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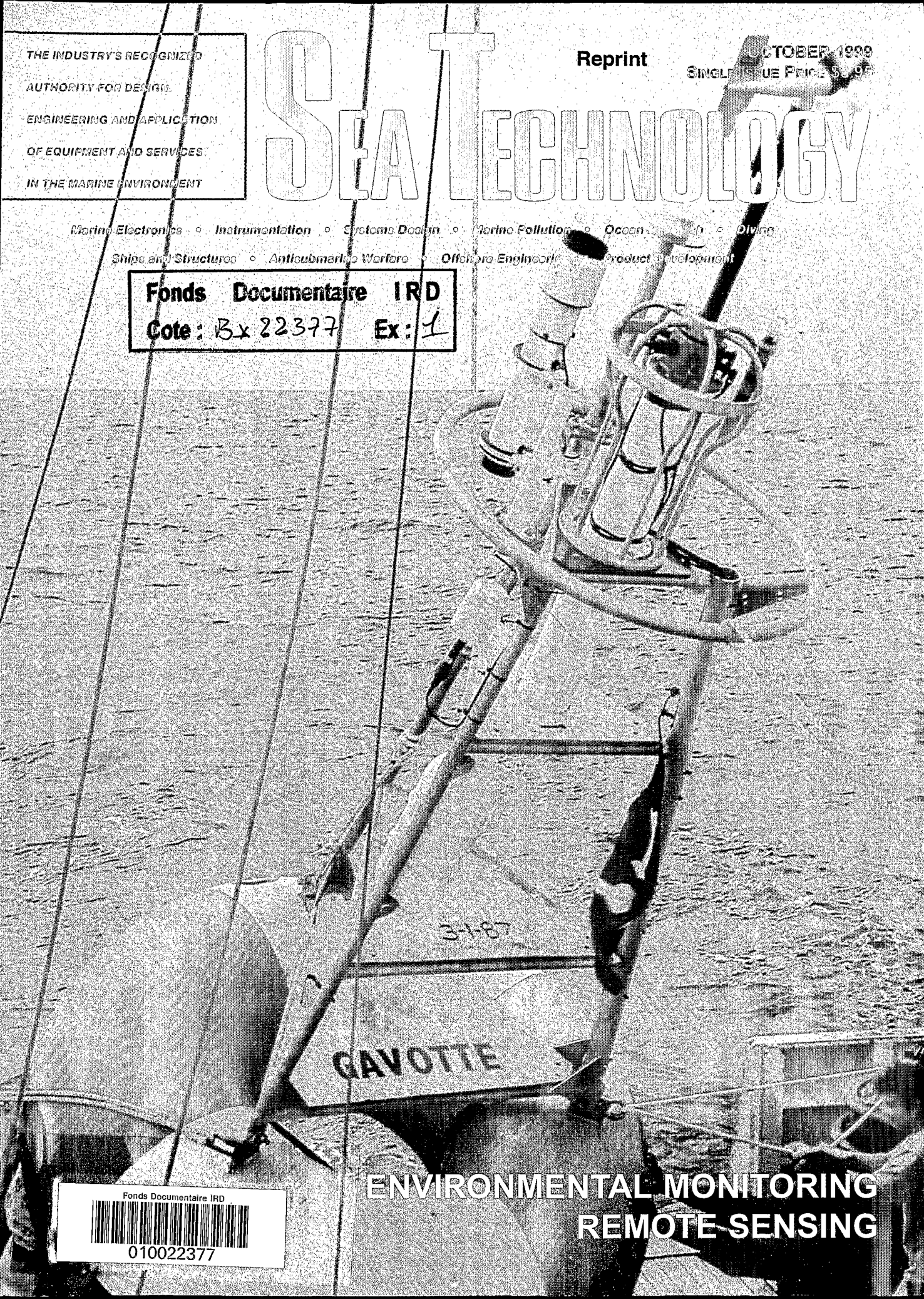

ENVIRONMENTAL MONITORING
REMOTE SENSING

The PIRATA Program: Monitoring Tropical Atlantic Waters

Atlas Moorings, Island Stations Extend the Pacific's TAO Array; Ocean Monitoring Supports Interannual and Decadal Climate Prediction

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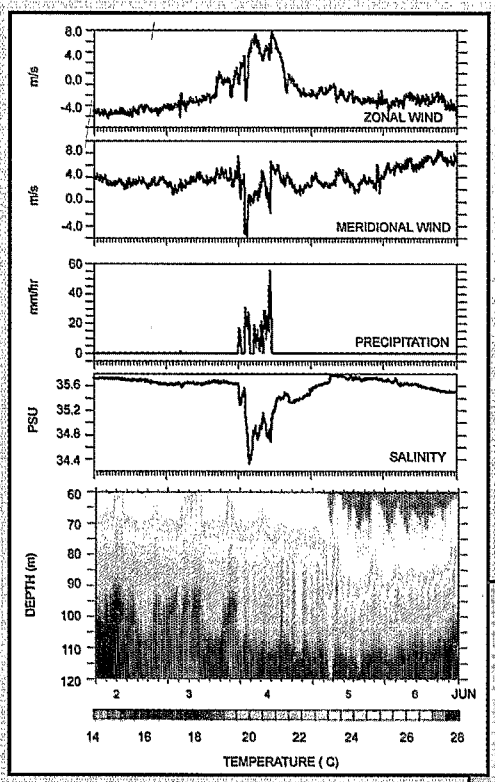
Initially conceived as an extension of the Pacific Tropical Atmosphere Ocean (TAO) Array (*Sea Technology*, October 1995), the PIRATA Project (pilot research moored array in the tropical Atlantic) is the result of a convergence of interests of scientists from Brazil, France, and the United States in developing an ocean monitoring capability in support of interannual and decadal climate prediction. In addition, interest in developing the requisite technology to monitor ocean and atmospheric parameters that are critical for understanding the local ocean-atmosphere processes was also an important consideration.

This convergence of interests made possible the funding of the project in a reasonable cost-sharing basis between the three partners.

PIRATA scientists propose to install and maintain an ocean observing system in the tropical Atlantic based on an initial array of 12 moored PMEL/NOAA next-generation ATLAS moorings (which extends the capability of the previous ATLAS technology). Also considered are

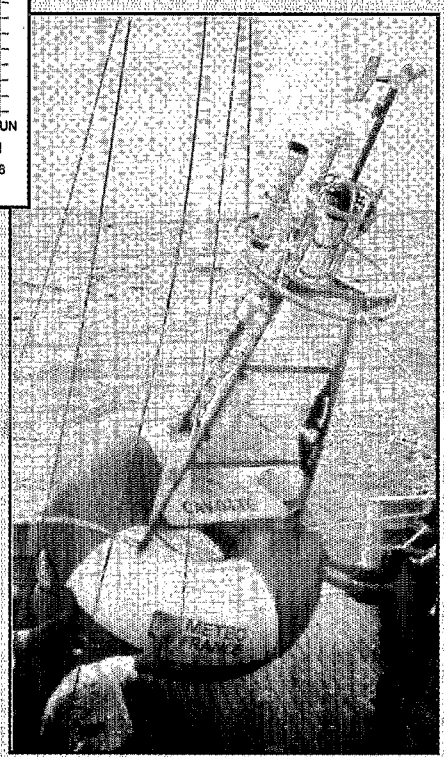


island meteorological and tide stations with satellite transmitting capability, one coastal meteorological buoy, and one internally recording ADCP current meter mooring on the equator.

The principal objective is to monitor atmospheric-oceanic surface variables and upper ocean thermal structure at optimal locations in the tropical Atlantic where the most important regional large-scale ocean-atmosphere interaction processes take place. The measurements are transmitted via satellite in real time and are available to all interested users in the research or operational communities, updated on a daily basis. In addition, the original data are recorded internally every 10 minutes for most of sensors in the acquisition system, to be retrieved one year later during mooring substitution and refurbishment operations.

Implementation started with the first deployment in September 1997. The scheduling anticipates an end of the pilot phase in March 2001, but the partners are presently agreeing upon extension of this phase up to 2006.

Three years of measurements will give a good start on the issues of seasonal to interannual variations in the tropical Atlantic but will not be enough to relate directly to decadal scale variability, although these



funds and coordinates shipping to and from the theater of operations and participates in deployment as well recovery of mooring systems at sea. It is responsible for all calibration, laboratory checkouts, and instrument refurbishment. It maintains a database of real-time and research-quality delayed mode data (10-minute data) for all variables, which will become available in the PIRATA web pages as soon as the data are processed.

The logistical support in terms of ship time for developing and maintaining the PIRATA moored array is under the responsibility of Brazil and France (about 90 days per year of ship time for servicing the entire array). The Brazilian R/V *Antares* (DHN) services the western half of the array and the mid-basin mooring at the equator, departing from Fortaleza or Natal. Brazil will install wind and sea-level data collection platforms at St. Peter and St. Paul Archipelago, Atol das Rocas, and at the coastal meteorological buoy (0 0°N-44°W). The French R/V *Antéa* (IRD) services the eastern half of the array from Abidjan, Côte d'Ivoire. France maintains a sea-level data collection platform at Sao Tomé island (0.5°N-6.5°E).

All the PIRATA daily data are available at PMEL/NOAA-Seattle via the worldwide web at http://www.pmel.-noaa.gov/pirata, with an electronic link with IRD-Brest at http://www.if-remer.fr/orstom/pirata/piratafr.html and INPE at http://www.cmcd.-inpe.br/pirata.

Interaction with Other Programs

As with the TAO program in the Pacific, the PIRATA program is not conceived as a self-sufficient program. The main role of PIRATA is to offer high quality geographically fixed time series of ocean surface and subsurface measurements, to complement existing Lagrangian measurements offered by other projects in the tropical Atlantic, and to give verifiable elements to future model experiments. Consequently, many scientific interactions take place between PIRATA and other climate change programs that are being developed in the tropical Atlantic region (see a partial list below). Such interactions are of mutual benefit to PIRATA and these other programs.

International programs: CLIVAR (Climate Variability and Predictability) and its sub-programs, CLIVAR-Africa, EuroCLIVAR, and VAMOS (Variability of American Monsoon Systems); GCOS (Global Climate Observing System); and GOOS (Global Ocean Observing System).

Brazilian programs: GOOS-Brazil and its subprograms (e.g., National Drifter Program-PNBoia).

French programs: ECLAT (Etudes Climatiques dans l'Atlantique Tropical) and Clipper-MERCATOR-CORIOLIS (operational oceanography).

USA programs: ACVE (Atlantic Climate Variability Experiment), PACS (Pan American Climate Studies), and ACCE (Atlantic Climate and Circulation Experiment).

"One of the main issues facing PIRATA now is the feasibility of participation of other countries as it will continue post-2001 after the first pilot phase ends. Presently there are statements from both Brazil and France assuring ship time to the end of this first phase."

PIRATA Status (August 1999)

During the first phase of PIRATA (autumn 1997 to early 1998), five deployments were made, two in the eastern basin (Gulf of Guinea) and three in the western basin. The eastern equatorial mooring at 0°N-10°W failed after only two months, therefore an additional deployment was made at 0°N-0°W, which also failed after ten months. These losses, both along the equator in the Gulf of Guinea, were certainly due to vandalism associated with tuna fisheries, which are very frequent in that region. These vandalism issues were debated during the PIRATA-5 meeting (9-10 November at Abidjan, Côte d'Ivoire) and the idea to seek international relief banning was advanced. Such a resolution was submitted (November 27, 1998) by the IOC Secretariat to the attention of the XXth session of the IOC Assembly.

During the second phase of PIRATA deployment (autumn 1998 to early 1999), four replacements (three in the west, one in the east) and six new deployments (three in the west and three in the east) were made. The ATLAS system at 0°N-0°W was again vandalized and set adrift (only two months after its second deployment), but fortunately the upper part of the mooring was recovered by a French tuna ship and then discharged in Abidjan.

High-resolution data from three Brazilian moorings and one French mooring are now available on the PIRATA web page. Since November 1998, nine deployments have been made, giving a data return statistics around 90 percent, except for one recent failure at 4°N, 38°W. Details may be obtained directly from the PIRATA web page. As of August 1999, the PIRATA array was working as follows: the western and central parts of the PIRATA array are fully operational at 15°N-38°W; 12°N-38°W, 0°N-35°W, and 0°N-23°W experienced some loss as well; 8°N-38°W died off due to anomalous battery drain; 4°N-38°W stopped suddenly on June 20 due to possible vandalism; the wind sensor at 0°N-35°W was vandalized, according to the science crew of the R/V *Thallassa*, which passed by during the 1999 French Equalant Cruise and whose crew tried to refurbish the wind sensor; and three ATLAS systems are operational over the meridional line in the eastern basin (0°N-10°W, 5°N-10°W, and 10°S-10°W).

The third (and final) phase of the 1999 PIRATA deployment, scheduled for July 1999—with the instrumentation of two new sites in the eastern basin (2°N-10°W and 2°S-10°W) and a third attempt of maintenance at 0°N-0°W—had to be postponed due to problems with the IRD vessel *Antéa*.

An intensive flux measurement (with a meteorological instrumented mast aboard a French research vessel) was done this summer in the vicinity of three PIRATA equatorial sites (one in the western equatorial basin, two in the eastern basin). This will be useful for calibrating the turbulent air-sea fluxes estimated from the PIRATA observations via the bulk formula, and some data can be checked against the future high resolution data to be retrieved next year. An ADCP mooring (with measurements all along 0-300 meters) is also scheduled to be deployed at the PIRATA 0°N-23°W site by March 2000, as well as a meteorological buoy at 0°N-44°W.

PIRATA's scientific and technical goals are many:

- 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 and freshwater fluxes, and ocean dynamics, in the formation of the oceanic and atmospheric mixed layer to be able to understand the seasonal and interannual variability of SST within the tropical Atlantic basin via predictive models of the coupled Atlantic climate system
- To provide a dataset that can be used to develop and improve this detailed understanding of how basic mass, momentum, heat, and freshwater fluxes couple in the oceanic and atmospheric mixed layer
- To design, deploy, operate, and maintain a pilot array of moored buoys and island stations, similar to the ones used during the TOGA program in the tropical Pacific
- To collect high-resolution (10 minute time steps) data and transmit via satellite in real time a set of quality controlled oceanic and atmospheric daily average data to observe and study the upper ocean and the ocean-atmosphere interface of the tropical Atlantic.

The PIRATA Array

PIRATA consists of 12 ATLAS moorings, four spanning the equator and eight spanning two meridional lines. This specific configuration has been chosen to provide coverage along the equator of regions of strong wind forcing in the western basin and significant seasonal-to-interannual variability in SST in the central and eastern basin. The meridional arrays cover the regions of high SST variability associated with the SSTa dipole mode with the northwestern meridional line cutting across the ITCZ during most of the year. 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 meters), subsurface conductivity (presently three depths in the upper 150 meters, four depths in future moorings), and subsurface pressure (at 300 and 500 meters). An acoustic doppler current profiler mooring is proposed for 0°N-23°W to monitor the vertical current profile variations in the central Atlantic where high zonal current variability occurs, close to the ATLAS mooring sited at 0°N-23°W (the 20°W mooring position had to be displaced to the west due to difficulties with local bottom topography).

The present importance of obtaining good subsurface temperature and salinity data, especially in the upper 150 meters, is driven by the need to monitor the influence of shallow mixed layers (30 meters) occurring with waters of different temperature and salinity stratifications (causing what is known as a "barrier layer"), which have impacts on the vertical heat transfer in the ocean, affecting SST. Mixed layer parameterizations for predictive models should take into account such salinity effects, which will be even better monitored once the ATLAS moorings to be deployed in the year 2000 will carry conductivity sensors at five depths (1 meter, 20 meters, 40 meters, 80 meters, and 120 meters). The demand for these five depths is the result of the observation of barrier layers in the vertical profiling with CTDs, which form a necessary part in the data collection made during the deployment cruises.

The initial ATLAS deployments were made during 1997-1999. In addition to the ATLAS mooring observations, wind measurements and tide-gauge data are scheduled to be available in real time from a few equatorial sites: Brazil will deploy systems at St. Peter and St. Paul Rocks Archipelago (0.7°N-29.2°W) and Atol das Rocas (3.9°S-33.5°W) while France will maintain the tide gauge at Sao Tomé island (0.5°N-6.5°E). Brazil must also deploy a coastal meteorological buoy at 0°N-44°W, offshore the State of Maranhão.

Resource Commitments

PIRATA is realized as part of a multinational effort involving Brazil, with INPE responsible for the national coordination, funding, and technical work and the ship time furnished by the Directory of Hydrography and Navigation (DHN) of the Brazilian Navy (which collaborates with the most extensive civil oceanographic programs in Brazil).

France involves IRD in the coordination, funding, and ship time and Météo-France and CNRS/INSU with funding.

The United States—through the Pacific Marine Environmental Laboratory (NOAA/PMEL)—is responsible for mooring construction, maintenance of systems, and support in deployment operations, quality control and distribution of data through the Internet, construction and maintenance of the main PIRATA web page, as well as funding via NOAA/OGP.

During the pilot study (1997-2001), all the ATLAS mooring systems are being built by NOAA/PMEL at Seattle, Washington. NOAA/PMEL also

The PIRATA Executive Committee

It was during the 4th TAO Implementation Panel Meeting in September 1995 that a decision was made to prepare a proposal for a TAO array extension into the tropical Atlantic. The first ad-hoc committee was formed with the task of preparing a proposal and involving those parties that could make possible the funding and the ship time required. A first meeting was scheduled for February 1996 in Natal. The components of this first "PIRATA Executive Committee" were the present authors plus Drs. Mike McPhaden (PMEL/NOAA), Antonio Divino Moura (INPE—in the move to IRI/NOAA), Gilles Reverdin (LEGOS/GRGS), and Steve Zebiak (LDEO/Columbia University), with Moura and Servain as co-chairs. The first version of the PIRATA-Science and Implementation Plan for an Observing System to Support Tropical Atlantic Climate Studies was discussed in the PIRATA-1 meeting in Natal where feasibility issues for initiating implementation in 1997 were first examined. Subsequent meetings (in Brest, 1996; Seattle, March 1997; Rio de Janeiro, November 1997; Abidjan, November 1998) have been important to discuss the logistic and implementation issues of PIRATA. Last year, in the PIRATA-5 meeting in November 1998 in Abidjan, Zebiak, who gave much of his time with ideas that made possible the materialization of PIRATA, rotated off the PEC. The PEC is now enlarged by Drs. Serge Planton (IRD), Ping Chang (Department of Oceanography, Texas A&M University), and Ilana Wainer (Instituto Oceanografico, Universidade de S. Paulo), with Servain now acting as chairman.–*the Authors*

Graphs show impact of a one-day westerly wind burst in the vertical structure of the equatorial western Atlantic, as seen with the 10-minute data from the Brazilian mooring at the equator, 035W, June 2-7, 1998. The internal tide signal seen at T60 sensor suddenly migrates downwards and is seen at T80 subsequently, exhibiting the sudden deepening of the mixed layer one day later. By looking at the corresponding daily average data, this wind burst appears like an outlier, but its effect can be nevertheless seen as somewhat corresponding spikes in the other variables.

Below left, the PIRATA array begins deployment (1997-1999) in the tropical Atlantic.

observations will make it possible to understand a few key processes thought important for forcing variability on this long time scale. PIRATA has the potential to establish the foundation for a longer term monitoring network that will address more completely these important scientific problems under the auspices of CLIVAR (*Sea Technology*, September 1998), GOOS and GCOS.

Scientific Questions of Interest

Of the main socio-economic drivers for the establishment of PIRATA, two are noteworthy:

• Strong long-term correlation between seasonal precipitation anomalies in the semi-arid north-northeastern Brazil and the African Sahel and off-equatorial Atlantic SST anomalies (correlation has an inter-hemispheric dipolar distribution) that reveal variability peaking on a decadal (12-13 years) scale, as compared to a smaller correlation with El Niño/La Niña in the Pacific at this scale.

• An "Atlantic El Niño," the El Niño-like warm event in the Eastern Atlantic that modulates and also disturbs fisheries ecosystems, from the Gulf of Guinea down to Namibia, and equally influences the terrestrial climate, this process having a seasonal to decadal variability. The latter phenomenon is better known as a consequence of the efforts during the TOGA period in which the TAO array has been the centerpiece and its behavior may be more easily understood and its evolution predicted. These intersections of significant climatic signals and important socioeconomic ramifications are very compelling since they generate a demand for developing efficient prediction schemes that may be used to mitigate the effects of the well-known droughts of northeast Brazil and floods elsewhere in the region.

The scientific questions may therefore be formulated thus:

• What processes are responsible for changes in the off-equatorial meridional SST gradient *vs.* those changes in SST along the equator and the related problem of variability of the excursions of the Inter-tropical convergence zone (ITCZ)?

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

• To what extent is the predictability of the equatorial coupled effects affected by the meridional off-equatorial variability?

• 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 the El Niño-Southern Oscillation (ENSO) and the extra-tropical North Atlantic Oscillation (NAO)?

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

Although the full explanation for the tropical Atlantic variability should involve the coupling of possibly unknown processes, the PIRATA proposal included, from the outset, the suggestion that one attribute, the so-called "dipole mode," referring to a coherent inter-hemispheric tropical SST anomaly field (SSTa) of opposite signs in each hemisphere, should be important for predictability. Presently, there is a debate in the scientific community as to whether this interhemispheric gradient in SST is a physical mode or a statistical artifact.

One of the possible hypotheses for such a process is now well stated in the literature, involving a wind-induced evaporation-SST feedback such that the SST anomalies maintain the anomalous wind field, via surface latent heat flux, while low frequency ocean motions should set the restoring force for the oscillation to be sustained. Other processes may emerge from future studies based on new data to explain why the net SSTa variance seem to involve departures from the dipole mode, suggesting some independence between SSTa variability in the north and the south. That is to say that the net result should possibly include the coupling of the dipole mode with other still unknown processes to be proposed to produce the observed SSTa variance.

The final phase of the PIRATA experiment (spring 2000 to early 2001) will be mainly dedicated to yearly maintenance of the ATLAS sites and other *in-situ* observing systems. Thus, an integrated ocean observing system (full PIRATA array + equatorial current measurements + equatorial sea level data + equatorial Met observations) will be operational within (at least) one year.

We expect that at the end of the first pilot phase of PIRATA (basically in 2001), other nations will join in the maintenance and possible expansion of PIRATA (and other types of *in-situ* oceanic observations) to constitute a tropical Atlantic Ocean "fixed" *in-situ* observing system in complement to other systems. A dedicated meeting to discuss all of the oceanographic projects and proposals within the tropical Atlantic (Climate Observing System in the tropical Atlantic, COSTA) was hosted by Dr. Sylvia Garzoli at AOML/NOAA in Miami (May 3-7, 1999) where this discussion took place, at the same time of the sixth meeting of PIRATA (PIRATA-6, Miami, 2-3, 1999) where discussions about practical and strategic aspects during the final phases of the PIRATA project have been discussed. To facilitate the management of this increasingly complex implementation, a PIRATA Resources Committee (PRC) is being formed by the major sponsors of the project. It will establish a long-term strategy for funding, logistics, training, and national priorities and interests regarding the future of PIRATA (where the "P" will then stand for "permanent.").

One of the main issues facing PIRATA now is the feasibility of participation of other countries as it will continue post-2001 after the first pilot phase ends. Presently there are statements from both Brazil and France assuring ship time to the end of this first phase, but discussions will continue the extension of the project feasible up to 2006, including geographical extensions of the array. Some extensions are only possible with the entrainment of other countries, some are being proposed by the present partners. This issue is also dependent on capacity building in the region in the form of an efficient training and technology transfer program needed to help alleviate the burden being placed on PMEL.

The COSTA meeting was very successful in producing a first synthesis of all of the scientific issues contemplated by ongoing, large-scale oceanographic projects in the region, underlying the complementarity between these initiatives. The report of this important meeting may be obtained at the AOML website http://www.aoml.noaa.gov/phod/COSTA/report/. /st/

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Dr. Marcio Vianna has been conducting research in marine science since 1982, when he participated in the French FOCAL 1 cruise as a professional diver. His present interest is focused on the technology of ocean observing systems for climate studies and he is an enthusiast of paleoclimate studies. Vianna has been supervising graduate students in ocean science at INPE since 1988, being presently the coordinator of PIRATA in Brazil, also serving on the International Science Steering Group for PIRATA.

Dr. Jacques Servain has been assistant professor at the University of Brest, France, from 1973 to July 1999. He has been conducting research in tropical marine climate from the beginning of the 1980s in association with the Institut de Recherche pour le Développement (IRD, formerly ORSTOM). Servain collaborated in several international projects and programs in climate research such as FOCAL, TOGA, and now CLIVAR. He is now fully integrated in IRD and leads several activities related to the French participation in CLIVAR/Tropical Atlantic.

Dr. Antonio J. Busalacchi received his Ph.D. degree in oceanography from Florida State University. Since that time he has served as an oceanographer at the NASA/Goddard Space Flight Center. In 1991, he was appointed to the senior executive service in the U.S. government as chief of the NASA/Goddard Laboratory for Hydrospheric Processes. Busalacchi's interests include the development and application of numerical models combined with in situ *and space-based ocean observations to study the tropical ocean response to surface fluxes of momentum and heat.*