.
+Laboratory for Hydrospheric Processes, NASA/Goddard Space Flight Center, Greenbelt, Maryland.
#NOAA/Pacific Marine Environmental Laboratory, Seattle, Washington.
@International Research Institute for Climate Prediction, Lamont-Doherty Earth Observatory, Palisades, New York.
&LEGOS/GRGS, Toulouse, France.
**INPE/Oceanografia, São José dos Campos, São Paulo, Brazil.
++Lamont-Doherty Earth Observatory, Palisades, New York.
Corresponding author address: Dr. Jacques Servain, Centre ORSTOM de Brest, B.P. 70, 29280 Plouzané, France.
E-mail: servain@orstom.fr
In final form 1 June 1998.

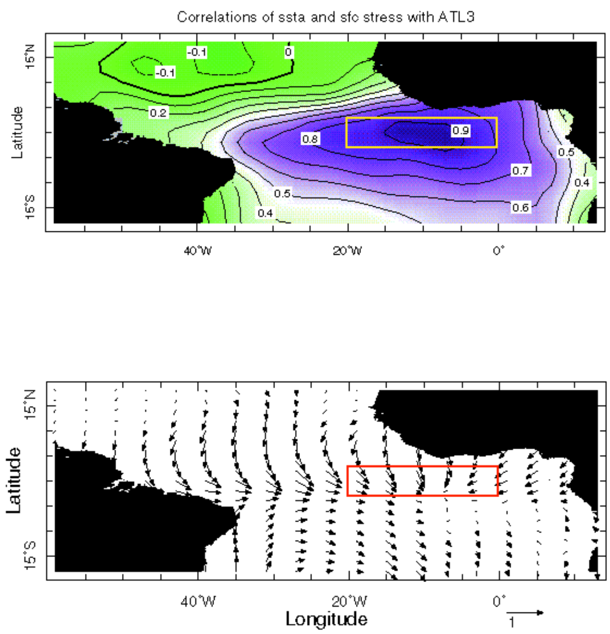

FIG. 1. (upper panel) Correlation between the SST anomaly index ATL3 (the area-averaged SSTA in the outlined region) and SST anomalies at all points in the tropical Atlantic basin, based on the Servain et al. (1996) analyses for the period 1964–88 according to Zebiak (1993). (lower panel) Correlation between ATL3 and the zonal and meridional pseudostress anomalies (plotted in vector format) based on the same analyses and observation period.

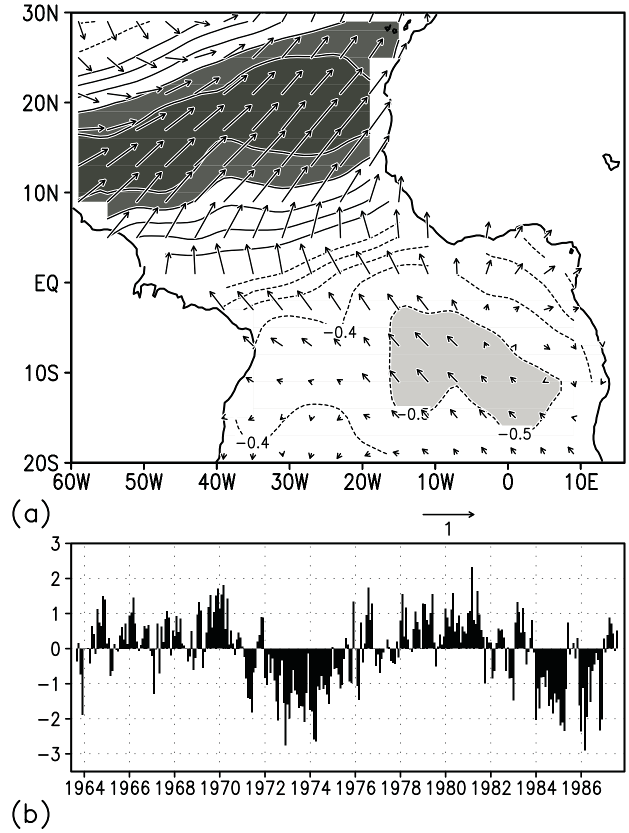

FIG. 2. The first joint EOF of SST, τ^x, and τ^y monthly anomalies over the tropical Atlantic from September 1963 to August 1987 according to Nobre and Shukla (1996). (a) The spatial pattern and (b) the associated coefficient time series. The contours represent the SST loadings; contour interval is 0.1; 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.

western equatorial Atlantic are weak and SSTs near the equator are unusually high, especially in the eastern basin. During a cold phase, trade winds 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 timescales of weeks to months, mediated by the excitation and propagation of wind-forced equatorial Kelvin and Rossby waves. Climatic impacts of equatorial warm events include increased rainfall in and around the Gulf of Guinea and disruption of the marine ecosystem in the Benguela current region (Wagner and da Silva 1994; Crawford et al. 1990).

Another mode of interannual climatic variability, 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; Huang and Shukla 1997). This mode involves spatially coherent SST variations in either hemisphere between about 5°–25°N and 5°N–20°S, with seasonal, interannual, and decadal timescales (Fig. 2). One hypothesis is that the SST dipole structure may be affected by the signals from upwellings off the African coast, where the SST anomalies are the largest. If the anomalies usually appear with opposite sign in each hemisphere, such development is not always simultaneous, and there is a debate over whether the northern and southern components of this dipole are dynamically related or not. Although some data analysis studies using rotated empirical orthogonal functions (EOFs) exhibit independent variability at high frequency of the two sides of the dipole (Houghton and Tourre 1992; Mehta and Delworth 1995; Enfield and Mayer 1995), use of other techniques (i.e., frequency domain EOFs that separate the timescales of variability) do exhibit a true tropical dipole mode at the decadal timescale (Nobre and Shukla 1996; Tourre et al. 1998, manuscript submitted to *J. Climate*). An SST dipole index (Servain 1991), characterized by low-frequency (decadal) oscillations during the last three decades, showed recently (from the beginning of the 1990s) large and rapid fluctuations marked by a succession of positive and negative patterns close to annual–biennial timescales (see *Climate Diagnostics Bulletin*, Vol. 98, No. 1, p. 47). Interhemispheric SST anomalies are intimately related to the position and intensity of the ITCZ and thus exert a considerable influence on the rainfall over Nordeste and the Sahel (Moura and Shukla 1981; Folland et al. 1986; Servain 1991; Enfield and Mayer 1995). In particular, a dipole situation such as a warm north and a cold south is associated with an intensified ITCZ displaced north of its normal position, leading to extreme severe drought conditions in Nordeste and unusually high rainfall totals in the Sahel. Conversely, SST anomalies of opposite sign are associated with a southward displacement of the ITCZ, favoring more abundant rainfall in Nordeste (Fig. 3) and drought in the Sahel. 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., Ropelewski and Halpert 1987; 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. 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; Gray et al. 1993; Shaeffer 1996; Krishnamurti et al. 1998).

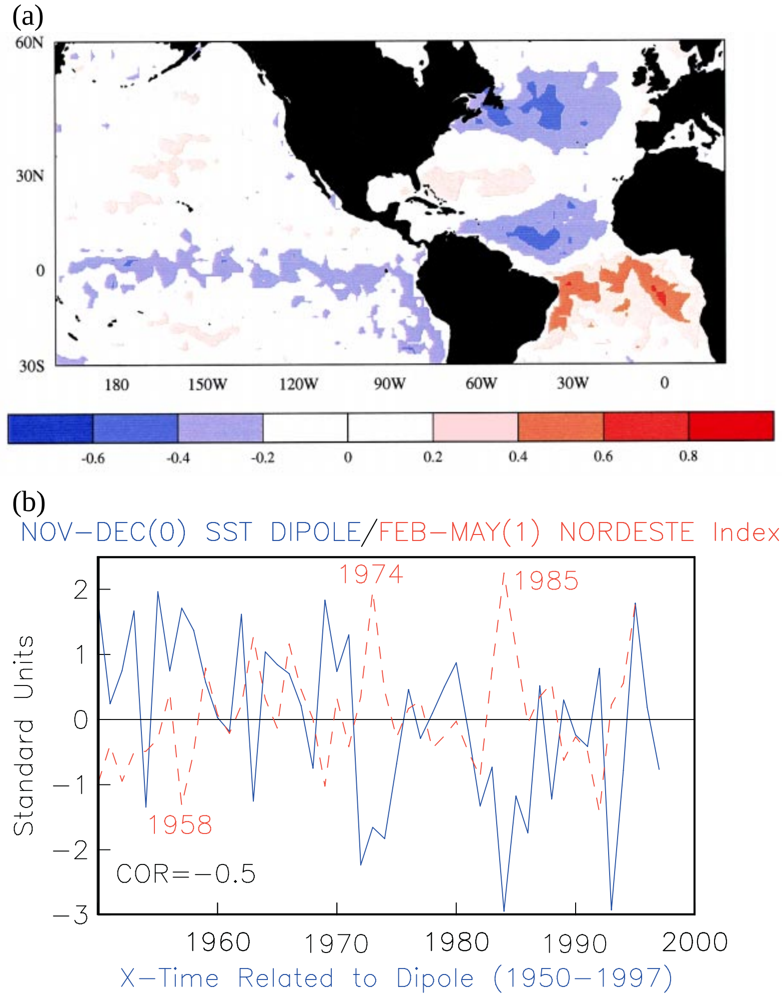

FIG. 3. (a) Correlation between average February through May precipitation in the Nordeste region of Brazil and SST. Red (blue) shading indicates regions in which above-normal SSTs tend to be observed in conjunction with above (below) normal rainfall in Nordeste (Figure previously published in the PACS Scientific Prospectus; courtesy of T. Mitchell). (b) The blue line is the SST dipole index averaged during November–December (year 0) of each year (1951–97) using northern and southern SST indices from the Climate Diagnostic Data Base, Climate Prediction Center; the dashed red line, shifted from 1 yr to the left vs the x labels, corresponds to a Nordeste rainy season (February to May; year 1) anomaly index (C. A. Repelli 1998, personal communication).

Although some recent modeling studies do suggest that the thermodynamic feedback between SST, surface winds, and latent heat fluxes is important in the physical processes responsible for interhemispheric SST variations in the Atlantic (Carton et al. 1996; Chang et al. 1997), other processes may still play a role. There has been an oceanic general circulation model simulation establishing that fluctuations of the upper-ocean heat content also occur on decadal timescales and may play the role of connecting the two hemispheres (Huang and Shukla 1997). In other respects, very new results based on surface and subsurface observed and simulated oceanic temperature (Servain et al. 1998; Servain et al. 1998, manuscript submitted to *Geophys. Res. Lett.*) evidenced that the dipole mode and the equatorial mode appear to be dynamically linked at interannual timescales. Furthermore, the dominant pattern of variability in both modes involves north–south displacements of the ITCZ, as in the annual response. However, the precise physical processes that would link them are not fully understood and must continue to be addressed.

Low-frequency variations in winds and SST do not appear to be self-sustaining through coupled ocean–atmosphere interactions in the tropical Atlantic alone, and some external stimulus is required to initiate these oscillations (Zebiak 1993). ENSO provides one possible source of external forcing (Delécluse et al. 1994), given that a low Southern Oscillation index (SOI)—characteristic of warm conditions in the Pacific—is associated with strong western Atlantic easterlies, and vice versa (Fig. 4). That was particularly the case in mid-1997 during the rapid growth of the exceptional 1997–98 El Niño. Thus, another mode of climate variability that affects the Atlantic basin, albeit remotely, is the ENSO cycle. There is a significant correlation at lags of a few months between the ENSO and the development of SST anomalies in the north tropical Atlantic (Enfield and Mayer 1997; Penland and Matrasova 1998), though the ENSO could also be associated with the development of the dipole mode in both hemispheres of the tropical Atlantic (Servain 1991). 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 (Enfield and Mayer 1997; Harzallah et al. 1996). So ENSO may be a factor that weakens the antisymmetric pattern of the tropical Atlantic on interannual timescales.

2. A need for a new monitoring system in the tropical Atlantic

Unresolved issues concerning the genesis and evolution of ocean–atmosphere interactions in the tropical Atlantic require further investigation in order to advance our understanding of climate variability in the region. For example, what role does the mean seasonal cycle play in the development of interannual and longer timescale anomalies? What is the dynamical relationship (if any) between the northern and southern poles of the dipole mode? Besides the recently proposed processes outlined above, are there other coupled ocean–atmosphere processes that give rise to the observed SST and upper temperature anomalies in both the dipole mode and the equatorial mode? What sets the timescale for their development? What is the relative importance of the Pacific ENSO versus regional-scale ocean–atmosphere interactions in determining the evolution of climate variability in the Atlantic? 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 sig-

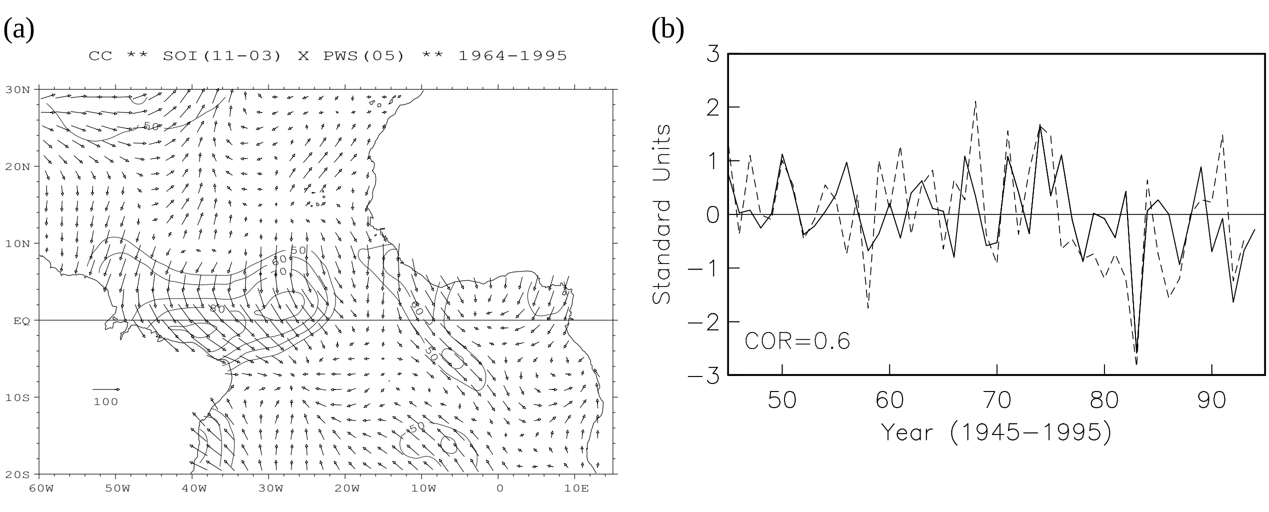

FIG. 4. (a) Complex correlation coefficient of the 1964–95 SOI anomaly time series, 5-month average centered on January, with observed wind stress anomaly in May in the total tropical Atlantic. Coefficients are multiplied by 100; only values greater than or equal to 50 (95% confidence level) are represented. (b) The full line is the time series of 1945–95 SOI anomaly, 3-month average centered on February; the dashed line is the time series of 1945–93 zonal wind stress anomaly in May at 0°, 35°W. All anomalies [(a), (b)] are standardized. SOI data are from Climate Diagnostic Data Base, Climate Prediction Center; wind data in (a) are from Servain et al. (1996), wind data in (b) are from University of Wisconsin—Milwaukee/Comprehensive Ocean–Atmosphere Data Set (da Silva et al. 1994).

nificance. 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 datasets, 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 Delécluse 1993; Bryan et al. 1995; Mehta and Delworth 1995). Hence, high quality climate datasets 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 datasets.

The oceanic in situ 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 datasets collected during the 1982–84 Français–Océan–Climat Atlantique Equatorial/The Seasonal Response of the Equatorial Atlantic (FOCAL/SEQUAL) experiment (Weisberg and Weingartner 1986; Houghton and Colin 1986; Katz 1987) 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 supply little data in critical regions near and south of the equator. Satellite estimates of some key variables (surface winds, SST, and sea level) are available over the whole Atlantic basin with more uniform spatial and temporal resolution. Indeed, the satellites are valuable tools in providing spatial coherence and cover of surface properties. However, satellites do not deliver direct measurements of subsurface thermal structure in the ocean, which is essential for understanding processes affecting the evolution of SST. Moreover, 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.

Therefore, in view of present limitations in the existing database for tropical Atlantic climate studies, we have developed in the Atlantic a program of moored measurements similar to the Tropical Atmosphere–Ocean (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.

Specifically, the scientific goals of PIRATA are 1) 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, 2) 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, and 3) to provide a dataset that can be used to develop and improve predictive models of the coupled Atlantic climate system. PIRATA also has important technical goals: to design, deploy, and maintain a pilot array of moored oceanic buoys, similar to the TAO array used during the Tropical Ocean Global Atmosphere (TOGA) program in the tropical Pacific, and 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.

3. The PIRATA program

The field phase of the PIRATA program began in late 1997 and is scheduled to last for three years. Indeed, PIRATA came at a very opportune time when the Atlantic was experiencing the largest and most

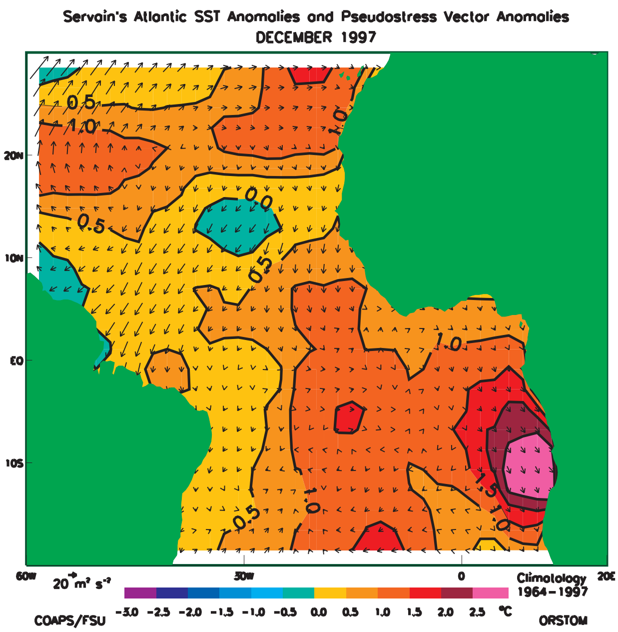

FIG. 5. SST and pseudo–wind stress anomaly in December 1997, during one of the warmest episodes that occurred in the tropical Atlantic in many decades [courtesy of J. Stricherz (COAPS/FSU)].

widespread SST anomalies since 1984 (Fig. 5).

PIRATA is envisioned as part of a multinational effort involving Brazil, France, and the United States. The moorings used in the PIRATA array are primarily ATLAS (Autonomous Temperature Line Acquisition System) moorings like those used in the equatorial Pacific as part of the TAO Array (Hayes et al. 1991; McPhaden et al. 1998). ATLAS mooring design has been upgraded, with several new-generation systems already deployed in the Pacific since the beginning of 1996. In general, the new-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 (Milburn et al. 1996). Measurements below the surface are transmitted to a processor on the surface buoy from sensors inductively coupled to the mooring line. All the data is relayed to shore via the Service Argos satellite system. The design lifetime of the mooring is 1 yr.

The variables measured are surface winds, SST, sea surface conductivity (salinity), air temperature, relative humidity, incoming shortwave radiation, rainfall, subsurface temperature (10 depths in the upper 500 m), subsurface conductivity (three depths in the upper 500 m), and subsurface pressure (at 300 and 500 m). The latter measurements are made to determine mooring line shape, which can be used to correct for any significant vertical movement in the subsurface sensor arrays. Placement of the subsurface temperature and conductivity sensors on the mooring line are 20, 40, 60, 80, 100, 120, 150, 200, 300, and 500 m. Winds, air temperature, and relative humidity are measured using R.M. Young wind assemblies and Rotronic air/humidity sensors. Rainfall is measured with an R.M. Young Siphon gauge similar in design to that deployed during TOGA Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) on the Woods Hole Oceanographic Institution Improved Meteorological Sensor (IMET) mooring (Weller and Anderson 1996). Incoming shortwave radiation is measured with an Eppley Precision Spectral Pyranometer (PSP). All ocean temperature measurements are made with the Pacific Marine Environmental Laboratory (PMEL) minitemperature recorders. Salinity is determined from SeaBird SeaCat-type electromechanical sensors. Based on laboratory calibrations and field tests, we expect accuracies of about 0.2–0.5 m s^{-1} for wind speed, 0.2°C for air temperature, 2%–4% for relative humidity, 0.03°C for ocean temperatures, 0.02–0.05‰ for salinity, and 3% relative accuracy for shortwave radiation (McCarty and McPhaden 1993; Mangum et al. 1994; Freitag et al. 1995; Cronin and McPhaden 1997). 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 provide measurements of rain rate accurate to within 0.010%, which would be better than the 0.030% accuracies obtained from optical rain gauges on TAO buoys during COARE (Cronin and McPhaden 1997). All data are collected and internally recorded at 10-min intervals. Daily averages and some spot 10-min samples are telemetered to shore via Service Argos. A subset of the data is retransmitted via the Global Transit System (GTS) for distribution to support operational weather and climate forecasting at national meteorological and oceanographic centers around the world.

The PIRATA moored array consists of 12 ATLAS moorings spanning 15°N–10°S, 38°W–0° (Fig. 6). The schedule for development of the moored array is shown in Table 1.

The dates in Table 1 are approximate and should be viewed as indicative of the preferred phasing of the implementation plan. The first phase of five buoys (shown by solid red circles in Fig. 6) has been deployed during the period September 1997–February 1998. These buoys will be recovered 1 yr later and a second set of five buoys will be deployed at the beginning of 1999. The array will be at full strength by July 1999. This array of 12 moorings will then be maintained for a full year (at least) until July 2000. Thus, we will have accumulated 3 yr of data at the original five sites in the array and a full year of higher spatial-resolution data at all 12 sites.

The total number of new moorings required to implement the PIRATA plan is 20, which accounts for the 1-yr design lifetime of the ATLAS mooring system and the staggering of cruises in 1999–2000 at 6-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. By prior agreement the responsibility for purchasing ATLAS mooring systems is shared by Brazil (five systems), France (five systems), and the United States (10 systems). All moorings during the pilot study are built by PMEL, which is also responsible for shipping, calibration, laboratory check outs, and instrument refurbishment. Logistic support in terms of ship time for developing and maintaining the PIRATA moored array is mainly the responsibility of Brazil and France. A Brazilian research vessel (RV) is servicing the western half of the array and a French RV is servicing the eastern half of the array. Servicing the entire 12 mooring arrays once a year requires about a total of 80 days of ship time. During PIRATA cruises conductivity–temperature–depth probe (CTD) stations are occupied every 1° along latitude transects and every 4° along longitude transects.

The specific configuration of the PIRATA array 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. Hackert et al. (1998) performed a series of observing system simulation experiments to help determine the optimal location of a limited number of PIRATA moorings when considering vertically integrated and related quantities such as upper-ocean heat content, dynamic topography, and thermocline fluctuations. The spacing of moorings near the equator (10°–15° zonally and 2° meridionally) has been chosen to resolve the rapid equatorial Kelvin wave responses to abrupt wind changes in the western Atlantic (the ENSO-like mode). Meridional mooring sections extend northward along 38°W from 4° to 15°N, and southward along 10°W from 2°N to 10°S. This array covers 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 timescales across the range of latitudes on

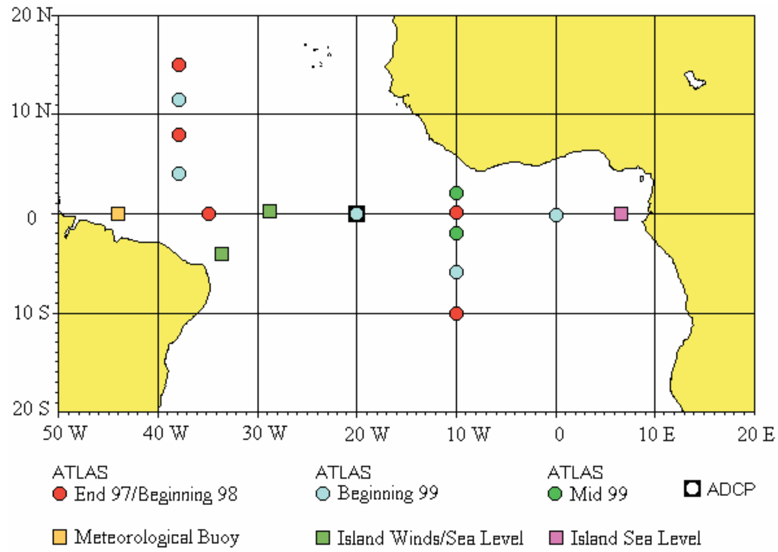

Fig. 6. The PIRATA array deployment, 1997–2000. Five buoys (shown by solid red circles) were already deployed during the first phase between September 1997 and February 1998. The second and third phases of deployment are represented by solid blue and green circles, respectively. Other observational sites (wind, sea level, . . .) are also schematized.

Table 1. PIRATA implementation schedule.

	First phase	Second phase	Third phase	End of PIRATA
Date (month/year)	Sep 1997–Feb 1998	Mar 1999	July 1999	July 2000–Mar 2001
Total moorings at sea	5	10	12	12

each of the two lines (38° 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 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. Meridionally, the array traverses the ITCZ, a region of high SST, weak winds, high cloudiness and precipitation, low solar irradiance, and low evaporation. In contrast, in the northeast tradewind region north of the ITCZ along 38°W, conditions are drier and less cloudy, the winds are stronger, and the SSTs are lower. The region south of the equator along 10°W is in the southeast trade wind 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. 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 will be deployed at 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 at the equator, the array will provide indices of zonal geostrophic mass transport along 38° 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 ocean wave dynamical processes argue strongly for the incorporation into the array of wind and sea level measurements at a few strategically located islands (Fig. 6). 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 SOI. Wind measurements 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 São Tomé (0.5°N, 6.5°E) allows 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 trade wind 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. High priority will 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, to be 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).

In addition to the real-time GTS data stream, PMEL maintains data processing, error checking, archiving, and dissemination based on well-established procedures developed over the past 20 years of Pacific-based mooring research. All data are available via anonymous FTP and via the World Wide Web (http://www.pmel.noaa.gov/pirata) (Fig. 7). Thanks to an electronic link between PMEL (Seattle, Washington) and Centre ORSTOM (Brest, France), the real-time data (and news updates about the PIRATA progress) are also directly available on the ORSTOM–Brest

Web site (http://www.ifremer.fr/orstom/pirata/piratafr.html). Complete in situ PIRATA archives will be maintained at PMEL, ORSTOM–Brest, and INPE (São José dos Campos and/or Natal, Brazil).

As noted above, the PIRATA program was fortunate to have begun during the growth of the 1997–98 ENSO, which is now considered to be one of the largest, if not the largest, El Niño event of the century (see, e.g., *Climate Diagnostics Bulletin*, 1997–98 collection). This climatic episode is having worldwide implications spanning at least five different continents. It is unlikely that the large SST anomalies observed from VOSs in the tropical Atlantic during the second half of 1997 are a mere coincidence (e.g., Fig. 5). Consistent with past El Niño events, the anomalous SST variability in the tropical Atlantic may be related, in whole or in part, to the 1997–98 ENSO. The ongoing time series of climate variables measured by the first PIRATA moorings will permit much-needed insight to the development both at the surface and subsurface of such a warm-event phenomenon (Fig. 8).

PIRATA System Overview

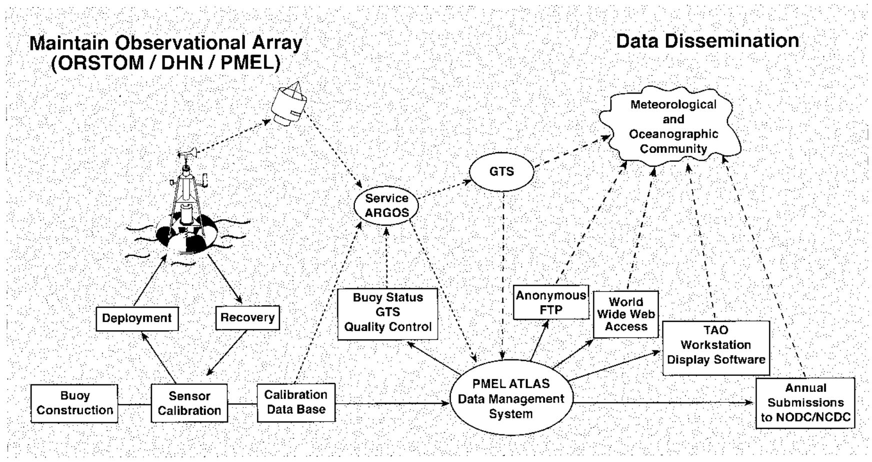

FIG. 7. Schematic of the PIRATA real-time data flow.

4. Interactions with other programs

As is the case of 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 provide validation data to future model experiments. Consequently, many scientific interactions will take place between PIRATA and other climatic programs that will develop in the tropical Atlantic region.

First of all, PIRATA addresses the general call for further development of the tropical Atlantic Ocean observing system under the auspices of Climate Variability and Predictability (CLIVAR) (WCRP–CLIVAR 1995, 1998). As such, PIRATA provides an observational foundation to the CLIVAR principal research area, tropical Atlantic variability. Furthermore, due to the geographical and climatic domain PIRATA is situated within, these observations will also support the CLIVAR research areas of variability of the American monsoon system and African climate variability. PIRATA also responds to specific recommendations that consideration be given to expanding the TAO array into the Atlantic basin for climate studies (National Research Council 1994a,b; Ocean Observing System Development Panel 1995) and is now considered as a pilot contribution to GOOS and the Global Climate Observing System (GCOS) (GCOS 1997).

With respect to national participation, PIRATA is viewed as integrated in Brazilian, French, and U.S. climate programs. Within Brazil, 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 Brazilian buoy program (PnBoia) 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. Within France, Etudes Climatiques dans l'Atlantique Tropical (ECLAT) is a multidisciplinary program designed to be the French contribution to CLIVAR in the tropical Atlantic. The French part of PIRATA belongs to ECLAT. PIRATA 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 (PACS Scientific Working Group 1996). The Atlantic Climate and Circulation Experiment (ACCE) is set to study the role of the Atlantic's thermohaline circulation in global atmospheric climate. It is centered mainly in the North Atlantic region but includes the equatorial basin where

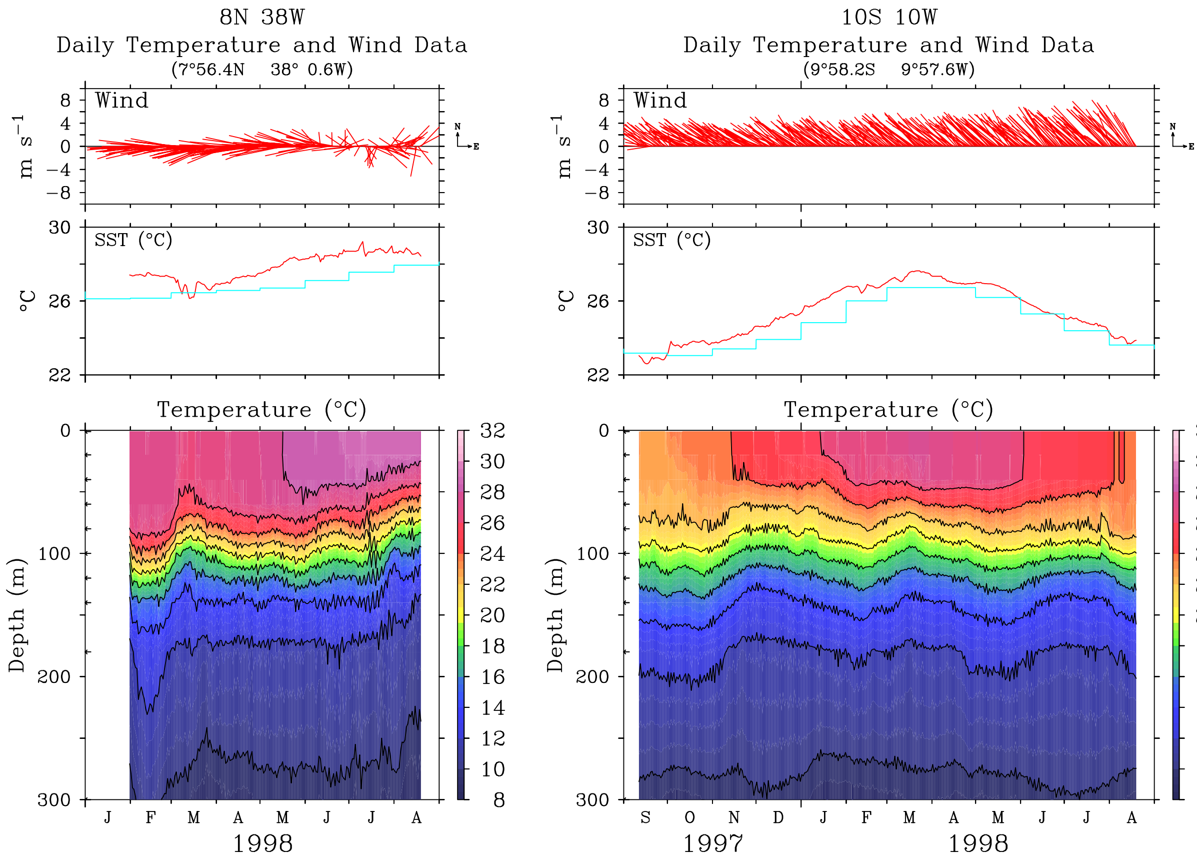

FIG. 8. Examples of real-time data from two PIRATA sites, one at 10°S, 10°W (deployed in September 1997) and one at 8°N, 38°W (deployed in January 1998). Shown are winds, SST, and temperatures in the upper 300 m. SST climatology is also shown in the middle panels as a light blue line.

drifters will be deployed (ACCE 1995), according a potential collaboration with PIRATA activities. Hence, PIRATA is 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.

5. Toward a comprehensive observing system in the tropical Atlantic

The PIRATA measurements will provide during a limited 3-yr period an improved description of SST, air temperature, winds, humidity, precipitation, and shortwave radiative fluxes for the tropical Atlantic 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 temperature and salinity in the upper ocean. In addition, observations of upper-ocean velocity will be made at one key location. 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. These measurements will be valuable as ground truth for satellite missions, and in some cases in the development of blended satellite–in situ analyses.

PIRATA salinity and precipitation measurements will be the first systematically collected from moorings in the tropical Atlantic. These data will help to characterize 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 (Murtugudde and Busalacchi 1998) as has been hypothesized for the equatorial Pacific (Lukas and Lindstrom 1991; Ando and McPhaden 1997).

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 timescales 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 that 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 better understanding 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. 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. PIRATA data are already on the GTS telecommunication network data stream and making their way into the operational analyses at the major national weather prediction centers. PIRATA data will serve as important input to 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. Finally, the PIRATA data will help in determining the relationships between regional impacts of climate variations used in agriculture and fisheries in South America and West Africa.

The idea of PIRATA as a pilot project is to establish the extent to which the ATLAS moored technology is a meaningful and cost-effective observational system in the Atlantic. During the 3-yr period 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 after demonstration of the success of the observational system and the science performed, other nations will join in the maintenance and desirable expansion of the array in order to make PIRATA a routine basic observational system in the tropical Atlantic as part of GOOS and GCOS.

We hope that this paper, along with another such article containing initial results when available, can go a long way toward convincing the scientific community and funding agencies to support such an observing program. Thus the PIRATA array will be put in place permanently in the tropical Atlantic to quantitatively study seasonal to longer-term climatic variability.

Acknowledgments. We would like to thank Jim Carton, Jean Citeau, Silvia Garzoli, Nick Graham, Ed Harrison, Charles McClain, Christophe Menkes, Bob Molinari, Paulo Nobre, Michel Ollitraut, Jean-Paul Rebert, Kevin Trenberth, Fritz Schott, Jean-Marc Verstraete, Bob Weisberg, and Bill Woodward for their editorial contributions to the early PIRATA Scientific Prospectus [available online at http://www.ifremer.fr/orstom/pirata/piratafr.html]. Useful comments were also provided by several participants attending the first four PIRATA meetings, as well by three reviewers of the final draft. The PIRATA logo was designed by Pierre Campana.

References

ACCE, 1995: A program design for an Atlantic circulation and climate experiment. U.S. Contribution to WOCE and ACCP, 112 pp. [Available from U.S. WOCE Office, Dept. of Oceanography, Texas A&M Univ., College Station, TX 77843-3146.]

Ando, K., and M. J. McPhaden, 1997: Variability of surface layer hydrography in the tropical Pacific Ocean. *J. Geophys. Res.*, **102**, 23 063–23 078.

Blanke, B., and P. Delécluse, 1993: Variability of the tropical Atlantic Ocean simulated by a general circulation model with two different mixed layer physics. *J. Phys. Oceanogr.*, **23**, 1363–1388.

Bryan, F. O., I. Wainer, and W. R. Holland, 1995: Sensitivity of the tropical Atlantic circulation to specification of wind stress climatology. *J. Geophys. Res.*, **100**, 24 729–24 744.

Carton, J. A., and B. Huang, 1994: Warm events in the tropical Atlantic. *J. Phys. Oceanogr.*, **24**, 888–903.

——, X. Cao, B. S. Giese, and A. M. da Silva, 1996: Decadal and interannual SST variability in the tropical Atlantic. *J. Phys. Oceanogr.*, **26,** 1165–1175.

Chang, P., L. Ji, and H. Li, 1997: A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air–sea interactions. *Nature,* **385**, 516–518.

Crawford, R. J. M., W. R. Siegfried, L. V. Shannon, C. A. Villacastin–Herroro, and L. G. Underhill, 1990: Environmental influences on marine biota off southern Africa. *S. Afr. J. Sci.,* **86**, 330–339.

Cronin, M., and M. J. McPhaden, 1997: The upper ocean heat balance in the western equatorial Pacific warm pool during September–December 1992. *J. Geophys. Res.,* **102**, 8533–8553.

da Silva, A. M., C. C. Young, and S. Levitus, 1994: *Anomalies of Directly Observed Quantities.* Vol. 2, *Atlas of Surface Marine Data.* U.S. Department of Commerce, 416 pp.

Delécluse, P., J. Servain, C. Levy, K. Arpe, and L. Bengsston, 1994: On the connection between the 1984 Atlantic warm event and the 1982–83 ENSO. *Tellus,* **46A**, 448–464.

Enfield, D. B., and D. A. Mayer, 1995: Tropical Atlantic SST variability and its relation to Pacific SST and western hemisphere rainfall. *ACCP Notes*, **2**, 4–8.

——, and ——, 1997: Tropical Atlantic SST variability and its relation to El Niño–Southern Oscillation. *J. Geophys. Res.,* **102**, 929–945.

Folland, C., T. Palmer, and D. Parker, 1986: Sahel rainfall and worldwide sea temperatures: 1901–85. *Nature,* **320**, 602–606.

Freitag, H. P., Y. Feng, L. J. Mangum, M. P. McPhaden, J. Neander, and L. D. Stratton, 1995: Calibration procedures and instrumental accuracy estimates of TAO temperature, relative humidity and radiation measurements. NOAA Tech. Memo. ERL PMEL-104, 32 pp. [Available from Pacific Marine Environmental Laboratory, 7600 Sand Point Way, Seattle, WA 98115.]

GCOS, 1997: In situ observations for the Global Observing Systems. GCOS-28, WMO/TD 793, and UNEP/DEIA/MR.97-3. [Available from World Meteorological Organization, Case Postale 2300, CH-1211, Geneva 2, Switzerland.]

Graham, N., 1994: Experimental predictions of wet season precipitation in Northeastern Brazil. *Proc. 18th Annual Climate Diagnostics Workshop,* Boulder, Colorado, NOAA. [Available from Pacific Marine Environmental Laboratory, 7600 Sand Point Way, Seattle, WA 98115.]

Gray, W. M., 1990: Strong association between west African rainfall and U.S. landfall of intense hurricanes. *Sciences,* **249**, 1251–1256.

——, C. W. Landsea, P. W. Mielke, and K. J. Berry, 1993: Predicting Atlantic basin seasonal tropical cyclone activity by 1 August. *Wea. Forecasting,* **8**, 73–86.

Hackert, E. C., R. N. Miller, and A. J. Busalacchi, 1998: An optimized design for a moored instrument array in the tropical Atlantic Ocean. *J. Geophys. Res.,* **103**, 7491–7509.

Harzallah, A., J. O. Rocha de Aragao, and R. Sadourny, 1996: Interannual rainfall variability in north-east Brazil: Observation and model simulation. *Int. J. Climatol.,* **16**, 861–878.

Hastenrath, S., and L. Greishar, 1993: Further work on the prediction of northeast Brazil rainfall anomalies. *J. Climate,* **6**, 743–758.

Hayes, S. P., L. J. Mangum, J. Picaut, A. Sumi, and K. Takeuchi, 1991: TOGA–TAO: A moored array for real-time measurements in the tropical Pacific Ocean. *Bull. Amer. Meteor. Soc.,* **72**, 339–347.

Houghton, R. W., and C. Colin, 1986: Thermal structure along 4°W in the Gulf of Guinea during 1983–1984. *J. Geophys. Res.,* **91**, 11 727–11 739.

——, and Y. Tourre, 1992: Characteristics of low-frequency sea surface temperature fluctuations in the tropical Atlantic. *J. Climate,* **5**, 765–771.

Huang, B., and J. Shukla, 1997: Characteristics of the interannual and decadal variability in a general circulation model of the tropical Atlantic Ocean. *J. Phys. Oceanogr.,* **27**, 1693–1712.

Katz, E. J., 1987: Seasonal response of the sea surface to the wind in the equatorial Atlantic. *J. Geophys. Res.,* **92**, 1885–1893.

Krishnamurti, T. N., R. Correa–Torres, M. Latif, and G. Daughenbaugh, 1998: The impact of current and possible future sea surface temperature anomalies on the frequency of Atlantic hurricanes. *Tellus,* **50A**, 186–210.

Lindzen, R. S., and S. Nigam, 1987: On the role of sea surface temperature gradients in forcing low-level winds and convergence in the tropics. *J. Atmos. Sci.,* **44**, 2418–2436.

Lukas, R. L., and E. Lindstrom, 1991: The mixed layer in the western equatorial Pacific. *J. Geophys. Res.,* **96** (Suppl.), 3343–3357.

Mangum, L. J., H. P. Freitag, and M. J. McPhaden, 1994: TOGA–TAO array sampling schemes and sensor evaluations. *Proc. OCEANS 94 OSATES,* Brest, France, Communité Urbaine de Brest, II-402–II-406.

McCarty, M. E., and M. J. McPhaden, 1993: Mean seasonal cycles and interannual variations at 0°N, 165°E during 1986–1992. NOAA Tech. Memo. ERL PMEL-98, 64 pp. [Available from Pacific Marine Environmental Laboratory, 7600 Sand Point Way, Seattle, WA 98115.]

McPhaden, M. J., and coauthors, 1998: The Tropical Ocean Global Atmosphere (TOGA) observing system: A decade of progress. *J. Geophys. Res.,* **130** (C7), 14 169–14 240.

Mehta, V. M., and T. Delworth, 1995: Decadal variability of the tropical Atlantic Ocean surface temperature in shipboard measurements and in a global ocean–atmosphere model. *J. Climate,* **8**, 172–190.

Milburn, H. B., P. D. McLain, and C. Meinig, 1996: ATLAS buoy—Reengineering for the next decade. *Proc. IEEE/MTS Ocean'96,* Fort Lauderdale, FL, Institute of Electrical and Electronics Engineers, 698–702.

Moura, A., and J. Shukla, 1981: On the dynamics of droughts in northeast Brazil: Observations, theory, and numerical experiments with a general circulation model. *J. Atmos. Sci.,* **38**, 2653–2675.

Murtugudde, R., and A. J. Busalacchi, 1998: Salinity effects in a tropical ocean model. *J. Geophys. Res.,* **103** (C2), 3283–3300.

National Research Council, 1994a: Ocean-atmosphere observations supporting short-term climate predictions. National Academy Press, Washington, DC, 51 pp.

——, 1994b: GOALS: Global Ocean–Atmosphere–Land System for Predicting Seasonal-to-Interannual Climate. National Academy Press, Washington, DC, 103 pp.

Nobre, P., and J. Shukla, 1996: Variations of sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America. *J. Climate,* **9**, 2464–2479.

Ocean Observing System Development Panel, 1995: Scientific design for the common module of the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS): An ocean observing system for climate. Department of Oceanography, Texas A&M University, College Station, TX, 265 pp.

PACS Scientific Working Group, cited 1996: Pan American climate studies: A scientific prospectus. [Available online at http://tao.atmos.washington.edu/pacs.]

Penland, C., and L. Matrasova, 1998: Prediction of tropical Atlantic sea surface temperatures using linear inverse modeling. *J. Climate,* **11**, 483–496.

Ropelewski, C. F., and M. Halpert, 1987: Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Mon. Wea. Rev.,* **115**, 1606–1626.

Schmitt, R. W., P. S. Bogden, and C. Dorman, 1989: Evaporation minus precipitation and density fluxes in the North Atlantic. *J. Phys. Oceanogr.,* **19**, 1208–1221.

Servain, J., 1991: Simple climatic indices for the tropical Atlantic Ocean and some applications. *J. Geophys. Res.,* **96**, 15 137–15 146.

——, J. N. Stricherz, and D. L. Legler, 1996: *TOGA Atlantic Pseudo-Stress Atlas 1985–1994.* Centre ORSTOM de Brest, 162 pp.

——, I. Wainer, and A. Dessier, 1998a: Evidence d'une liaison entre les deux principaux modes de variabilité climatique interannuelle de l'Atlantique tropical. *Compte-Rendus de l'Académie des Sciences de Paris,* **327,** 1–8.

Shaeffer, J. D., 1995: Tropical cyclone activity as a diagnostic climate indicator. *Proc. 20th Annual Climate Diagnostics Workshop,* Seattle, WA, NOAA Climate Prediction Center and Joint Institute for the Study of Atmosphere and Ocean, 113–116.

Wagner, R. G., and A. da Silva, 1994: Surface conditions associated with anomalous rainfall in the Guinea coastal region. *Int. J. Climatol.,* **14**, 179–199.

WCRP–CLIVAR, 1998: CLIVAR–A study of climate variability and predictability, science plan. WCRP 89, WMO/TD 690, 157 pp. [Available from World Meteorological Organization, Case Postale 2300, CH-1211, Geneva 2, Switzerland.]

——, 1998: CLIVAR initial implementation plan, World Climate Research Programme. WCRP 103, WMO/TD 869, 340 pp. [Available from World Meteorological Organization, Case Postale 2300, CH-1211, Geneva 2, Switzerland.]

Weisberg, R. H., and T. J. Weingartner, 1986: On the baroclinic response of the zonal pressure gradient in the equatorial Atlantic Ocean. *J. Geophys. Res.,* **91**, 11 717–11 725.

Weller, R. A., and S. P. Anderson, 1996: Surface meteorology and air–sea fluxes in the western equatorial Pacific warm pool during the TOGA Coupled Ocean–Atmosphere Response Experiment. *J. Climate,* **9**, 1959–1990.

Yoo, J. M., and J. A. Carton, 1990: Annual and interannual variations of the freshwater budget in the tropical Atlantic Ocean and the Caribbean Sea. *J. Phys. Oceanogr.,* **20**, 831–845.

Zebiak, S. E., 1993: Air–sea interaction in the equatorial Atlantic region. *J. Climate,* **6**, 1567–1586.

——, and M. A. Cane, 1987: A model El Niño–Southern Oscillation. *Mon. Wea. Rev.,* **115**, 2262–2278.