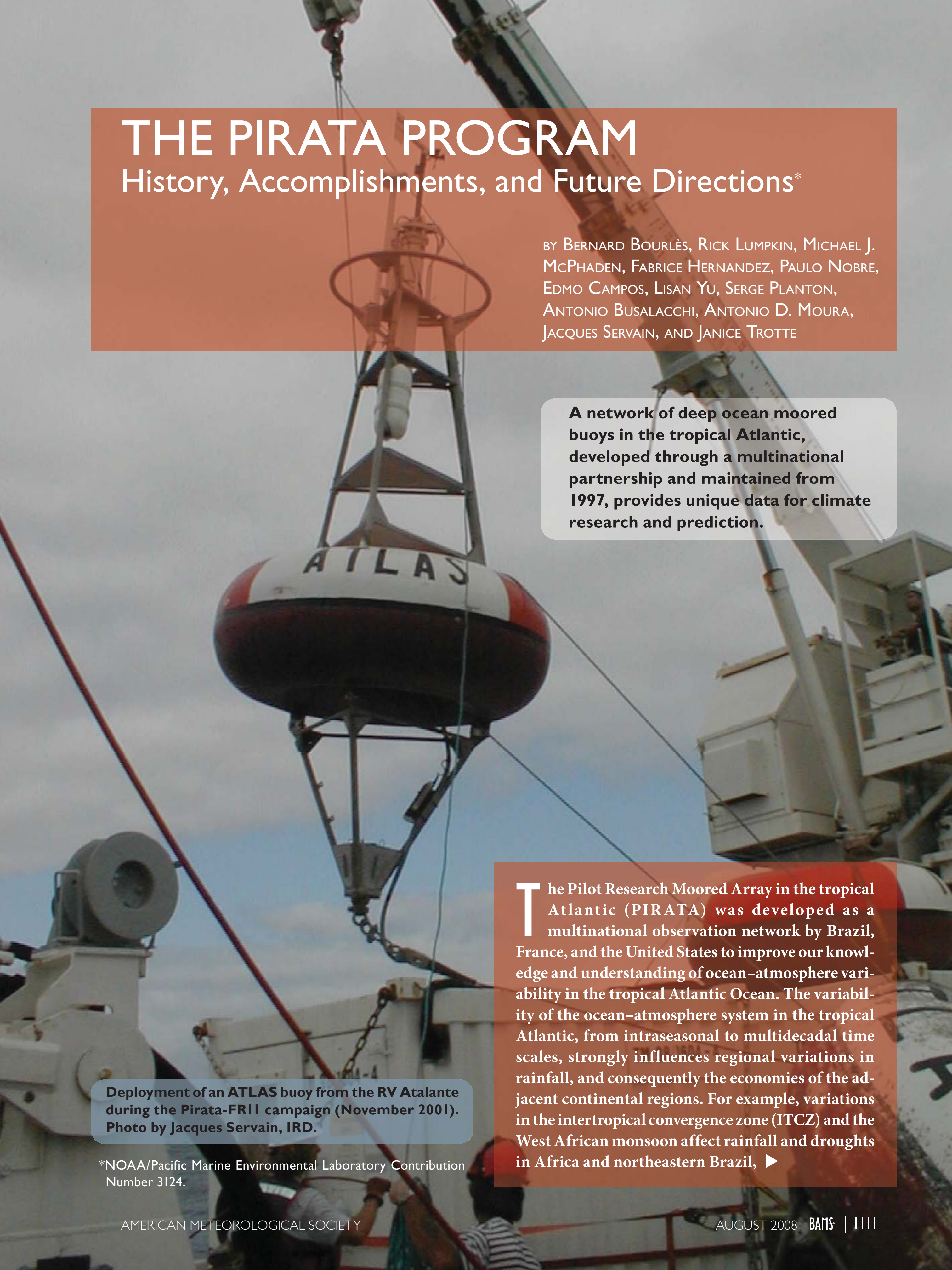
THE PIRATA PROGRAM

History, Accomplishments, and Future Directions*

BY BERNARD BOURLÈS, RICK LUMPKIN, MICHAEL J. MCPHADEN, FABRICE HERNANDEZ, PAULO NOBRE, EDMO CAMPOS, LISAN YU, SERGE PLANTON, ANTONIO BUSALACCHI, ANTONIO D. MOURA, JACQUES SERVAIN, AND JANICE TROTTE

A network of deep ocean moored buoys in the tropical Atlantic, developed through a multinational partnership and maintained from 1997, provides unique data for climate research and prediction.

The Pilot Research Moored Array in the tropical Atlantic (PIRATA) was developed as a multinational observation network by Brazil, France, and the United States to improve our knowledge and understanding of ocean–atmosphere variability in the tropical Atlantic Ocean. The variability of the ocean–atmosphere system in the tropical Atlantic, from intraseasonal to multidecadal time scales, strongly influences regional variations in rainfall, and consequently the economies of the adjacent continental regions. For example, variations in the intertropical convergence zone (ITCZ) and the West African monsoon affect rainfall and droughts in Africa and northeastern Brazil, ▶



Deployment of an ATLAS buoy from the RV Atalante during the Pirata-FR11 campaign (November 2001). Photo by Jacques Servain, IRD.

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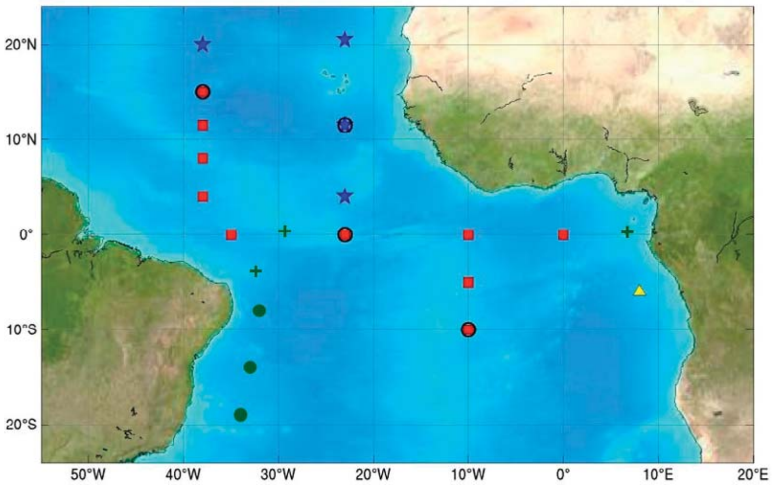

Fig. 1. The PIRATA backbone of ATLAS buoys (red squares), Northeast Extension (blue stars), Southwest Extension (green circles), Southeast Extension pilot project (yellow triangle), and island-based observation sites (green crosses). Buoys with barometers and the ability to estimate net heat flux are indicated with black circles.

and hurricane activity in the West Indies and the United States. PIRATA is thus motivated by fundamental scientific issues, but also by the societal need for improved prediction of the tropical Atlantic climatic system and its impacts on surrounding countries.

Implementation of PIRATA started in 1997 with an array of meteorological and oceanic buoys in the Atlantic (Servain et al. 1998), similar to the Tropical Atmosphere–Ocean (TAO) array used to study El Niño–Southern Oscillation (ENSO) variability in the equatorial Pacific (McPhaden et al. 1998). After a “pilot phase” from 1997 to 2001, during which the backbone array (Fig. 1) was fully implemented, institutions in the three supporting countries decided to extend the array maintenance for a 5-year “consolidation phase” to allow for a meaningful demonstration that the data would contribute significantly to both scientific research and operational applications. In 2006, PIRATA underwent a formal review by the International Climate Variability and Predictability (CLIVAR) Program sponsored by the World Climate Research Programme (WCRP) and the Ocean Observations Panel for Climate (OOPC) sponsored by the WCRP and the Intergovernmental Oceanographic Commission. These organizations endorsed continuation of PIRATA as part of the Global Ocean Observing System and Global Climate Observing System. PIRATA is now entering a “sustained phase,” in which extensions are added to the PIRATA backbone and new technologies are explored to enhance the array’ measurement capability.

The overarching goals of PIRATA are to

- improve the description of the intraseasonal to interannual variability in the atmospheric and oceanic boundary layers in the tropical Atlantic;
- improve our understanding of the relative contributions of air–sea fluxes and ocean dynamics to variability in sea surface temperature (SST) and subsurface heat content at intraseasonal to interannual time scales;
- provide a set of data useful for developing and improving the predictive models of the ocean–atmosphere coupled system;
- document interactions between tropical Atlantic climate and variability outside the region (e.g., ENSO or the North Atlantic Oscillation); and
- design, deploy, and maintain an array of moored oceanic buoys and collect and transmit a set of oceanic and atmospheric data, via satellite in real time, to monitor and study the upper ocean and atmosphere of the tropical Atlantic.

ACCOMPLISHMENTS. *Technological and organizational.* PIRATA provides free, open, and timely access to data relevant to tropical Atlantic climate studies. PIRATA places high priority on

AFFILIATIONS: Bourlès—LEGOS, IRD, Cotonou, Benin; Lumpkin—NOAA/AOML, Miami, Florida; McPhaden—NOAA/PMEL, Seattle, Washington; Hernandez—IRD, Mercator-Océan, Toulouse, France; Nobre—INPE/CPTEC, Sao Paulo, Brazil; Campos—IOUSP, Sao Paulo, Brazil; Yu—DPO/WHOI, Woods Hole, Massachusetts; Planton—Météo-France, CNRM/GAME, Toulouse, France; Busalacchi—ESSIC, University of Maryland, College Park, College Park, Maryland; Moura—INMET, Brasília, Brazil; Servain—LOCEAN, IRD/FUNCEME, Fortaleza, Brazil; Trotte—DHN, IOC/UNESCO, Niteroi, Brazil
CORRESPONDING AUTHOR: Bernard Bourlès, IRD/SCAC, Ambassade de France à Cotonou, 128 bis rue de l’Université, 75351 Paris 07 SP, France
E-mail: bernard.bourles@ird.fr

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high-resolution time series measurements of surface heat and moisture fluxes, sea surface temperature and salinity, and subsurface temperature and salinity in the upper 500 m, collected by a network of Autonomous Temperature Line Acquisition System (ATLAS) moored buoys (see sidebar). The configuration of the original 12 PIRATA buoys (Servain et al. 1998) was chosen to resolve the two main modes of tropical Atlantic climate variability: the equatorial mode and the meridional mode (Zebiak 1993; Chang et al. 1997). Two buoy sites (2°S, 10°W and 2°N, 10°W) were rapidly decommissioned in 1999 because of fishing vandalism. As explained in more detail in the section titled "PIRATA expansions," extensions to the backbone array were anticipated in the original PIRATA science and implementation plan. Three extensions (in the Southwest, the Northeast, and the Southeast) were initiated in 2005 and the present PIRATA network is shown in Fig. 1.

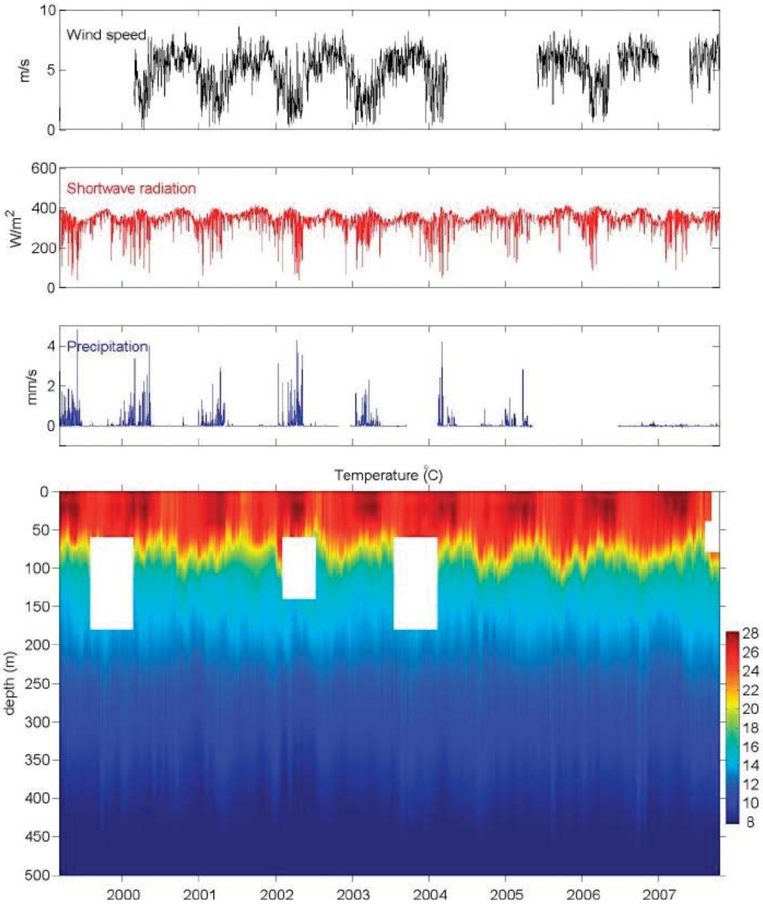

Fig. 2. PIRATA time series of atmospheric and oceanic properties at 0°, 23°W. Gaps indicate missing data due to instrument failure or vandalism.

As an example of the time series collected by PIRATA buoys, Fig. 2 displays the evolution of daily averaged wind speed, shortwave radiation, precipitation, and the vertical distribution of temperature at 0°, 23°W. These time series demonstrate intraseasonal to interannual variability superimposed on a strong seasonal cycle. PIRATA moorings are ideally suited to resolve variability across these time scales.

PIRATA data return percentages from the deployment of the first buoy in September 1997 to the end of December 2006 were 72% in real time and 79% when delayed mode data are accounted for (Table 1). This difference reflects a combination of Service Argos transmission failures and instrumental prob-

ATLAS BUOYS

ATLAS moored buoys measure surface meteorological variables (wind direction and speed, air temperature and humidity, rainfall and solar radiation) and oceanic properties between the surface and 500 m. PIRATA mooring hardware, sensor types, calibration procedures, temporal sampling and resolution, data processing, accuracy standards, and data transmission and dissemination protocols are identical to those of ATLAS moorings in the Pacific TAO array. TAO project Web pages maintained by NOAA at www.pmel.noaa.gov/tao/ contain an extensive description of technical details on the moorings. ATLAS mooring technology and protocols were developed over a 25-yr period to ensure the highest quality data for climate research and operational applications. Daily mean observations are available in near real time at www.pmel.noaa.gov/tao/data_deliv/deliv-pir.html and www.cptec.inpe.br/, via Service Argos and Brazilian satellite transmissions. Daily mean subsurface data and hourly meteorological data at the times of satellite overpasses are also placed on the GTS by Service Argos for real-time distribution to operational centers. Measurements carried out at high frequency (from 1 min to 1 h, depending on the parameters) are stored internally and recovered during maintenance operations before being processed, calibrated, and made available to the community.

lems that cause occasional loss of real-time transmission to internally logged data. The spatial pattern of data return rate reflects to a large degree the effects of fishing vandalism (Fig. 3). This problem is not unique to the Atlantic, as similar problems arise in the Pacific and Indian Ocean arrays in regions where tuna fishing activity is intense. The greatest PIRATA losses are in the eastern equatorial cold tongue region of the Gulf of Guinea, where biological productivity is high and data return is around 50% (the lowest data return of 25%–40% refers to decommissioned sites at 2°N and 2°S along 10°W). Data return is typically 75%–90+% in the central, western, and southern portions of the array.

Data return percentage also varies by sensor type, as summarized in Table 1. Rain and conductivity sensors are sensitive to noise contamination and fouling in the marine environment (e.g., biological growth for conductivity and bird guano for rainfall). In addition, rainfall and wind sensors are high on the buoy tower and relatively exposed to tampering by vandals and to damage from fishing vessels when they tie up to the buoy.

The number of PIRATA data files delivered via the Web is shown in Fig. 4. The rapidly increasing demand for these data reflect the growing visibility of PIRATA in the research community and the increasing value of the data for climate studies as the length of the time series increases. In 2006, the most recent year for which statistics are available, 52,854 PIRATA data files were delivered via the National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory (NOAA/PMEL) PIRATA data delivery Web site.

Service Argos places ATLAS mooring data on the Global Telecommunication System (GTS) for real-time distribution to operational weather, climate, and ocean forecasting centers. Prior to February 2005, around 300–800 hourly meteorological data were received at these centers. From late 2004 to late 2005, PIRATA data throughput on the GTS increased by a factor of 4–5 for three reasons: a) Service Argos began to deliver data to users using a multisatellite relay system instead of a two-satellite relay system at no extra charge, allowing increased temporal coverage at all sites. b) NOAA/PMEL reprogrammed its buoy data transmission firmware to transmit during four 4-h windows per day instead of the previous two 4-h windows. c) Three new PIRATA moorings were deployed as part of the Southwest Extension in August 2005, which led to an additional 30% increase in throughput. In its present configuration, the PIRATA array should continue to provide 4,000–4,500 unique hourly values per month of wind and other surface meteorological variables to the GTS. PIRATA GTS data have thus grown in value for constraining operational weather, climate, and ocean analyses and forecasts, and will continue to do so into the future.

PIRATA also includes two automatic meteorological stations at Fernando de Noronha Island and St. Peter and St. Paul Rocks, serviced by Brazil (two western green crosses in Fig. 1). Brazilian satellites collect data from both island stations at 3-h intervals; these data are subsequently made available in near–real time via the Internet. The installation of a tide gauge is planned at St. Peter and St. Paul Rocks in 2008.

At São Tomé (0°, 6°30'E), a tide gauge station was installed by the French Institut de Recherche pour le Développement (IRD) in 1989 to meet the requirements of climate research programs (eastern green cross in Fig. 1). The gauge measures sea level, sea temperature and salinity, and atmospheric pressure. These measurements are taken hourly and transmitted daily via Service Argos. Another meteorological station has been installed at São Tomé Island in the framework of the African Monsoon Multidisciplinary Analyses (AMMA) program, and constitutes an eastern continuation of PIRATA meteorological measurements along the equator. Since October 2006, the IRD Center at Brest, France, has put these data on the GTS for real-time transmission.

In order to monitor mixing and circulation in the ocean surface layer, the 0°, 23°W ATLAS site also includes an acoustic Doppler current profiler (ADCP) that continuously measures the two horizontal components of the current with 4-m vertical resolution, from the surface to approximately 100-m depth.

Table 1. Percentage of data return in real-time and delayed mode by sensor type for Sep 1997 to Dec 2006 (SW rad: shortwave radiation; RH: relative humidity; Air *T*: air temperature; SST: sea surface temeprature; *T*(*z*): subsurface temperature).

	Winds	SW rad	Rain	RH	Air T	SST	*T*(*z*)	Conductivity	Total
Real time	70	81	68	79	79	73	72	66	72
Delayed	75	82	73	85	85	82	82	72	79

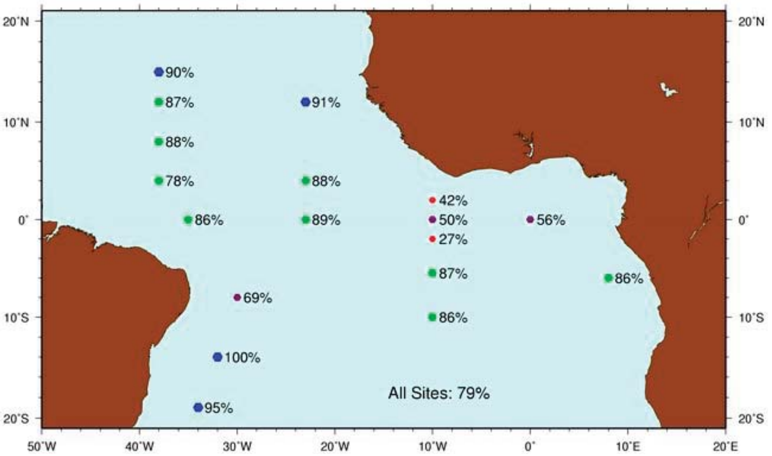

FIG. 3. PIRATA mooring delayed mode data return rate, Sep 1997–Dec 2006. Colors indicate data return rate of 0%–50% (red), 50%–75% (purple), 75%–90% (green) and 90%–100% (blue).

These in situ measurements have been collected since the end of 2001 and are available to the scientific community from the PIRATA Web site after mooring recovery and data postprocessing.

Each ATLAS buoy is serviced approximately once a year. A large number of supporting measurements such as temperature and salinity profiles, upper-layer currents, and meteorological properties are measured during dedicated PIRATA cruises. At present, 31 PIRATA cruises have been conducted by Brazil (responsible for the maintenance of the five western backbone buoys and the three Southwest Extension buoys), France (responsible for the maintenance of the five eastern backbone buoys and of the current meter mooring at 0°, 23°W), and the United States (responsible for the maintenance of the four Northeast Extension buoys).

Contributions to tropical Atlantic climate and ocean science. The North Atlantic has historically been the most heavily observed region of the world's oceans; the same cannot be said for other portions of the Atlantic. Two ingredients are needed to improve prediction of the tropical Atlantic coupled climate system: advances in understanding the physical processes limiting forecast skill and enhanced observations in the tropical Atlantic required by the forecasts. From experience in the Pacific, it is known that sufficient subsurface data are of major importance to develop and test coupled prediction systems, and to initialize forecasts of evolving conditions. In situ surface flux observations are needed to evaluate the surface fluxes from numerical weather prediction and coupled climate models. As described in this section, the PIRATA array backbone has provided sustained observations used i) for a better description and understanding of the climate tropical Atlantic variability and circulation, ii) to improve ocean numerical model simulations, and iii) in the routine generation of assimilated ocean products for both state estimation and initialization of coupled atmosphere–ocean prediction models (e.g., Brasseur et al. 2005).

MERIDIONAL AND EQUATORIAL MODES OF VARIABILITY. Interannual variability in the tropical Atlantic can be described principally by two modes: an equatorial mode associated with SST anomalies in the eastern equatorial Atlantic, analogous in some respects to the ENSO mode in the equatorial Pacific, and a meridional mode associated with SST anomalies on either side of the ITCZ (Zebiak 1993; Chang et al. 1997). The meridional mode generally achieves its maximum development during boreal spring (March–April) when the ITCZ is at its southernmost position, whereas the equatorial mode is at its maximum during boreal summer (June–August), when the ITCZ is at its northernmost position (e.g., Xie and Carton 2004; Chang et al. 2006). The four ATLAS buoys located along the equator (35°W, 23°W, 10°W, and 0°) have been used to estimate the zonal fluctuations of the thermocline depth (vertical thermal structure), as well as the SST

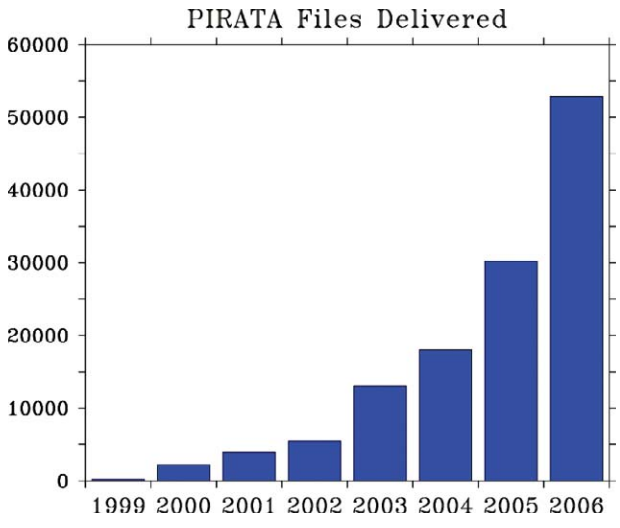

FIG 4. PIRATA files delivered over the period 1999–2006.

zonal gradient, which are both associated with the east–west equatorial mode. A 2-month lagged relationship between the two modes (equatorial mode leading) has been statistically observed (Servain et al. 1999) and also discussed from numerical model results (Servain et al. 2000; Murtugudde et al. 2001). Using a 1999–2000 PIRATA dataset, a first check of that relationship was performed by Servain et al. (2003).

Okumura and Xie (2006) used PIRATA and other datasets to define a new mode of tropical Atlantic variability that is similar to the equatorial mode but peaks in November–December. The new mode develops in association with an anomalous intensification of the equatorial easterlies, which causes upwelling and cooling in the Gulf of Guinea. This new mode significantly affects rainfall in the eastern basin on interannual time scales and can subsequently develop into a meridional mode during the following March–April. Okumura and Xie's (2006) results are thus broadly consistent with the 2-month lagged relationship between the conventional equatorial mode and the meridional mode noted in Servain et al. (1999).

Processes Governing Seasonal and Interannual Variability of SST. The ITCZ reaches 0°, 23°W in late boreal winter through early boreal spring. The ITCZ is a region of deep atmospheric convection, heavy rainfall, low solar heating, and weak mean wind speed (Fig. 2). The seasonal location of the Atlantic warm water pool (SST >27°C) is tightly coupled with the seasonal migration of the ITCZ. Many studies have focused on how the atmosphere interacts with the ocean to create the sea surface warming beneath the ITCZ. Early studies (e.g., Molinari et al. 1985; Hastenrath and Merle 1987) using archived ocean subsurface data showed that the seasonal surface warming over much of the tropical Atlantic basin is not always associated with increased subsurface heat content due to thermocline deepening. This led to the hypothesis that the major contributor to the surface mixed layer heat budget is the net surface heat flux through the air–sea interface rather than vertical exchange of heat with the thermocline (Niller and Kraus 1977). However, given that the tropical atmosphere and ocean are a coupled system, air–sea feedbacks should also be a major factor in SST seasonality. One clear example is the formation of the equatorial cold tongue in the eastern equatorial Atlantic, where the SST change is governed by the upwelling of cold water induced by monsoonal winds (Mitchell and Wallace 1992).

In order to understand the relative roles of air–sea heat fluxes and ocean dynamics in setting seasonal SST variations, Yu et al. (2006) used analysis products from the Objective Analyzed Air–Sea Fluxes (OAFlux) project (Yu and Weller 2007) and the International Satellite Cloud Climatology Project (ISCCP); (Zhang et al. 2004). They found two regimes (Fig. 5), delineated by correlation coefficients of 0.9 (significant at 99% confidence level) between net heat flux and the SST change rate. High correlation coefficients (higher than 0.9) in the region outside the equatorial band 5°S–10°N suggest the dominant role of air–sea heat fluxes, while low coefficients (less than 0.9) in the equatorial band indicate a significant role played by ocean dynamics. Of particular interest is the zonal alignment of very low coefficients along two narrow bands, one on the equator and the other slightly north of the equator, associated with the location of the ITCZ.

Foltz et al. (2003) evaluated the role of surface fluxes, lateral advection, and vertical entrainment in the seasonal heat balance at the PIRATA backbone mooring sites. They found that SST variations are predominantly driven by the seasonal cycle of latent heat loss and shortwave gain at northwestern (12°N, 38°W) and southeastern (10°S, 10°W) sites. At the equatorial sites (10°, 23°, and 35°W), latent heat variations were less significant, while horizontal heat advection and vertical entrainment play a major role. These conclusions agree qualitatively with the results of Yu et al. (2006; Fig. 5) and with the model study of Carton and Zhou (1997), although details differ.

PIRATA data have been instrumental in identifying the factors that contributed to the record high SSTs in the tropical North Atlantic in 2005. These high SSTs were probably one of the factors that contributed to the unusual 2005 Atlantic hurricane season, which was the most active and destructive on record. Foltz and McPhaden (2006) performed a mixed-layer heat budget analysis based on PIRATA and other buoy data and found that the primary cause of the anomalous warming in 2005 was a weakening of the northeasterly trade winds and an associated decrease in latent heat loss from the ocean. Important secondary factors include changes in shortwave radiation due to cloudiness and horizontal oceanic heat advection. Foltz and McPhaden (2008) also used PIRATA data to demonstrate that that dust-induced changes in shortwave radiation did not play a major direct role in the cooling that led up to the unexpected quiet 2006 Atlantic hurricane season, as hypothesized by Lau and Kim (2007). The anomalous cooling that occurred was driven primarily by wind-induced latent heat loss, with horizontal oceanic heat advection and shortwave radiation playing secondary roles.

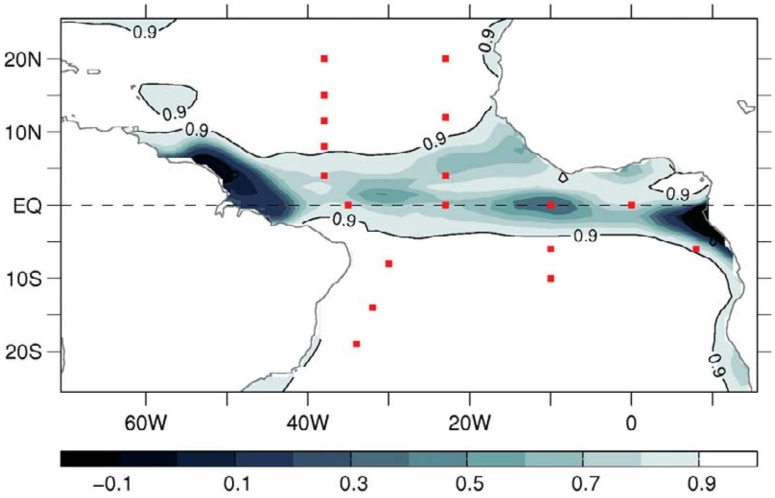

Fig. 5. Correlation between net air–sea heat flux and the rate of seasonal SST change (adapted from Yu et al. 2006).

Validation of Satellite and Model Products. Satellite data products (scatterometer winds, SST, surface topography, and rainfall) need to be evaluated against in situ measurements. In addition, numerical weather prediction (NWP) models need to assimilate air–sea meteorological variables to improve prediction skills, and NWP-reanalyzed outputs need to be validated against in situ benchmark time series to assess their accuracy for climate studies. The primary source for these in situ data is the GTS, which distributes observations from a network of fixed buoys, drifting buoys, and ships in real time. A secondary data source is delayed-mode, quality-controlled, postcalibrated fixed buoy measurements. The PIRATA array, along with buoy data from the National Data Buoy Center (NDBC) and TAO, establishes a central database for these two-phase validations (Ebuchi et al. 2002; Sun et al. 2003; Gentemann et al. 2004).

Equatorial Currents. The equatorial Atlantic exhibits a complex system of zonal currents at different depths and latitudes, along with areas of upwelling (upward flow) and subduction (downward flow) (e.g., Bourlès et al. 2002; Stramma et al. 2003; Schott et al. 2004; Lumpkin and Garzoli 2005; Fig. 6). The eastward currents are principally fed in the western equatorial Atlantic through retroflection of the North Brazil Current, but also through subsurface recirculation of the North Equatorial Current. They advect a considerable amount of warm and salty water eastward. Their transports and variability are of particular importance for the global thermohaline circulation, and they contribute to the mixed-layer balance and sea surface temperature variability.

Several studies dedicated to describing this circulation and its variability have been made possible by PIRATA cruises. Using measurements collected from many oceanographic cruises including PIRATA cruises, Schott et al. (2003) and Molinari et al. (2003) described the mean circulation along 35°W. They estimated a mean Equatorial Undercurrent (EUC) transport of about 21 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}) and demonstrated, for the first time solely from in situ data, the existence of vertical tropical circulation cells. At the same longitude, Urbano et al. (2008) determined that the North Equatorial Countercurrent was split into two branches.

Studies of the EUC variability have been made possible due to the PIRATA ADCP time series at 0°, 23°W (Provost et al. 2004; Grosdky et al. 2005; Provost et al. 2005; Brandt et al. 2006). Brandt et al. (2006) estimated a mean EUC transport of 14.1 Sv, confirming its decrease from west to east. Significant seasonal and intraseasonal cycles in both components of the horizontal current have also been demonstrated. The observed vertical displacements

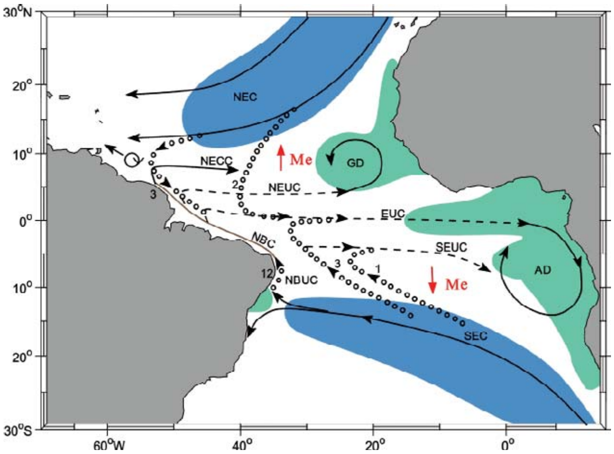

Fig. 6. Schematic of the surface (solid lines) and subsurface (dashed) circulation in the tropical Atlantic (from Schott et al. 2004). NEC: North Equatorial Current; NBC: North Brazil Current; SEC: South Equatorial Current; NECC: North Equatorial Countercurrent; EUC: Equatorial UnderCurrent; NEUC: North Equatorial UnderCurrent; SEUC: South Equatorial UnderCurrent; NBUC: North Brazil UnderCurrent; GD: Guinea Dome; AD: Angola Dome. Also represented are subduction (blue) and upwelling (green) areas, and wind-driven mean transport (red arrows "Me").

of the EUC appear to be associated with the seasonal cycle of the zonal wind field, but a full dynamical interpretation is still pending.

PIRATA ship-based ADCP data and the ADCP mooring also permit validation and improvement of equatorial Atlantic Ocean general circulation models. Such model improvements are particularly relevant for seasonal climate prediction, since most coupled ocean–atmosphere models exhibit strong systematic errors over the equatorial Atlantic (Davey et al. 2002). Giarolla et al. (2005) showed that the Modular Ocean Model (MOM) was able to simulate both strength and depth variations of the EUC (Fig. 7). A reference simulation of the French model CLIPPER has been conducted by tuning the momentum mixing parameters in order to reproduce the observed EUC. Arhan et al. (2006) used this reference simulation to diagnose the annual cycle of the EUC. They found two well-defined EUC transport maxima, one during boreal summer and autumn in the central part of the basin, and the other in boreal spring near the western boundary. They suggested that two different dynamical regimes drive the EUC seasonal cycle: in summer and autumn, the simulated EUC is mostly driven by equatorial zonal forcing, and supplied from the ocean interior; in winter and spring, it is driven by remote forcing through the rotational wind component, and supplied from the western boundary currents. Peter et al. (2006) also used this reference simulation to study the mass and heat balance in the mixed layer over the whole tropical Atlantic basin. They showed that, at the equator, the SST balance is the result of both cooling by subsurface processes (through vertical mixing at the base of the mixed layer, vertical advection, and entrainment) and heating from the atmospheric and by eddies (mainly tropical instability waves). Horizontal advection by time-mean currents plays only a minor role in the simulated heat budget. Outside of the equatorial band, the simulated SST variability is mainly governed by atmospheric forcing.

Ocean Predictive Models. Over the time period of PIRATA, ocean state estimation has progressed from a research activity to the operational generation of ocean products initiated under the framework of the Global Ocean Data Assimilation Experiment project (GODAE; see www.godae.org/). For many years, PIRATA has been a major source of tropical Atlantic observations to research assimilation schemes for the global ocean, such as the Simple Ocean Data Assimilation (SODA) of Carton et al. (2000a,b). The success of such efforts has paved the way for the development of operational ocean products.

For example, since 2001, the French operational oceanography project Mercator (see www.mercator-ocean.fr/) has provided weekly ocean estimates and forecasts. PIRATA buoy oceanic measurements are received via the GTS, averaged daily and quality controlled in real time by the French data center Coriolis (see www.coriolis.eu/org/), and assimilated along with other in situ and satellite data.

The operational oceanic community assesses PIRATA and other in situ, real-time data for their oceanographic operational usefulness. As an example, Fig. 8 shows the data type and amount transmitted in real time in 2005. There is lower data return in the eastern side of the basin, consistent with Fig. 3, and an increased data return in the southwestern tropical Atlantic due to the three Southwest Extension moorings. The number of expendable bathythermograph (XBT) profiles, which go as deep as 800 m along regular ship lines, is uneven in time. Conversely, the number of Argo profiling floats (autonomous sensors of temperature and salinity, profiling from the surface to 2,000-m depth; see www.argo.ucsd.edu/) has doubled from 2001 to 2005. Figure 8 illustrates the complementary nature of these different data: Argo floats provided ~3,000 temperature and salinity profiles to a depth of 2,000 m, mostly west of 10°W and south of 10°N, while PIRATA moorings continuously monitor the upper 500-m depth at chosen, fixed locations.

Since 2003, Mercator has been running an operational system over the tropical and North Atlantic,

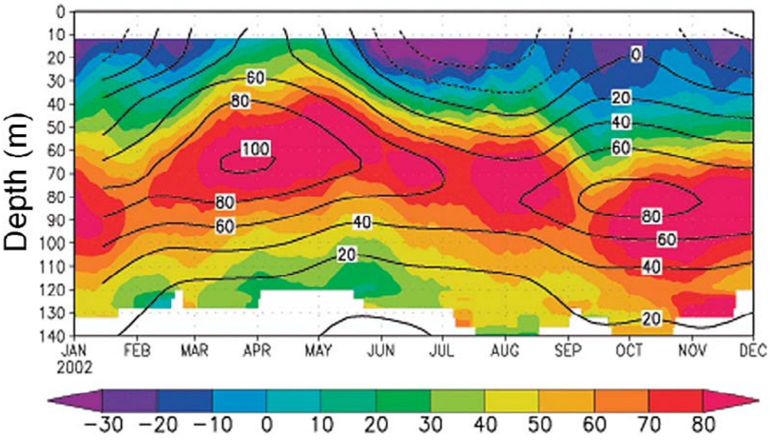

Fig. 7. Thirty-day running means of observed (PIRATA ADCP; colors) and simulated (MOM model; contours) zonal velocities at 0°, 23°W during 2002 (from Giarolla et al. 2005).

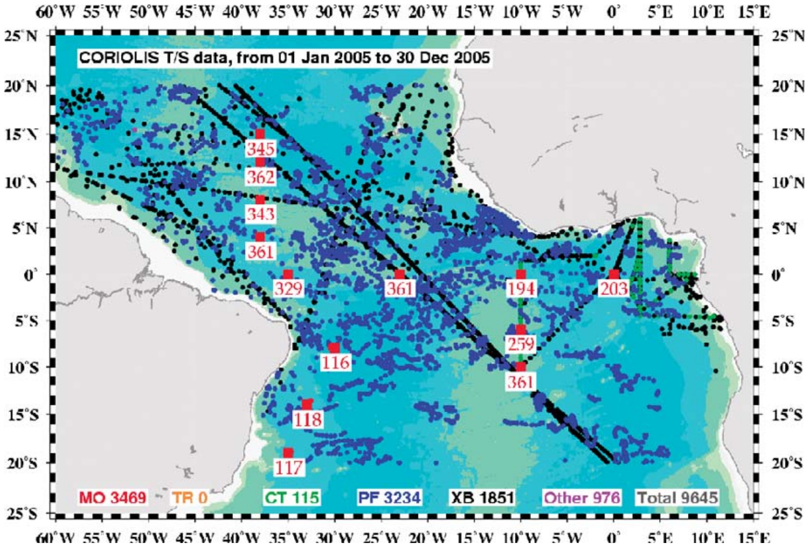

Fig. 8. Available subsurface temperature and salinity data from the Coriolis database transmitted in real time to Mercator in 2005. In the 20°N/20°S and 60°/15°W area, data are plotted and counted by type: red, blue, and black for PIRATA mooring daily data (MO), Argo profiling float (PF), and XBT Ship of Opportunity programs (XB), respectively. CT (green) corresponds to CTD data. "Other" means some specific mooring data. Below each PIRATA mooring, the corresponding number of daily profiles transmitted by Coriolis over the year is indicated.

corrected weekly by assimilating sea level (from satellite altimetry), SST, and temperature and salinity at depth (Etienne and Benkiran 2007). The PIRATA array supplies daily means of observed upper-ocean temperature and salinity at multiple locations, which have a positive influence on operational hindcasts and forecasts. These observations help the operational models to properly characterize the dynamics and to constrain estimates of heat content, a key climate parameter influencing the climate system. PIRATA moorings' high temporal sampling is critical to avoid misrepresenting tropical instability waves and equatorial waves in the models.

To evaluate PIRATA data impact on ocean circulation descriptions given by hindcasts and real-time forecasts, sensitivity studies were carried out using the Mercator system (named PSY1V2). Subsequently, the relative contributions of the different type of data (moorings, XBTs, and Argo floats) were also assessed. This system is based on a 1/3° resolution Océan Parallélisé (OPA) model (Madec et al. 1998) of the tropical and North Atlantic, from 70°N to 20°S, forced by daily European Centre for Medium-Range Weather Forecasts (ECMWF) wind stresses, heat, and salt fluxes (see the "science" topic in www.mercator-ocean.fr). The system is operated every week, starting by hindcast–nowcast mode two weeks backward in time, when available observations are gathered for sequential assimilation; the model is then run over 2-week forecasts (details are given in Etienne and Benkiran 2007). In Fig. 9, results of an impact study for 2003 data are shown. Two dedicated runs were performed, one run with all available data, the second with all but the daily PIRATA data. Both temperature and salinity model field were improved using PIRATA data, with more impact on salinity. The thermocline's heat content, position, and vertical extent are better represented when assimilating PIRATA data (not shown). Temperature differences below the thermocline are also reduced, demonstrating the positive impact of PIRATA temperature sensors at depth. Correcting the water masses, and thus the density gradients, also improves the zonal current structure. Using PIRATA data, the full tropical dynamics is better constrained, and all currents are better positioned both meridionally and vertically. For example, the slope and intensity of the EUC are realistically strengthened when using PIRATA data, and dubious currents near the surface or at depth are also reduced (Fig. 9).

Impact studies such as these indicate that the frequency and extent of the PIRATA measurements constrain the upper-ocean thermal structure where equatorial dynamics require high-resolution temporal sampling. Such studies can also be conducted to measure the future impact of the network extensions.

Prediction of the Coupled Atlantic Climate System. As with ocean data assimilation, the surface meteorological fields from the PIRATA buoys are assimilated in near–real time (via GTS) into predictive atmospheric models, for example, by the weather forecasting departments of Météo-France, ECMWF, Met Office, and the National Centers for Environmental Prediction (NCEP). Since the network was established, the number of PIRATA observations of sea surface temperature, wind, and air temperature being assimilated has been rising steadily. In 2005, the Centre National de Recherche Météorologique (CNRM) of Météo-France conducted an impact study of PIRATA data in the data assimilation system of Météo-France. The impact study does not provide the

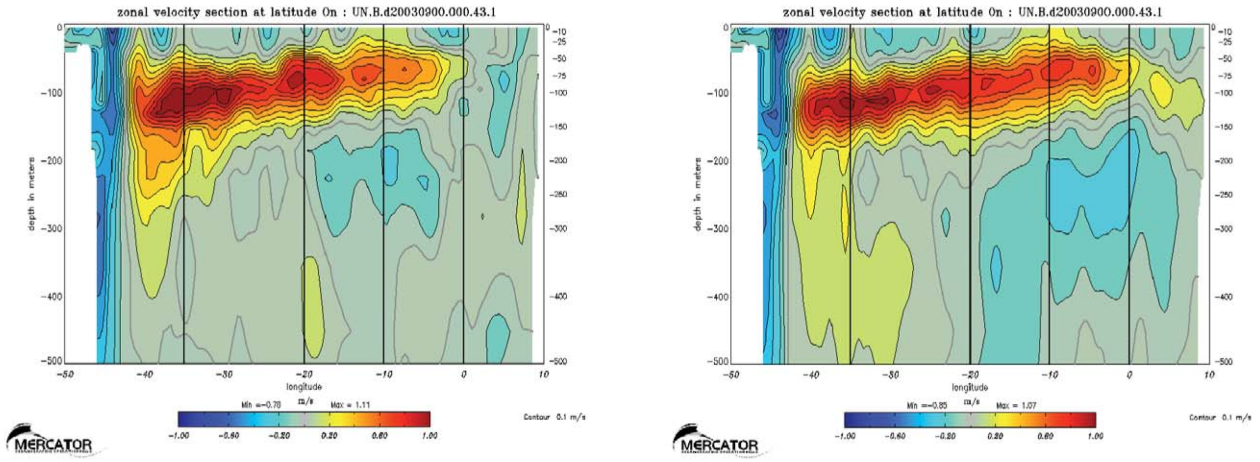

Fig. 9. Equatorial vertical section of monthly averaged (Sep 2003) zonal velocity, (left) with and (right) without assimilating PIRATA data. The vertical black lines indicate the location of the PIRATA moorings.

specific impact of the PIRATA dataset on the model forecast scores over the region. However, the root-mean-square difference between the PIRATA observations and the model guess field resulting from a 6-h forecast provides a measure of the potential impact of the assimilated data if given sufficient weight in the assimilation scheme. A typical value of the difference is 0.4 K for SST, 1.3 m s^{-1} for wind speed, 18° for wind direction, and 0.6 K for air temperature, significantly higher than measurement error or sensor accuracy (see the PIRATA Web site for more details on sensor accuracies). This result shows that PIRATA data have significant potential for improving the initial analysis of weather forecasting in the region. Another study conducted at ECMWF (Bidlot 2005) pointed out the need to account for the exact height of wind measurement in the data assimilation system. This study indicated that assimilating surface winds from moored and drifting buoys appears to improve the medium-range forecast scores (5 to 10 days) in most parts of the tropical Atlantic.

PIRATA data are used in operational seasonal forecasts, via data assimilated into oceanic and atmospheric models that provide initial conditions for coupled ocean–atmosphere models. In particular, specific data assimilation systems were implemented at ECMWF for newly provided multimodel seasonal forecasts using ECMWF, Met Office, and Météo-France coupled models. In the United States, NCEP has recently initiated an ocean analysis for the Atlantic Ocean in support of both operational oceanography and coupled ocean–atmosphere climate forecasting. For monthly forecasts, a real-time ocean analysis is required. An analysis of the impact of PIRATA observations on the ECMWF ocean assimilation system has been performed recently, but as in the case of NWP, the impact on the seasonal forecast scores has not been analyzed specifically (M. A. Balmaseda 2005, personal communication). Because of systematic model errors, interannual variability in the analysis is affected by changes in the observing system. PIRATA data have a large positive impact on the analyzed interannual variability (Segschneider et al. 2000; Balmaseda 2002, 2003; Stockdale et al. 2006; Vilard et al. 2007).

UNANTICIPATED ADVANCES. PIRATA has contributed to advances in areas not fully anticipated at its inception. For example, surface heat fluxes and SST variability were highlighted in the original science plan, but no explicit focus was initially placed on freshwater fluxes and ocean salinity variations. PIRATA was conceived and designed at a time of technological evolution, as rain and salinity measurements were becoming part of the instrument suite (Milburn et al. 1996). The accuracy of data from these sensors (e.g., Serra et al. 2001; Delcroix et al. 2005) has permitted studies of the space and time scales of sea surface salinity in the Atlantic (Delcroix et al. 2005) and the role of the barrier layer and its importance in the surface layer heat balance (Pailler et al. 1999; Foltz and McPhaden 2005). Salinity-related density fluctuations have been shown to strongly impact baroclinic energy conversion estimates due to tropical instability waves (Grodsky et al. 2005). PIRATA data have also contributed to studies of open-ocean rainfall variability, allowing resolution of the diurnal cycle of rainfall over the ocean (Serra and McPhaden 2003, 2004). Rainfall and salinity measurements from PIRATA have allowed a diagnosis of the seasonal cycle of the mixed-layer salt balance in the western tropical Atlantic (Foltz et al. 2004). Unlike the heat balance, which is primarily one dimension off the equator in this region, advection by horizontal currents is highly significant in the mixed-layer salt balance (Foltz et al. 2003).

PIRATA EXPANSIONS. Extensions to the backbone array were anticipated in the original PIRATA science and implementation plan. The goal of an extension is to enlarge the scope of the science and to improve the quality of regional climate predictions. Three extensions have been proposed and are already implemented or being implemented (Fig. 1).

Brazil proposed the PIRATA Southwest Extension (PIRATA-SWE); (Nobre et al. 2004). PIRATA-SWE was inaugurated in August 2005 with three ATLAS buoys moored at 8°S, 30°W; 14°S, 32°W; and 19°S, 34°W. The data transmitted by the three ATLAS systems of the PIRATA-SWE are collected by both the Service Argos satellites and the Brazilian data collection satellites and made available in the GTS by Service Argos and independently at the Centro de Previsão de Tempo e Estudos Climáticos/Instituto Nacional de Pesquisas Espaciais (CPTEC/INPE) Web page (www.cptec.inpe.br). The data from the PIRATA-SWE are used at CPTEC to assess the weather forecast skill of surface variables with its suite of atmospheric and coupled ocean–atmosphere models. This extension will allow monitoring the bifurcation of the Southern Equatorial Current (SEC) into the southward Brazil Current and the northward North Brazil Current, which is of fundamental importance in understanding the meridional heat transport in the Atlantic.

South Africa, Angola, and Namibia proposed the PIRATA Southeast Extension (PIRATA-SEE); Rouault 2004). It was a 1-yr demonstration project, funded by the Benguela Current Large Marine Ecosystem program (BCLME). Besides gaining information on the physics of the seasonal cycle of SST, ocean surface heat content and other key parameters, the extension could be used to monitor Benguela Niños (Shannon et al. 1986; Rouault et al. 2007) or other oceanic warm events detrimental to society as they affect the region. PIRATA-SEE was first implemented as a pilot phase at 6°S, 8°E (from June 2006 to June 2007) with an ATLAS mooring deployed and subsequently recovered on French PIRATA cruises. A permanent PIRATA-SEE (with perhaps one or two additional ATLAS moorings) would have applications to marine ecosystem processes, fisheries–environment interaction, climate variability, and regional forecasting.

The United States proposed a PIRATA Northeast Extension (PIRATA-NE) in 2005 (Lumpkin et al. 2006). It consists of three ATLAS systems at 23°W, at latitudes of 4°, 11.5°, and 20°N, and a fourth system at 20°N, 38°W. The PIRATA-NEE was implemented in June 2006 and May 2007 during two dedicated U.S. cruises. PIRATA-NEE observations capture processes impacting interannual variations in the seasonal migration of the eastern ITCZ; the impacts of intraseasonal variability on the development of SST anomalies in the region; biases in remotely inferred air–sea fluxes and SST due to, for example, Sahel dust outbreaks; and the dynamics governing evolution of upper-ocean heat in the tropical North Atlantic region where atmospheric easterly waves can develop into hurricanes.

PIRATA AND THE TROPICAL ATLANTIC OCEAN OBSERVING SYSTEM: LINKS TO OTHER PROGRAMS. Prior to PIRATA, the main source of sustained observations in the tropical Atlantic was the Ship of Opportunity XBT and surface drifting buoy programs, each with their attendant sampling limitations. The addition of Argo floats has complemented these data. Combined with time series measurements at the PIRATA mooring sites, this mix of complementary observational platforms has become, de facto, the Tropical Atlantic Ocean Observing System.

PIRATA is of particular value in providing large-scale long-term context for limited duration research field programs such as the Tropical Atlantic Climate Experiment (TACE) and the African Monsoon Multidisciplinary Analysis (AMMA). PIRATA is also a contribution to the Ocean Sustained Interdisciplinary Timeseries Environment observation System (OceanSITES) program (www.oceansites.org/), which aims to establish a worldwide system of long-term, deep water reference stations measuring variables relevant to air–sea interaction and ocean variability. In addition, beginning in 2005, four PIRATA sites (15°N, 38°W; 0°, 23°W; 10°S, 10°W; 11.5°N, 23°W) have been heavily instrumented with additional oceanographic and meteorological instrumentation to provide improved estimates of surface heat, freshwater, and momentum fluxes as well as higher-vertical-resolution temperature and salinity data in the mixed layer. Current meters were also added to these mooring sites to directly measure mixed-layer velocities. These sites are located in key climatic regimes of the tropical Atlantic, namely, in the cold tongue of the central equatorial Atlantic (0°, 23°W) where mean SST is relatively low and variability related to Atlantic warm events is high, and in regions north and south of the equator where variations related to the interhemispheric SST gradient mode are large.

PIRATA cruises are an opportunity to carry out other measurements or instrument deployments in the framework of other international programs, in otherwise poorly sampled regions of the tropical Atlantic. These measurements and deployments constitute an important contribution to Argo and GODAE (and their French components Coriolis/Mercator) and the Global Ocean Observing System (GOOS). Shipboard thermosalinograph data collected during cruises are routinely incorporated into the Global Surface Underway Data (GOSUD) project archive. For example, since 2004, 40 satellite-tracked surface drifting buoys, provided by NOAA/Atlantic Oceanographic and Meteorological Laboratory (AOML) in the framework of the Global Drifter Program, and 45 Argo profiling floats were deployed in the Gulf of Guinea during French PIRATA cruises. PIRATA cruises are also opportunities to conduct seawater sampling for salinity, nutrients, O_2, CO_2, C_{13}, and O^{18}, and to carry out biogeochemical measurements in the framework of national and international programs.

In 2006, three quasi-simultaneous cruises were carried out in May–July in the tropical Atlantic Ocean, as part of three international programs: PIRATA, AMMA, and CLIVAR-Germany. The cruises were conducted by the United States (in the north and central parts of the basin), Germany (in the western and central parts of the basin), and France (in the eastern part of the basin). These cruises, resulting from an efficient linkage and collaboration between the three programs, allowed for the collection of an impressive amount of oceanic (currents, hydrology, tracers) and atmospheric (bulk meteorological parameters, turbulent fluxes, wind and ozone profiles, etc.) measurements (Lebel et al. 2008, manuscript submitted to *Ann. Geophys.*; Bourlès et al. 2007). The analysis of the datasets obtained during these cruises will provide valuable information about the air–sea exchanges and flux parameterization, and will allow for a better definition of measurements needed in the tropical Atlantic Ocean for a sustained observation system, of which PIRATA will constitute a main component.

CONCLUDING REMARKS. PIRATA has demonstrated that a multinational program with specific scientific goals and coordinated field operations can be carried out and maintained for the long term. The PIRATA array was successfully deployed and maintained during the 10 yr of its pilot and consolidation phases, and will now be sustained for the foreseeable future as part of GOOS and GCOS. PIRATA data are used for scientific research that contributes to a better understanding of tropical Atlantic climate variability. The data are also widely used in operational weather, ocean, and climate forecasting that potentially provide significant economic benefits to countries surrounding the basin, with implications for agriculture, public health, and water resource management. The major scientific objectives of PIRATA, and the array design itself, have evolved with our understanding of the tropical Atlantic climate system, due in part to the data provided by the moored buoy network. It is clear from these developments that PIRATA has advanced beyond a "Pilot" program. As such, the PIRATA Scientific Steering Group has redefined the PIRATA acronym to be "Prediction and Research Moored Array in the Tropical Atlantic."

This article has attempted to provide a perspective on PIRATA's origins, accomplishments, and future directions. By adopting strategies developed in the Pacific Ocean, PIRATA evolved through a unique multinational partnership into a major Atlantic contribution to the global ocean observational system in support of climate. Its success can be measured from the 2006 review conducted by CLIVAR and the OOPC, which stated that maintaining the array and supporting its extensions will "establish PIRATA as the main backbone of the Tropical Atlantic Observing System."

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