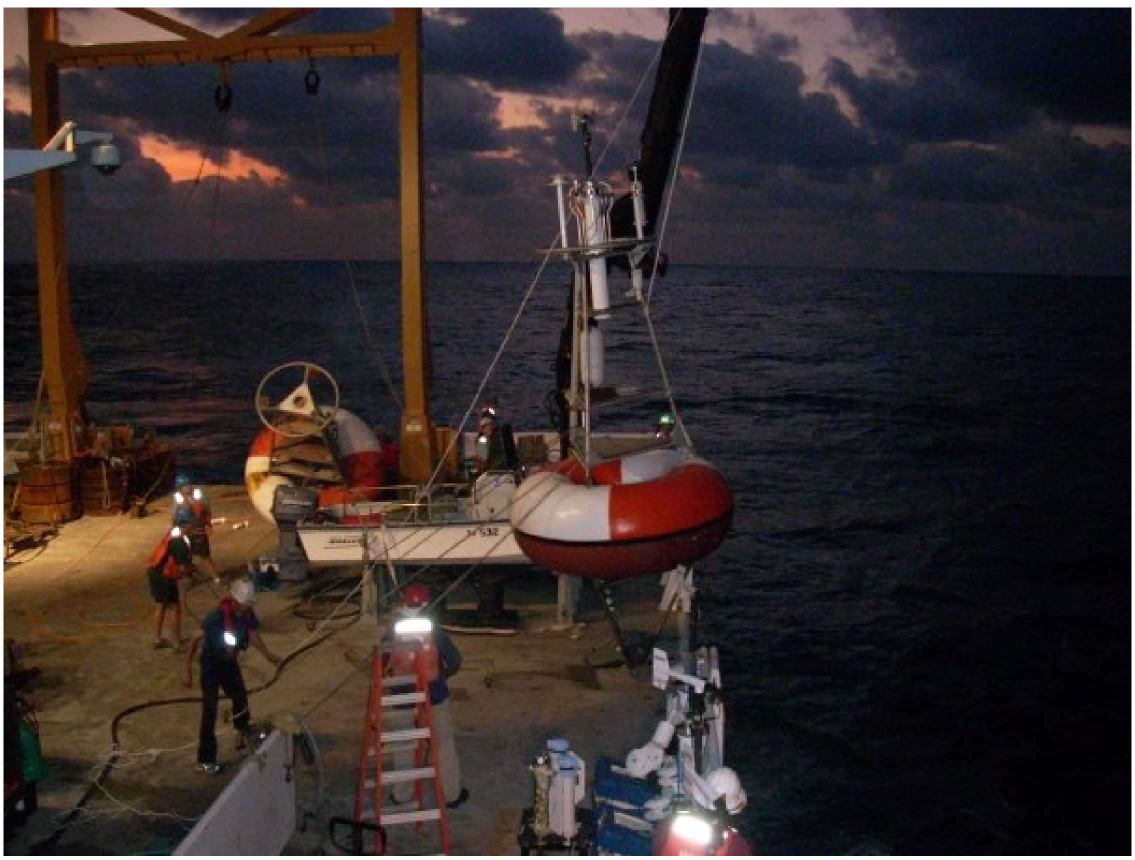
PIRATA Northeast Extension 2009 / AEROSE Cruise Report

NOAA Ship *Ronald H. Brown*
RB-09-04

11 July – 11 August 2009

Bridgetown, Barbados to Key West, Florida



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PIRATA Northeast Extension Scientific Party:

Oceanographic Observations:
Rick Lumpkin, Claudia Schmid, Grant Rawson, Kyle Seaton and Cheryl Brown (NOAA/AOML); Bob Oddo (NOAA Teacher at Sea)

ATLAS Moorings:
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M-AERI:
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AEROSE:
Nick Nalli (NESDIS/STAR); Vernon Morris, Everette Joseph, Adrian Flores, Ebony Roper, Jose Tirado, Lily Udumukwu (Howard Univ.); Chris Spells (Hampton Univ.); Adam Atia, Ibrahim Siddo (City College of New York); Luis Padilla (Univ. Puerto Rico); Mariana Guereque (Univ. Texas El Paso)

Note: this preliminary cruise report addresses only the hydrographic and mooring operations conducted during this PIRATA Northeast Extension cruise. Input by other scientists aboard the cruise will be included in the final cruise report. All figures and results reported here are subject to revision after quality control and final calibration.

OVERVIEW: the 2009 PIRATA Northeast Extension Cruise RB-09-04 was designed to collect a suite of oceanographic and meteorological observations in the northeast Tropical Atlantic, to service the northeast extension of the PIRATA array, and to repair a PIRATA backbone mooring at 0º, 23ºW. The cruise track was planned with a CTD section along 23ºW, a longitude cutting through the climatologically significant TNA (Tropical North Atlantic) region, including the southeast corner of the subtropical North Atlantic (a region of subduction for the subtropical cell circulation); the Guinea Dome and oxygen minimum shadow zone where the subtropical and tropical gyres meet, and the Tropical Atlantic current system and equatorial waveguide. All scientific goals of RB-09-04 were achieved.

We thank the crew and officers of the Ronald H. Brown for their tireless work and input before and during this cruise. Despite the additional task to service the 0° 23°W site, added to the already full cruise plan a few weeks prior to the scheduled commencement, all moorings were brought up to full operational capacity and all planned CTD casts were conducted. The FOO, Nicole Manning, did an excellent job of communicating with the scientific party and keeping operations running smoothly and successfully and expressed evident interest in the science. Our very sincere thanks go to the deck crew, led by Chief

Bosun Bruce Cowden. Their efficiency and expertise with ATLAS mooring operations was evident. We thank Chief Survey Technician Jonathan Shannahof for his continuous assistance and advice in CTD operations, Seabeam usage, XBT launches and various miscellaneous operations. We also thank all the rest of the crew who kept ship operations running smoothly, including the winch operators, Electronic Technician, galley crew, and all the other crewmen and women of the Brown. We happily note that the food has never been better on the Brown!

The overall attitude and morale of the crew was a dramatic and positive change from that experienced before the cancelled 2008 PIRATA cruise, and all parties responsible for the overall transformation of the ship should be commended for returning the Brown to operational status.

Introduction

1. PIRATA Northeast Extension (PNE)

The Pilot Research Moored Array in the Tropical Atlantic (PIRATA) is a three-party project involving Brazil, France and the United States that seeks to monitor the upper ocean and near surface atmosphere of the Tropical Atlantic via the deployment and maintenance of an array of moored buoys and automatic meteorological stations. The array consists of a backbone of ten moorings that run along the equator and extend southward along 10ºW to 10ºS, and northward along 38ºW to 15ºN.

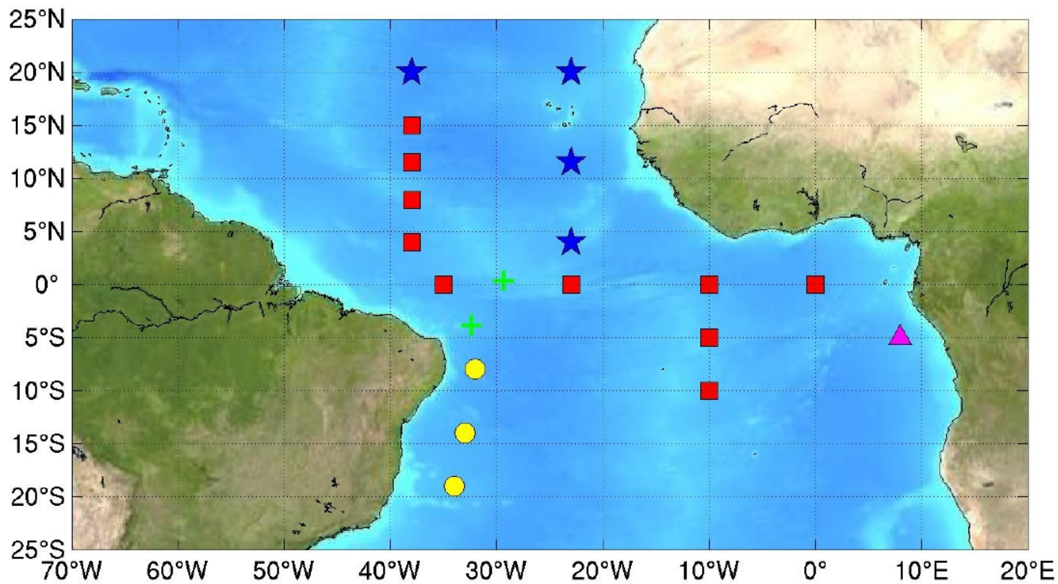

Fig. 1: The Tropical Atlantic PIRATA array: backbone (red squares), automatic meteorological stations (green +), Brazilian southwest extension (yellow circles), African southeast extension pilot site (magenta triangle), and the US Northeast Extension (blue stars).

The northeastern and north central Tropical Atlantic is a region of strong climate variations from intraseasonal to decadal scales, with impacts upon rainfall rates and storm strikes for the surrounding regions of Africa and the Americas. The northeastern Tropical Atlantic includes the southern edge of the North Atlantic subtropical gyre, defined by the westward North Equatorial Current (NEC), and the northern edge of the clockwise tropical/equatorial gyre defined by the North Equatorial Countercurrent (NECC). This area is the location of the North Atlantic's oxygen minimum zone at a depth of 400—600m. The size and intensity of this zone is a potential integrator of long-term North Atlantic circulation changes,, and the extremely low oxygen values have significant impacts on the biota of the region. The cyclonic Guinea Dome is centered near 10ºN, 24ºW, between the NECC and NEC in the eastern TA. It is driven by trade wind-driven upwelling, and may play an active role in modulating air-sea fluxes in this region.

The Tropical North Atlantic is the Main Development Region (MDR) of tropical cyclones. Many major hurricanes that ultimately threaten the eastern United States begin as atmospheric easterly waves that propagate off the African continent. Once over the MDR in the band 10-20ºN, these waves are exposed to convective instability driven by the upper ocean's heat content. The resulting infusion of energy can result in closed cyclonic circulation and development from tropical depression to tropical storm and hurricane. These hurricanes are known as Cape Verde-type hurricanes, to distinguish them from storms forming further west, and they are often the most powerful storms to strike the US east coast. Prominent examples include Andrew (1992), Floyd (1999) and Ivan (2004). An average season has two Cape Verde hurricanes, but some years have up to five while others have none. There is profound uncertainty regarding the specific atmospheric/oceanic conditions that determine which of the atmospheric waves will develop into tropical cyclones and then hurricanes (on average, one of ten). Specifically, the quantitative effects of the Saharan Aerosol Layer (SAL), anomalous sea surface temperatures (SST), upper layer oceanic heat content and atmospheric wind shear on the formation of tropical cyclones are poorly known.

Seasonal tropical storm and hurricane forecasts are generated annually and based primarily on statistical analyses of historical data and the formulation of empirical predictors (e.g., ENSO index, Atlantic SST, Sahel rainfall, etc.). Recent empirical studies have demonstrated that tropical storm and hurricane activity in the Atlantic Ocean varies on decadal and multi-decadal time-scales and that this variability is correlated with sea-surface temperature anomalies in the MDR. The SST signal in the MDR has been correlated with the North Atlantic Oscillation (NAO) on decadal time-scales. The multi-decadal signal indicates that an extended period of increased hurricane activity is to be expected. Other historical studies have also demonstrated spatial variability in storm formation areas and landfall locations on longer timescales.

Despite the climate and weather significance of the Tropical North Atlantic region, it was not sampled by the PIRATA backbone array apart from the 38°W line of moorings extending north to 15°N (Fig. 1). In 2005, a formal Northeast Extension of PIRATA was proposed as a joint project between NOAA/AOML and PMEL (Rick Lumpkin, Mike McPhaden and Bob Molinari, co-principal investigators). This PIRATA Northeast Extension (PNE) was proposed to consist of four moorings, three creating a northward arm up 23°W (building upon the equatorial backbone mooring there), and a fourth extending the 38°W arm to 20°N.

In June 2006, the first two moorings of this extension were deployed during RB-06-05a. The mooring at 11.5°N, 23°W was deployed on June 7, and the mooring at 4°N, 23°W was deployed on June 11. Both moorings were replaced in May 2007, during RB-07-03, and two more moorings were added at 20.5°N, 23°W and 20°N, 38°W. The four buoys were planned for servicing in the April 2008 cruise RB-08-03. Due to the cancellation of this cruise, the buoys failed and a data gap was created in mid to late 2008. All four sites were subsequently serviced in November 2008 by NOAA charter of the French R/V *Antea*. All four are currently successfully reporting meteorological and oceanographic data onto the Global Telecommunications System for weather and climate forecasting (latest status can be seen at http://www.pmel.noaa.gov/tao/global/status/buoystat-pirata.html). In the Memorandum of Understanding from the PIRATA-12 meeting (November 2006), the United States agreed that

> [I]t is recognized that the Parties are dependent upon year-to-year funding allocations from their governments, and thus commitments for future funding and logistical support can not be guaranteed. Given this proviso, the Parties affirm that PIRATA is a high priority for Brazil, France, and the United States, and that the institutions are making plans for continued support … NOAA will provide ship time for maintenance of four moorings in the North East Extension.

The Ronald H. Brown cruise RB-09-04 served to honor this commitment for the year 2009.

2. Aerosol and Ocean Science Expedition (AEROSE)

West Africa is part of the world's major source region of mineral dust aerosol. Given the great uncertainties regarding the impact of dust on weather and climate, there is an important opportunity to address aerosol issues. The mobilization, transport, and impacts of aerosol on weather and climate in West African and Atlantic regions need to be investigated. Saharan dust storms are estimated to inject over three billion metric tons of mineral aerosols into the troposphere annually. These aerosols impact phenomena ranging from cloud-seeding and precipitation, to ocean fertilization, and to downstream air quality and ecosystem impacts in the Caribbean and US eastern seaboard. Red tides, increasing rates of asthma, and precipitation variability in the eastern Atlantic and Caribbean have been linked to increases in the quantities of Saharan dust transported across the Atlantic. The contribution of the Saharan air layer (SAL) to the development of the West African Monsoon (WAM) and its role in tropical cyclogenesis are just beginning to be understood. The interplay between thermodynamics, microphysics, and aerosol chemistry are a currently unknown and these field measurements represent a unique data set for unraveling these complex interactions.

The Aerosol and Ocean Science Expeditions (AEROSE) constitute a comprehensive approach, in terms of both measurements and modeling, for gaining understanding of the impacts of long-range transport of mineral dust in the tropical Atlantic (Morris et al., 2006). The project involves international coordination of year-round monitoring in Puerto Rico, Mali, the Canary Islands, and Senegal coordinated with basic research, and multi-year, trans-Atlantic field campaigns in the tropical Atlantic. AEROSE is supported through collaborative efforts with NOAA's National Environmental Satellite Data and Information Service Center for Satellite Applications and Research (NESDIS/STAR) and the National Weather Service (NWS), as well as NASA and several academic institutions linked through the NOAA Center for Atmospheric Sciences at Howard University.

The AEROSE campaigns (to date, comprised of four, 4-week trans-Atlantic cruise legs) have provided a set of in situ measurements to characterize the impacts and microphysical evolution of continental African aerosol outflows (including both Saharan dust and sub-Saharan smoke from biomass burning) across the Atlantic Ocean. AEROSE has sought to address three central scientific questions:

1) How does Saharan dust and/or the SAL affect atmospheric and oceanographic parameters during trans-Atlantic transport?
2) How do the Saharan dust aerosol distributions evolve physically and chemically during transport?
3) Given these marine-based in situ aerosol measurements, along with concurrent radiosonde observations (RAOBs), what is the capability of satellite remote sensing algorithms and models for measuring and/or resolving the above processes?

Order of operations:

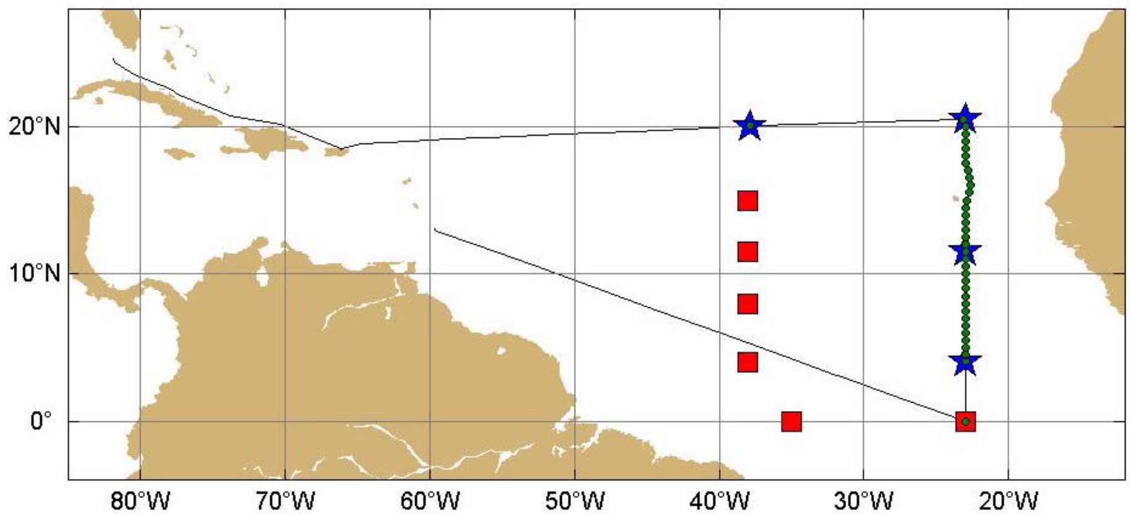

Fig. 2: cruise track of the R/V Ronald H. Brown during RB-09-04 (black), with CTD stations (green bullets), PNE mooring sites (blue stars), and the PIRATA backbone sites (red squares) superimposed.

The Ronald H. Brown (RHB) left Bridgetown, Barbados and commenced RB-09-04 at the scheduled time of 1700 UTC on 11 July, and transited to the first moored buoy site at 0° 23°W. On route, two test XBT cast were conducted, 16 drifters were deployed, and the AERSOSE team began launching radio- and ozonesondes. Between 18 July at 0300 local time (3° 9.16'N 31° 52.88'W) and 19 July at 1837 local (1° 3.74'N 26° 0.83'W), the RHB passed through the Brazilian EEZ of St. Peter and Paul Rocks and data acquisition, including drifter, XBT and sonde launches, was suspended.

The RHB arrived at 0° 23°W at ~1500 UTC on 20 July and immediately commenced the tube swap with the rigid inflatable boat after a visual confirmation that the buoy was not vandalized (anemometer intact, etc.). The new tube is Argos PTT ID 09793. The tube swap operation was completed by 1545 UTC, but no subsurface data were received by the Argos receiver setup on the RHB until after 1600 UTC despite extreme proximity to the buoy, which was in "dep" mode transmitting every two minutes (the buoy automatically leaves dep mode after 12 hours). Once the buoy and mooring were determined to be operating properly, the test CTD cast was conducted to a depth of 1500 dbar. The cast was completed at 1815 UTC, and the RHB began steaming for the 4°N 23°W PIRATA Northeast Extension site.

The RHB arrived at the 4°N 23°W Northeast Extension site at ~1430 UTC (1230 local time) on 21 July and released the existing buoy without incident. During the recovery, the mooring capstan blew a hydraulic seal, terminating operations with that capstan. The line was switched to the Woods Hole winch and the recovery continued, with the remainder of the mooring (the final 300m piece of nilspin and all nylon) wound onto the WHOI winch drum. Prior to deployment a backup capstan was positioned for use. Deployment took place using the WHOI winch drum and backup capstan. Although PMEL standard operating procedure calls for the deployment to halt once the upper 500m nilspin is deployed, in order to check buoy and subsurface sensor communications, deployment in this case proceeded without halt and communications were not verified (once this was noted, the buoy was already out of range of the Argos receiver/antennae). Also during the deployment a (false) fire alarm was reported in the exercise area. All crew mustered to their fire stations. The mooring was stopped off on the capstan and remained so until the crew returned from the fire alarm and completed the mooring deployment. The backup capstan was used for recovery and deployment at all subsequent sites.

From early in the deployment through the flyby, no communications were received from the buoy (PTT 27020). We at first assumed that there had been a tube failure upon deployment, but checked with PMEL technicians in Seattle via Iridium phone and learned that they were able to see data from the buoy on the (Argos) GTS data stream, with an approximately two-hour delay. We proceeded with CTD cast 1, and verified with a second call to PMEL that they were continuing to receive updated data despite our inability to hear the buoy. Having determined that the problem was with our Argos receiver, cable or antenna (or antenna placement), or with the buoy transmissions being stepped on by an unknown PTT (later determined to be a WHOI float from the NTAS cruise), we proceeded to the CTD cast 2 site at 4°30'N 23°W.

The 23°W CTD line between 4°N and 11°N was occupied on 21—24 July (for notes on specific casts, see the CTD section of this cruise report). The RHB arrived at the 11.5°N 23°W Northeast Extension site at ~1600 UTC on 24 July. Recovery and deployment was conducted without delay or complications apart from communications problems during deployment similar to those noted at the 4°N site. We lost communications with the new buoy once more than 700m of wire was deployed off the fantail, but had verified that all surface and subsurface sensors were transmitting after the first 500m of nilspin was in the water. After deployment and conducting CTD cast 16, the RHB did a flyby of the buoy but received no data. Chief scientist Rick Lumpkin elected to proceed to the site of CTD cast 17 (12°N 23°W) and continue the CTD operations through the night, with the possibility of returning to the 11.5°N site if data reception problems were not the culprit. However, subsequent communications with PMEL determined that the data were being received successfully there – again, the Argos data reception on the ship was at fault. Between this site and the 20.5°N 23°W site, Mike Strick and Korey Martin switched to their backup Argos receiver, moved their antenna to a higher point on the ship, and switched off the WHOI float. One or more of these factors appeared to solve the communications problems for the final two sites.

Throughout the occupation of the 23°W line, the oceanographic observations team was intermittently hampered by radio communications problems. We had access to two handheld radios, but the bridge could be heard responding on only one (although they could hear us transmitting on both). The second radio had one working battery, and three additional batteries which – although kept in their charging bay – would not function at all or for more than a few minutes when put in the radio. This inhibited effective and timely communications between the deck survey technician and the winch operator when the one good battery was charging, most notably during CTD cast 18.

The RHB conducted the 23°W CTD line between 12°N and 20°N (casts 18—33) on 25—27 July, passing around and within sight of the Cape Verde islands and over the Cape Verde plateau. The RHB arrived at the 20.5°N 23°W Northeast Extension site at ~2120 UTC on 27 July. CTD cast 34 was conducted and the ship hove to until sunrise, when recovery and redeployment commenced. These operations proceeded quickly and efficiently with no equipment problems. During this deployment, Korey Martin pulled a muscle lifting one end of a nylon spool; Chief Bosun Bruce Cowden recommended that PMEL switch to a jack system so that spools would not need to be hand-lifted during ATLAS operations.

The RHB transited to the final buoy/CTD site at 20°N 23°W from 28—31 July, arriving at the site at ~0730 UTC and commencing recovery and redeployment. As before, this operation proceeded smoothly and efficiently. The final CTD cast (35) was conducted, and the Brown began its transit to San Juan, Puerto Rico for scheduled refueling. The RHB entered Barbuda's EEZ on 4 August at 1550 UTC, when data logging was terminated. The RHB reached the Anegada Passage at ~2030 UTC on 5 August, entered US EEZ at 2211 UTC the same day, and docked at the Coast Guard pier in San Juan on the morning of 6 August. While in San Juan, the following eight members of the scientific party left the ship and returned home separately: Claudia Schmid, Everette Joseph, Nick Nalli, Adam Atia, Ibrahim Siddo, Luis Padilla, Mariana Guereque, Lily Udumukwu.

The RHB was refueled on 7 August and departed for Key West the same day at 1630 local time. The RHB arrived in Key West on the morning of 11 August and commenced unloading, completing the PNE2009 cruise RB-09-04.

Oceanographic data collected on this cruise:

1. ATLAS moorings of the Prediction and Research moored Array in the Tropical Atlantic (PIRATA) were recovered and redeployed at all four Northeast Extension sites (4°N/11.5°N/20.5°N 23°W; 20°N 38°W). A French PIRATA backbone mooring at 0º 23ºW was repaired via tube swap. The moorings are relaying real-time data including air temperature, relative humidity, wind speed and direction, rain rate,

shortwave and longwave radiation, barometric pressure, sea surface temperature, subsurface currents at ~10m depth, and subsurface temperature and salinity at multiple points through the upper 500m of the water column.

2. Conductivity-Temperature-Depth (CTD) data were collected at 36 casts: a test cast at 0º 23ºW, 34 casts at 30 nm spacing creating a meridional section from 4°N 23ºW to 20.5ºN 23ºW, and a cast at 20°N 38°W. All casts were conducted to a pressure of 1500dbar, or the bottom (if shallower). On all casts water samples were taken at various depths to calibrate salinity and oxygen sensors.
3. 32 satellite-tracked surface drifters were deployed to measure sea surface temperature and mixed layer currents, as part of the Global Drifter Program array.
4. 154 expendable bathythermographs (XBTs) were launched to measure temperature profiles of the upper ocean. During the first 12 CTD casts, including the test cast, a comparison study was conducted with several XBTs from various manufacturing dates, to examine how construction changes may have affected the drop rate of the XBTs. This was done, by launching multiple XBTs, in sequence while the CTD package was commencing the downcast.
5. Shipboard data was collected throughout the cruise (except in specific EEZs) using a 75 kHz Ocean Surveyor hull-mounted Acoustic Doppler Current Profiler (SADCP).

ATLAS moorings (text by J. Michael Strick and Korey Martin)

Summary of Mooring Operations		
Site	**Mooring ID #**	**Operation**
0 23W	PM779A / PM822A	Tube Swap
4N 23W	PM730A/PM831	REC/DEP
11.5N 23W	PM784A/PM832	REC/DEP
20.5N 23W	PM788A/PM833	REC/DEP
20N 38W	PM787A/835	REC/DEP

Lost or Damaged Instruments and Equipment *(from rec moorings)*				
Site	**Mooring ID**	**Sensor type**	**Serial No**	**Comments**
4N 23W	PM780A	Sontek	603	Broken fin
4N 23W	PM780A	Sontek	603	H2O in case
11.5N 23W	PM784A	TC	14614	Lost
11.5N 23W	PM784A	TC	14613	Lost
20N 38W	PM787A	SW RAD	32276	Bent shield
20N 38W	PM787A	Sontek	608	H2O in case

On-deck instrument or hardware failure ***(pre-deployment)***		
Sensor type	**Serial No**	**Comments**
Tube	723	Bad compass
SW Rad	35777	Bad cable

Fishing and Vandalism		
Site	**Mooring ID**	**Comments**
4N 23W	PM780A	Some fishing line in 300M TP+300M German O2

Shipping notes: *(Any problems with loading, agents…)*
None. The majority of the TAO gear was shipped to Charleston to be loaded on the Ronald H. Brown (RHB). We arrived In Barbados on July 9th. After landing and checking into the hotel we proceeded to the RHB. Upon boarding the ship we found all our gear and the buoy, bridle and tower already assembled. One noteworthy observation, our tube boxes which were labeled "STORE INSIDE" were however stored outside on deck. At the loading in Charleston, AOML personnel placed the tube boxes in the staging bay. At some point during the transit from Charleston to Barbados the tube boxes were relocated outside. Consequently some of the instrumentation in Tube Box 722 was submerged in water. An air shipment arrived in Barbados on 10 July and a $200.00 USD ($400.00 BD) fee, cash only of course, was due to the expeditor/ship's agent before the ship could depart.

Noteworthy Operational Details:
During operations at 0 23W and 4N 23W we experienced difficulty receiving Dep Mode data from the buoy. Reception range was spotty even at 0.2 nm. We were lucky to get 1 or 2 incomplete hits (i.e. partially filled AGOS Buffers on TWEEZERS) The usual fixes were tried (move antenna, change cables, change ARGOS receiver, reboot computer, clean and reseat all connectors, etc). None of the previous had any effect on improving the reception range. At 11.5N 23W we again went through the usual fix list, but this time we moved the antenna higher (on top of CTD winch house). We received all buoy data via ARGOS and TWEEZERS. This move of the antenna (we think) seemed to correct the spotty reception issue.

Instrumentation and Hardware Notes: *(Missing nuts from shackles, tower missing rain mount…)*
There was considerable difficulty in downloading the Sonteks from all sites. The 4N 23W and 20N 38W Sonteks both had water intrusion into their housings. There was some wire corrosion. Sonteks at 11.5N 23W and 20.5N 23W showed no signs of water intrusion, but still no comms with the instrument were possible. All possible actions were taken to communicate with the instruments.

Software Notes: *(problems with Tweezers, Filemaker…)*
None

Ship Notes or issues: *(SCS problems, problems with personnel or communications on board…)*
During the 4N recovery/deployment the mooring capstan blew a hydraulic seal. This effectively terminated operations with that capstan. The line was switched to the WHOI winch and the recovery continued, essentially winding the rest of the mooring onto the WHOI winch drum (300m piece of nilspin+all nylon). Prior to deployment a backup

capstan was positioned for use. Deployment took place using the WHOI winch drum and backup capstan.. During the deployment one complication occurred. A fire was reported in the Exercise Area (false alarm). All crew mustered to their fire stations. We remained with the mooring, stopped off on the capstan, until the crew returned from the incident and completed the mooring deployment. The backup capstan was used for Rec/Depl on all subsequent stations.

Miscellaneous:
The officer's and crew member's of the RHB did an outstanding job. There was excellent communications between the science party and the Ship. All in all an excellent trip. Deck operations went exceptionally smoothly. The officers on the bridge were well versed in buoy recovery and deployments. A good trip.

Recommendations:
During next year's turnarounds. All bridle plates should be replaced. Bring new bridle plates, new hardware, new bridle isolators and new micarta isolators.

<u>Conductivity-Temperature-Depth (CTD) casts</u>

AOML's CTD package was set up with 14 Niskin bottles, 12 to be fired at various depths to collect water samples for sensor calibration, and two as spares.

We conducted 36 CTD casts, including a test cast at 0º 23W, to 1500dbar (Fig. 2), except as noted below (casts at sites where the bottom was shallower than 1500dbar). The following sensors were used on all casts (numbers indicate serial numbers):

Temperature: 4799 (primary), 2958 (secondary), both calibrated 21 May 2009.
Salinity: 2980 (primary), calibrated 21 May 2009,
1347 (secondary), calibrated 19 March 2009.
Oxygen: 1329 (primary), 1348 (secondary), both calibrated 17 March 2009.

Between cast 1 (4°N 23°W) and cast 34 (20.5°N 23°W), CTD operations were conducted around the clock. The 11:30 am to 11:30 pm (2 hours behind UTC) shift was Rick Lumpkin (CTD console and salt sampler), Bob Oddo (sample recorder) and Grant Rawson (survey and oxygen sampler). The 11:30pm to 11:30am shift was Claudia Schmid (salt sampler), Cheryl Brown (CTD console and sample recorder) and Kyle Seaton (survey and oxygen sampler). The sample recorder shook the oxygen samples after the oxygen sampler pickled them. All oxygen samples were titrated by Seaton. Salts were processed on the Autosal "Dallas" and saved in runs with file names PNE09_#.dat; runs were conducted by Rawson (salt files 0, 3, 11, 15, 23, 27, 31) and by Seaton and Brown (7, 19). A small number (<5) of salt samples may have been run with improper suppression; these were obvious outliers (autsal salinity<34psu) and were discarded before calibrating the sensors.

The file “PNE0907_a.con” was set up by Kyle Seaton for the CTD casts. On 24 July, we discovered that the CTD acquisition computer was not recording the NMEA position data stream; these data were added a posteriori to the Matlab files, using the positions from the CTD log sheet. Also on this date, after cast 14, Grant Rawson discovered that the coefficients for the oxygen sensors were incorrect, causing a spurious (but not dramatic) offset in the upper ~100dbar of the casts. Grant and Kyle fixed this in “PNE0907_b.con” used for subsequent casts, and also created a file “PNE0907_a_playback.con” which they used to rerun casts 1—14.

CTD processing was performed using Seabird software, applied to the PNE09 casts by Kyle Seaton and Claudia Schmid, and Matlab routines developed by Carlos Fonseca and Rick Lumpkin and applied to the PNE09 casts by Rick Lumpkin.

CTD casts are tabulated in Table 1, and preliminary calibrated sections are shown at the end of this cruise report.

Notes on specific CTD casts:

Test cast (0°0.01.54’S 22°59.739’W): two modulo errors were recorded before the cast began, a third error was recorded during the downcast at ~1100 dbar, and a fourth during the upcast at ~1170dbar. No visible spikes in the data accompanied these errors, and none were associated with bottle fires. On this cast, all 14 bottles were fired. Several subsequent casts also had a few (1—4) modulo errors, but none indicated severe communications problems.

Cast 4 (5°30.113’N 22°59.987’W): at the end of the cast, the winch operator prematurely brought the package out of the water before the final surface bottle was fired. The package was put back in the water and the bottle was fired, but the pumps had stopped. Consequently, the surface bottle was not sampled.

Cast 7 (7°00.036’N 23°00.009’W): conducted over the Sierra Leone Rise, water depth 1516m. The altimeter worked very well on this and subsequent bottom approaches, and the package was stopped 20m above the bottom.

Cast 18 (12°30.007’N 22°59.994’W): at the beginning of this cast, after being held at 10m depth for two minutes with pumps on, the package was brought to the surface and handed over to the CTD operator for control (as per standard operating procedures). The operator (Cheryl Brown) requested that the package begin descent. The winch operator inadvertently began lifting the package instead of lowering it, bringing it out of the water before stopping the winch. Kyle Seaton, on the deck, observed the package going up but was unable to effectively communicate with the winch operator due to a faulty radio. The package was recovered on deck and inspected for damage; none was evident apart from chafing of the Chinese fingers, and the cast was resumed without any communications problems.

Cast 22: five modulo errors experienced during upcast. The connection between the sensors and the CTD was examined and cleaned after this cast.

Cast 25 (15°59.988'N 22°35.989'W): on the Cape Verde plateau in water depth 591m. CTD package stopped 10m above bottom; 8 bottles fired during upcast.

Cast 27 (16°59.998'N 22°48.967'W): on the Cape Verde plateau in water depth 1296m. CTD package stopped 9m above bottom; 12 bottles fired during upcast.

Cast 30 (18°29.984'N 23°00.024'W): CTD operator Cheryl Brown noted that she hadn't done "mark scan" until at 20dbar; marked then. *A posteriori* edit to mark scan file created by Claudia Schmid to capture upper 20dbar of data.

Cast 33 (20°00.031'N, 23°00.046'W): no mark scan file recorded, despite operator (Rick Lumpkin) noting it had been marked on log sheet. Mark scan file created *a posteriori* by Claudia Schmid, to flag data before downcast initiation. Also on this cast, a dramatic oxygen jump was noted at a depth of 310dbar with corresponding temperature and salinity anomalies. This oxygen gradient was the sharpest observed during the cruise.

Cast	Day (July 2009)	time (UTC)	Lat (N)	Lon (W)
0	20	1656	-0.0256	22.9957
1	22	139	4.0864	23.0111
2	22	609	4.5024	23.0001
3	22	1025	5.0001	23.0001
4	22	1441	5.5038	22.9980
5	22	1851	6.0044	22.9983
6	22	2300	6.5007	22.9983
7	23	306	7.0006	23.0001
8	23	723	7.4996	23.0005
9	23	1122	7.9999	22.9994
10	23	1524	8.5001	22.9999
11	23	1923	8.9998	22.9998
12	23	2328	9.5002	22.9998
13	24	335	9.9988	23.0000
14	24	752	10.4996	23.0004
15	24	1159	10.9978	23.0003
16	24	2322	11.4998	23.0003
17	25	409	12.0003	22.9992
18	25	807	12.5000	22.9995
19	25	1151	13.0025	22.9997
20	25	1539	13.4998	22.9998
21	25	1928	13.9997	23.0000
22	25	2322	14.5003	23.0000
23	26	314	15.0000	22.8667
24	26	717	15.4995	22.7335
25	26	1118	15.9998	22.5998
26	26	1501	16.5012	22.7347

27	26	1901	17.0000	22.8162
28	26	2300	17.4998	23.0003
29	27	302	17.9982	23.0002
30	27	710	18.4988	23.0000
31	27	1118	18.9995	23.0000
32	27	1528	19.4997	22.9990
33	27	1927	20.0005	23.0005
34	27	2332	20.4723	23.1238
35	31	1820	20.0415	37.8505

Table 1: locations, dates and start time of CTD casts.

The Temperature-Salinity structure along 23ºW from the CTD casts is shown in Fig. 3. The nearly linear T-S relationship at intermediate densities is the signature of Central Water. The lowest salinity measurements indicate the presence of Antarctic Intermediate Water, with local minima in surface salinity associated with the ITCZ. Maximum salinity measurements were seen in the near-surface, associated with salinity maximum water created in the subduction region of the subtropical North Atlantic.

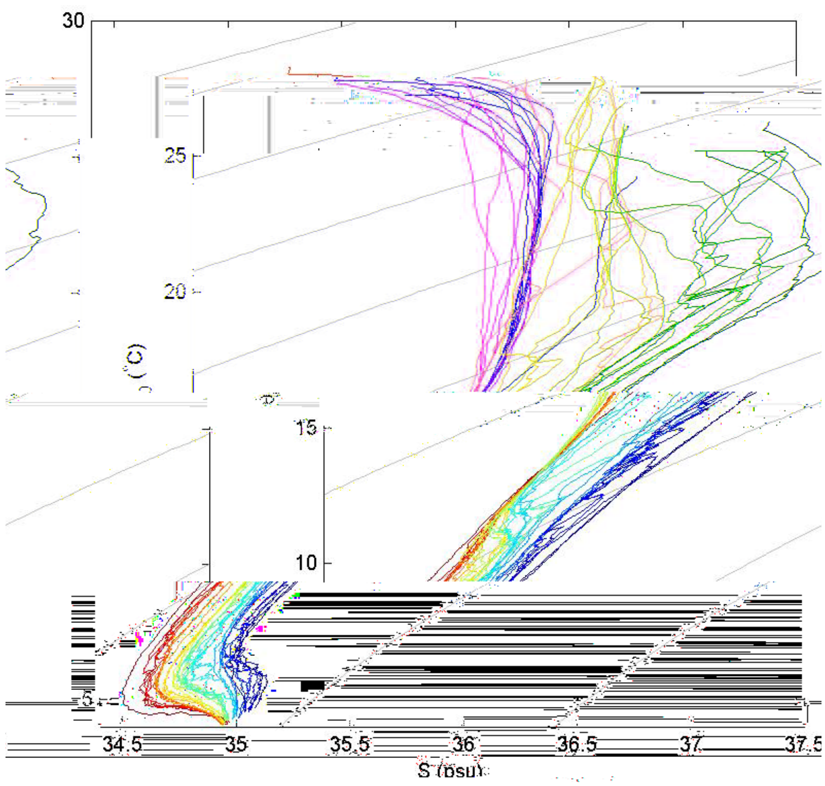

Fig. 3: salinity vs. potential temperature along the 23ºW section. Colors indicate latitude, ranging from red (equator) to blue (20.5°N). Gray lines indicate constant density values.

Satellite-tracked Surface Drifters

Thirty-two satellite-tracked drifters were deployed during the cruise, as shown in Fig. 5 and compiled in Table 2. The drifters were mini-Surface Velocity Program types, drogued at 15m to follow mixed layer currents. All included a thermistor on the surface buoy for SST. Their data are transmitted in real time via the Argos system. A number of the drifters were launched in pairs, one immediately after the other, with initial separation of a few meters, to permit studies of ocean dispersion. All drifters were manufactured by Metocean, and were deployed from the port side fantail of the Brown.

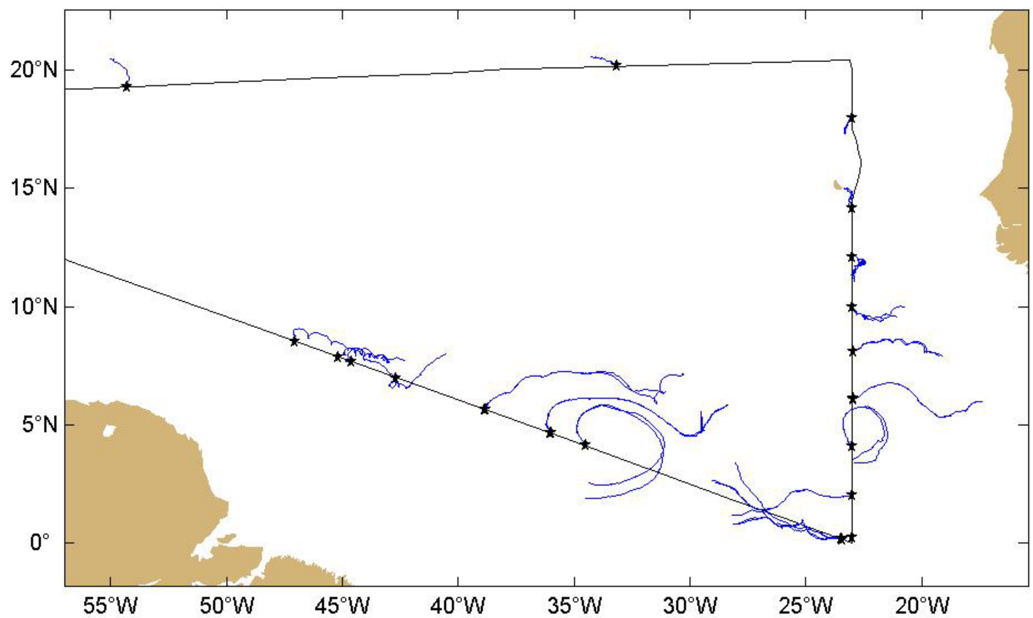

Fig. 5: location of surface drifter deployments (stars; see Table 2). The subsequent trajectories of the drifters (blue lines) as of 10 August 2009 (blue lines) are also shown.

Drifter deployments, PIRATA Northeast Extension 2009

	ID	deployed by	date	time (UTC)	latitude (N) deg	min	longitude (W) deg	min
1	88640	Rick Lumpkin	7/14	16:57	8	31.25	47	0.95
2	88636	Rick Lumpkin	7/15	2:42	7	52.01	45	10.209
3	88632	Kyle Seaton	7/15	5:36	7	40.634	44	37.376
4	88615	Bob Oddo	7/15	16:04	6	58.56	42	38.2
5	88584	Rick Lumpkin & Bob Oddo	7/16	13:00	5	37.552	38	50.488
6	88597	"	"	"	"	"	"	"
7	88612	Kyle Seaton	7/17	4:22	4	37.079	36	0.1
8	88622	"	"	"	"	"	"	"
9	88610	Rick & Bob	7/17	13:06	4	4.48	34	28.37
10	88620	"	"	"	"	"	"	"
11	88635	Grant Rawson & Bob	7/20	12:23	0	8.5	23	25.85

12	88613	"	"	"	"	"	"	"
13	88594	Rick Lumpkin	7/20	19:36	0	13.42	22	59.28
14	88602	"	"	"	"	"	"	"
15	88575	Kyle, Claudia, Cheryl	7/21	4:21	2	1.45	22	59.89
16	88604	"	"	"	"	"	"	"
17	88645	Grant & Bob	7/22	1:21	4	4.664	23	0.171
18	88647	"	"	"	"	"	"	"
19	88603	Grant & Rick	7/22	20:41	6	4.036	22	59.997
20	88641	"	"	"	"	"	"	"
21	88637	Kyle, Claudia, Cheryl	7/23	12:46	8	0.32	22	59.98
22	88606	"	"	"	"	"	"	"
23	88630	Kyle, Claudia, Cheryl	7/24	5:02	10	0.247	22	59.996
24	88625	"	"	"	"	"	"	"
25	88639	Claudia and Cheryl	7/25	5:54	12	5.377	22	59.996
26	88618	"	"	"	"	"	"	"
27	88608	Rick, Grant and Bob	7/25	19:32	14	8.9256	22	59.9968
28	88607	"	"	"	"	"	"	"
29	88605	Kyle, Claudia, Cheryl	7/27	4:21	18	0.094	23	0
30	88595	"	"	"	"	"	"	"
31	88565	Kyle Seaton	7/30	12:51	20	10.474	33	8.6906
32	88623	Rick and Bob	8/3	23:35	19	18.573	54	19.819

Table 2: drifter deployment log. Locations and times are repeated for second drifter in pair deployments.

Expendable Bathythermograph (XBT) casts

A total of 154 XBTs were deployed and successfully collected data during the cruise (Fig. 6 and Table 3). Most XBTs (exceptions noted in Table 3) were Deep Blue, manufactured on 11/26/2008, with serial numbers in the range 1085470—1085793. All XBTs were launched from the stern of the ship, using the hand launcher and the WinMk21 software for data acquisition.

During the first 12 CTD casts including the test cast, a comparison study was conducted with several XBTs from various manufacturing dates, to examine how construction changes may have affected their drop rate (Fig. 7). This was done by launching the XBTs in sequence while the CTD package was commencing the downcast. In addition to launching one of the Deep Blues manufactured on 11/26/2008, we also drew an XBT from older boxes of T7 XBTs that had been stored at AOML. These older batches were:

1. A box of 12 T7s manufactured in April 1986, noted “4/86 (1)” in Table 3, with serial numbers in the range 552664—552674. The first XBT to be launched from this batch, serial number 552671, was not recognized as “loaded” by the WinMk21 software and was not launched.

2. A box of 12 T7s manufactured in April 1986, noted “4/86 (2)”, with serial numbers in the range 552748—552759. XBT serial number 552749 failed when the wire broke upon deployment.
3. Box of 10 T7s manufactured 4/23/91, serial numbers 727812—727823. Serial number 727817, file name “T7_00071”, started recording data on deck and was logged as “failure”.
4. Box of 12 T7s manufactured 7/11/95, serial numbers 897565—897576.
5. A single T7 manufactured 8/3/90, serial number 695092.
6. A single T7 with no manufacture date indicated, serial number 703273 (suggesting it was manufactured in the late 1990s).

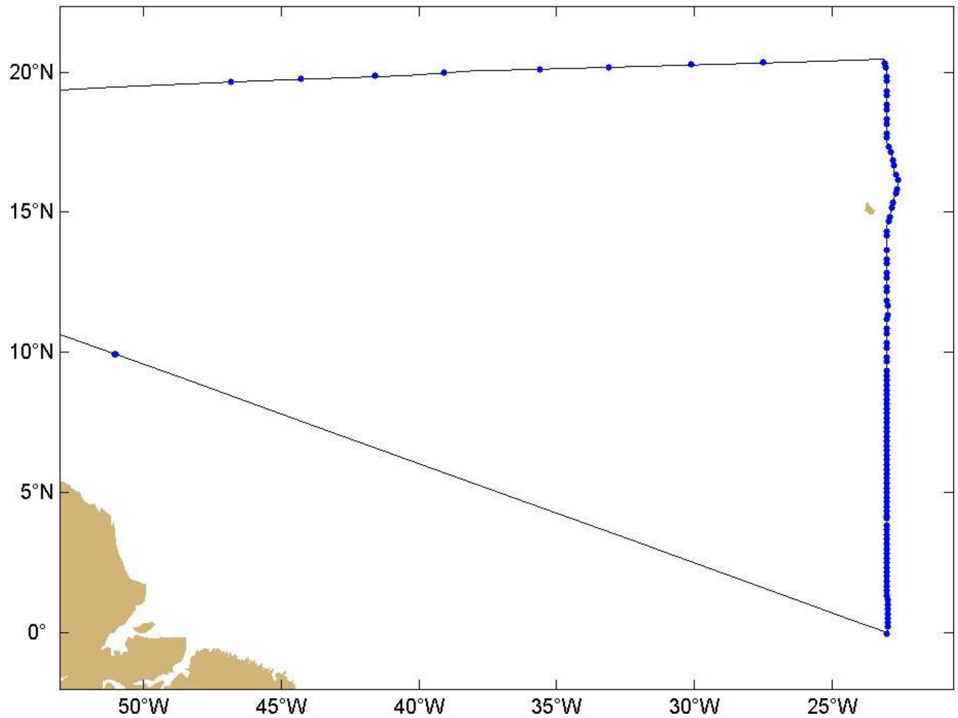

Fig. 6: location of XBT deployments (blue bullets).

#	FILE	TYPE	MANUF. DATE	DATE 2009	TIME (UTC)	LAT (N)	LON (W)
1	TD_00030	DB	11/26/08	7/13	19:06	9.940	51.060
2	TD_00031	DB	11/26/08	7/13	19:15	9.930	51.030
3	T7_00032	T7	4/86 (2)	7/20	17:11	-0.030	23.000
4	T7_00033	T7	late 90s	7/20	17:14	-0.030	23.000
5	T7_00034	T7	4/23/91	7/20	17:17	-0.030	23.000
6	T7_00035	T7	7/11/95	7/20	17:20	-0.030	23.000
7	TD_00036	DB	11/26/08	7/20	17:22	-0.030	23.000
8	TD_00037	DB	11/26/08	7/20	19:30	0.210	22.990
9	TD_00038	DB	11/26/08	7/20	20:11	0.350	22.990

10	TD_00039	DB	11/26/08	7/20	20:53	0.500	22.990
11	TD_00040	DB	11/26/08	7/20	21:42	0.670	22.990
12	TD_00041	DB	11/26/08	7/20	22:33	0.830	22.990
13	TD_00042	DB	11/26/08	7/20	23:19	0.990	22.990
14	TD_00043	DB	11/26/08	7/21	00:10	1.170	22.990
15	TD_00044	DB	11/26/08	7/21	00:58	1.330	22.990
16	TD_00045	DB	11/26/08	7/21	01:46	1.500	23.000
17	TD_00046	DB	11/26/08	7/21	02:34	1.660	23.000
18	TD_00047	DB	11/26/08	7/21	03:24	1.830	23.000
19	TD_00049	DB	11/26/08	7/21	04:18	2.010	23.000
20	TD_00050	DB	11/26/08	7/21	05:02	2.160	23.000
21	TD_00051	DB	11/26/08	7/21	05:49	2.330	23.000
22	TD_00052	DB	11/26/08	7/21	06:36	2.490	23.000
23	TD_00053	DB	11/26/08	7/21	07:25	2.660	23.000
24	TD_00054	DB	11/26/08	7/21	08:12	2.830	23.000
25	TD_00055	DB	11/26/08	7/21	09:00	2.990	23.000
26	TD_00056	DB	11/26/08	7/21	09:48	3.160	23.000
27	TD_00057	DB	11/26/08	7/21	10:37	3.330	23.010
28	TD_00058	DB	11/26/08	7/21	11:25	3.500	23.010
29	TD_00059	DB	11/26/08	7/21	12:11	3.660	23.010
30	TD_00060	DB	11/26/08	7/21	12:59	3.830	23.010
31	T7_00061	T7	4/86 (1)	7/22	02:02	4.090	23.010
32	T7_00062	T7	4/86 (2)	7/22	02:05	4.090	23.010
33	T7_00063	T7	8/3/90	7/22	02:09	4.090	23.010
34	T7_00064	T7	4/23/91	7/22	02:12	4.090	23.010
35	T7_00065	T7	7/11/95	7/22	02:15	4.090	23.010
36	TD_00066	DB	11/26/08	7/22	02:18	4.090	23.010
37	TD_00067	DB	11/26/08	7/22	04:02	4.150	23.010
38	TD_00068	DB	11/26/08	7/22	05:04	4.330	23.000
39	T7_00069	T7	4/86 (1)	7/22	06:20	4.500	23.000
40	T7_00070	T7	4/86 (2)	7/22	06:23	4.500	23.000
41	T7_00072	T7	7/11/95	7/22	06:33	4.500	23.000
42	T7_00073	T7	7/11/95	7/22	06:36	4.500	23.000
43	T7_00074	T7	4/23/91	7/22	06:40	4.500	23.000
44	TD_00075	DB	11/26/08	7/22	08:27	4.660	23.000
45	TD_00076	DB	11/26/08	7/22	09:23	4.830	23.000
46	T7_00077	T7	4/86 (1)	7/22	10:42	5.000	23.000
47	T7_00078	T7	4/86 (2)	7/22	10:45	5.000	23.000
48	T7_00079	T7	4/23/91	7/22	10:48	5.000	23.000
49	T7_00080	T7	7/11/95	7/22	10:50	5.000	23.000
50	TD_00081	DB	11/26/08	7/22	10:53	5.000	23.000
51	TD_00082	DB	11/26/08	7/22	12:51	5.160	23.000
52	TD_00083	DB	11/26/08	7/22	13:45	5.330	23.000
53	T7_00084	T7	4/86 (1)	7/22	14:55	5.500	23.000
54	T7_00085	T7	4/86 (2)	7/22	14:58	5.500	23.000
55	T7_00086	T7	4/23/91	7/22	15:01	5.500	23.000
56	T7_00087	T7	7/11/95	7/22	15:04	5.500	23.000
57	TD_00088	DB	11/26/08	7/22	15:07	5.500	23.000

58	TD_00089	DB	11/26/08	7/22	17:03	5.660	23.000
59	TD_00090	DB	11/26/08	7/22	17:57	5.830	23.000
60	T7_00091	T7	4/86 (1)	7/22	19:06	6.000	23.000
61	T7_00092	T7	4/86 (2)	7/22	19:09	6.000	23.000
62	T7_00093	T7	4/23/91	7/22	19:12	6.000	23.000
63	T7_00094	T7	7/11/95	7/22	19:15	6.000	23.000
64	TD_00095	DB	11/26/08	7/22	19:18	6.000	23.000
65	TD_00096	DB	11/26/08	7/22	21:12	6.170	23.000
66	TD_00097	DB	11/26/08	7/22	22:04	6.330	23.000
67	T7_00098	T7	4/86 (1)	7/22	23:11	6.500	23.000
68	T7_00099	T7	4/86 (2)	7/22	23:16	6.500	23.000
69	T7_00100	T7	4/23/91	7/22	23:21	6.500	23.000
70	T7_00101	T7	7/11/95	7/22	23:24	6.500	23.000
71	TD_00102	DB	11/26/08	7/22	23:27	6.500	23.000
72	TD_00103	DB	11/26/08	7/23	01:11	6.660	23.000
73	TD_00104	DB	11/26/08	7/23	02:07	6.830	23.000
74	T7_00105	T7	4/86 (1)	7/23	03:22	7.000	23.000
75	T7_00106	T7	4/86 (2)	7/23	03:25	7.000	23.000
76	T7_00107	T7	4/23/91	7/23	03:28	7.000	23.000
77	T7_00108	T7	7/11/95	7/23	03:31	7.000	23.000
78	TD_00109	DB	11/26/08	7/23	03:34	7.000	23.000
79	TD_00110	DB	11/26/08	7/23	05:33	7.170	23.000
80	TD_00111	DB	11/26/08	7/23	06:26	7.330	23.000
81	T7_00112	T7	4/86 (1)	7/23	07:31	7.500	23.000
82	T7_00113	T7	4/86 (2)	7/23	07:34	7.500	23.000
83	T7_00114	T7	4/23/91	7/23	07:36	7.500	23.000
84	T7_00115	T7	7/11/95	7/23	07:39	7.500	23.000
85	TD_00116	DB	11/26/08	7/23	07:42	7.500	23.000
86	TD_00117	DB	11/26/08	7/23	09:37	7.660	23.000
87	TD_00118	DB	11/26/08	7/23	10:28	7.830	23.000
88	T7_00119	T7	4/86 (1)	7/23	11:36	8.000	23.000
89	T7_00120	T7	4/86 (2)	7/23	11:39	8.000	23.000
90	T7_00121	T7	7/11/95	7/23	11:41	8.000	23.000
91	TD_00122	DB	11/26/08	7/23	11:44	8.000	23.000
92	TD_00123	DB	11/26/08	7/23	13:37	8.170	23.000
93	TD_00124	DB	11/26/08	7/23	14:27	8.320	23.000
94	T7_00125	T7	4/86 (1)	7/23	15:37	8.500	23.000
95	T7_00126	T7	4/86 (2)	7/23	15:39	8.500	23.000
96	T7_00127	T7	7/11/95	7/23	15:43	8.500	23.000
97	TD_00128	DB	11/26/08	7/23	15:46	8.500	23.000
98	TD_00129	DB	11/26/08	7/23	17:34	8.660	23.000
99	TD_00130	DB	11/26/08	7/23	18:28	8.830	23.000
100	T7_00131	T7	7/11/95	7/23	19:43	9.000	23.000
101	TD_00132	DB	11/26/08	7/23	19:46	9.000	23.000
102	TD_00133	DB	11/26/08	7/23	21:32	9.160	23.000
103	TD_00134	DB	11/26/08	7/23	22:29	9.330	23.000
104	TD_00135	DB	11/26/08	7/24	01:40	9.670	23.000
105	TD_00136	DB	11/26/08	7/24	02:36	9.830	23.000

106	TD_00137	DB	11/26/08	7/24	06:00	10.170	23.000
107	TD_00138	DB	11/26/08	7/24	06:53	10.330	23.000
108	TD_00139	DB	11/26/08	7/24	10:04	10.660	23.000
109	TD_00140	DB	11/26/08	7/24	11:02	10.840	23.000
110	TD_00141	DB	11/26/08	7/24	14:25	11.170	23.000
111	TD_00142	DB	11/26/08	7/24	15:20	11.330	22.990
112	TD_00143	DB	11/26/08	7/25	02:28	11.660	22.990
113	TD_00144	DB	11/26/08	7/25	03:18	11.830	23.000
114	TD_00145	DB	11/26/08	7/25	06:15	12.160	23.000
115	TD_00146	DB	11/26/08	7/25	07:02	12.330	23.000
116	TD_00147	DB	11/26/08	7/25	10:09	12.660	23.000
117	TD_00148	DB	11/26/08	7/25	10:58	12.830	23.000
118	TD_00149	DB	11/26/08	7/25	13:59	13.170	23.000
119	TD_00150	DB	11/26/08	7/25	14:48	13.330	23.000
120	TD_00151	DB	11/26/08	7/25	17:47	13.670	23.000
121	TD_00152	DB	11/26/08	7/25	21:39	14.170	23.000
122	TD_00153	DB	11/26/08	7/25	22:31	14.330	23.000
123	TD_00154	DB	11/26/08	7/26	01:27	14.670	22.960
124	TD_00155	DB	11/26/08	7/26	02:18	14.830	22.910
125	TD_00156	DB	11/26/08	7/26	05:24	15.170	22.820
126	TD_00157	DB	11/26/08	7/26	06:18	15.330	22.780
127	TD_00158	DB	11/26/08	7/26	09:27	15.660	22.690
128	TD_00159	DB	11/26/08	7/26	10:21	15.830	22.650
129	TD_00160	DB	11/26/08	7/26	12:55	16.160	22.600
130	TD_00161	DB	11/26/08	7/26	14:00	16.340	22.670
131	TD_00162	DB	11/26/08	7/26	17:15	16.680	22.760
132	TD_00163	DB	11/26/08	7/26	18:11	16.850	22.790
133	TD_00164	DB	11/26/08	7/26	21:05	17.160	22.880
134	TD_00165	DB	11/26/08	7/26	22:00	17.330	22.940
135	TD_00166	DB	11/26/08	7/27	01:07	17.670	23.000
136	TD_00167	DB	11/26/08	7/27	02:05	17.830	23.000
137	TD_00168	DB	11/26/08	7/27	05:17	18.160	23.000
138	TD_00169	DB	11/26/08	7/27	06:12	18.330	23.000
139	TD_00170	DB	11/26/08	7/27	09:24	18.670	23.000
140	TD_00171	DB	11/26/08	7/27	10:18	18.830	23.000
141	TD_00172	DB	11/26/08	7/27	13:35	19.170	23.000
142	TD_00173	DB	11/26/08	7/27	14:31	19.340	23.000
143	TD_00174	DB	11/26/08	7/27	17:38	19.670	23.000
144	TD_00175	DB	11/26/08	7/27	18:31	19.840	23.000
145	TD_00176	DB	11/26/08	7/27	21:37	20.170	23.040
146	TD_00177	DB	11/26/08	7/27	22:38	20.330	23.090
147	TD_00178	DB	11/26/08	7/29	11:37	20.340	27.490
148	TD_00179	DB	11/26/08	7/29	23:12	20.260	30.100
149	TD_00180	DB	11/26/08	7/30	12:45	20.180	33.120
150	TD_00181	DB	11/26/08	7/30	23:53	20.100	35.610
151	TD_00182	DB	11/26/08	8/1	01:24	19.990	39.090
152	TD_00183	DB	11/26/08	8/1	12:39	19.870	41.590
153	TD_00184	DB	11/26/08	8/2	00:55	19.750	44.300

154	TD_00185	DB	11/26/08	8/2	12:43	19.640	46.850

Table 3: deployment log for XBTs. Type is “DB” for Deep Blue, or T7 for drop rate comparison sites. “Manuf. Date” is the manufacture date indicted on the XBT; the remaining information is for the date, time, and location of launch in PNE09.

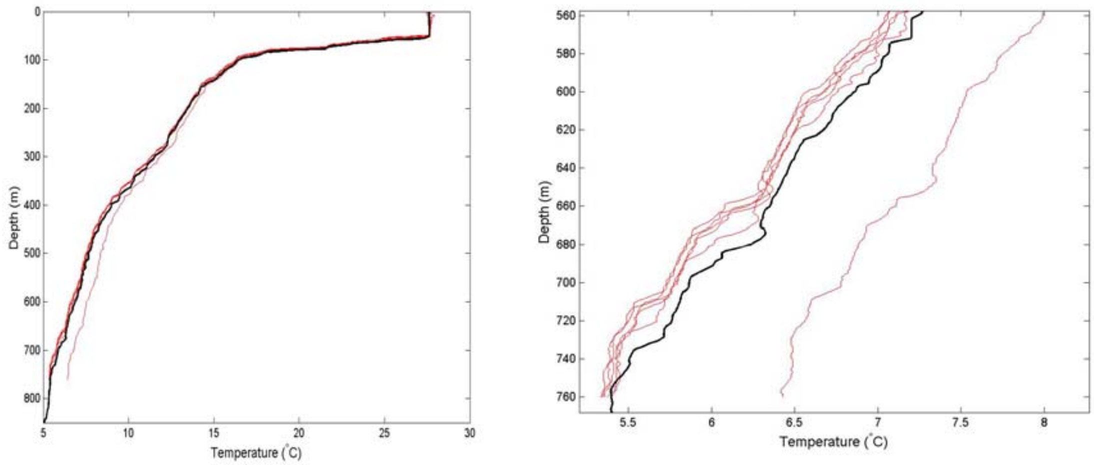

Fig. 7: comparison plot of 5 XBT temperature profiles (red) and CTD temperature vs. depth (black) at 4°N, 23°W. The right-hand panel shows a closeup at the bottom of the XBT casts. All XBTs underestimated depth by 7—28m, and one (serial number 552666, batch 4/86(1)) had a linearly increasing bias with depth (1.2°C too warm at 645m depth).

Preliminary property sections

Due to the large number of XBT deployments, it was highly desirable to combine XBT and CTD data to obtain the highest resolution section of water properties. This was done with the Deep Blue XBT profiles, after adjusting their drop rate to match the simultaneous CTD casts at the comparison sites using the following, determined by minimizing the least-squares differences between XBT and CTD T(z) at the sites:

$$z_{true}=1.014\ z_{measured}.$$

Salinity *S* for the XBT observations of temperature *T* vs. (true) depth *z* was calculated as follows:

1. For each $T_{xbt}(z)$ measured by the XBT, convert to pressure *p* using the Matlab seawater routine “sw_press.m”.
2. Identify the distance *D* of each CTD cast from the XBT drop site.

3. Identify all observations of temperate T_{ctd} and salinity S_{ctd} within 50 dbar of p for all N CTD casts where D<2000 km.
4. For each profile of T_{ctd}, S_{ctd} observations spanning the 50dbar range, calculate the T/S relationship using a linear fit.
5. For each T/S relationship, calculate salinity S_{xbt} for the observed T_{xbt}.
6. Calculate a mean S_{xbt} from the N estimates (one from each cast identified in step 3), weighted by $1/D^2$.

To estimate oxygen, it was assumed that oxygen values at a given sigma-theta (calculated from T, S and pressure) would match those at the neighboring CTD casts, weighted as for salinity.

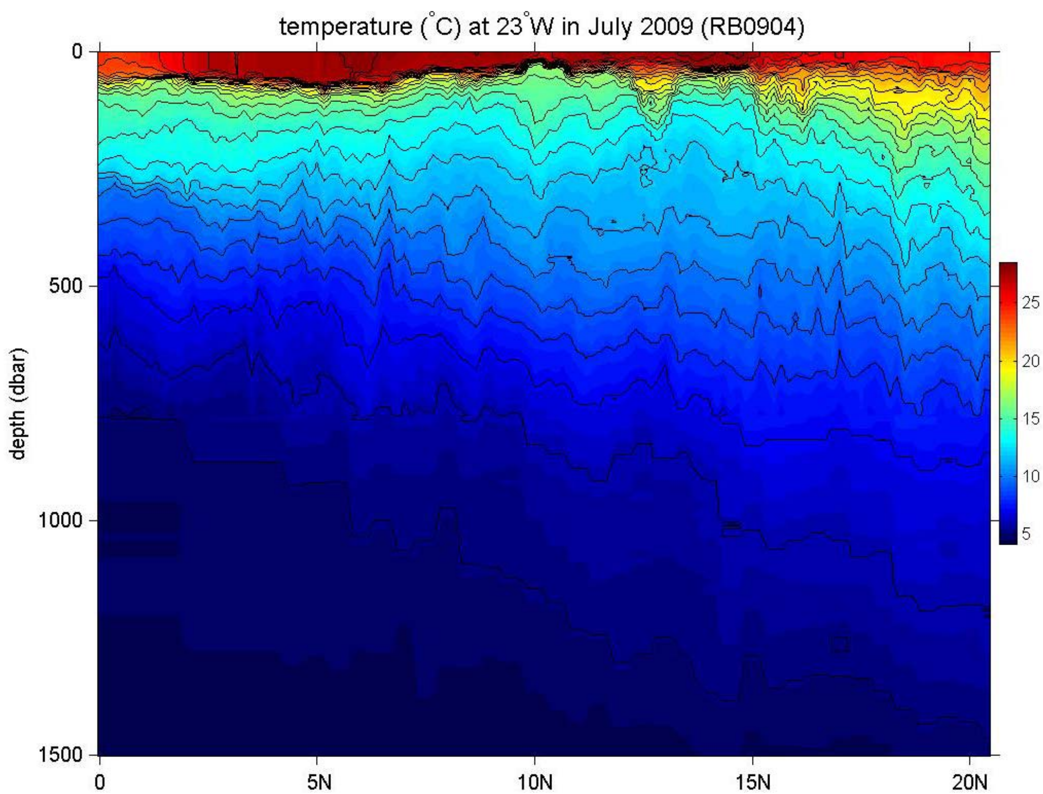

Fig. 8: temperature (ºC) vs. depth at 23ºW.

Temperature vs. depth along the 23ºW section is shown in Fig. 8. Surface features include the warm, thick subtropical gyre and hot, shallow tropical surface water layer. Subsurface isotherms reveal the equatorial shoaling. At depths of 100—800 dbar, shoaling isotherms at 14ºN are associated with the cyclonic Guinea Dome.

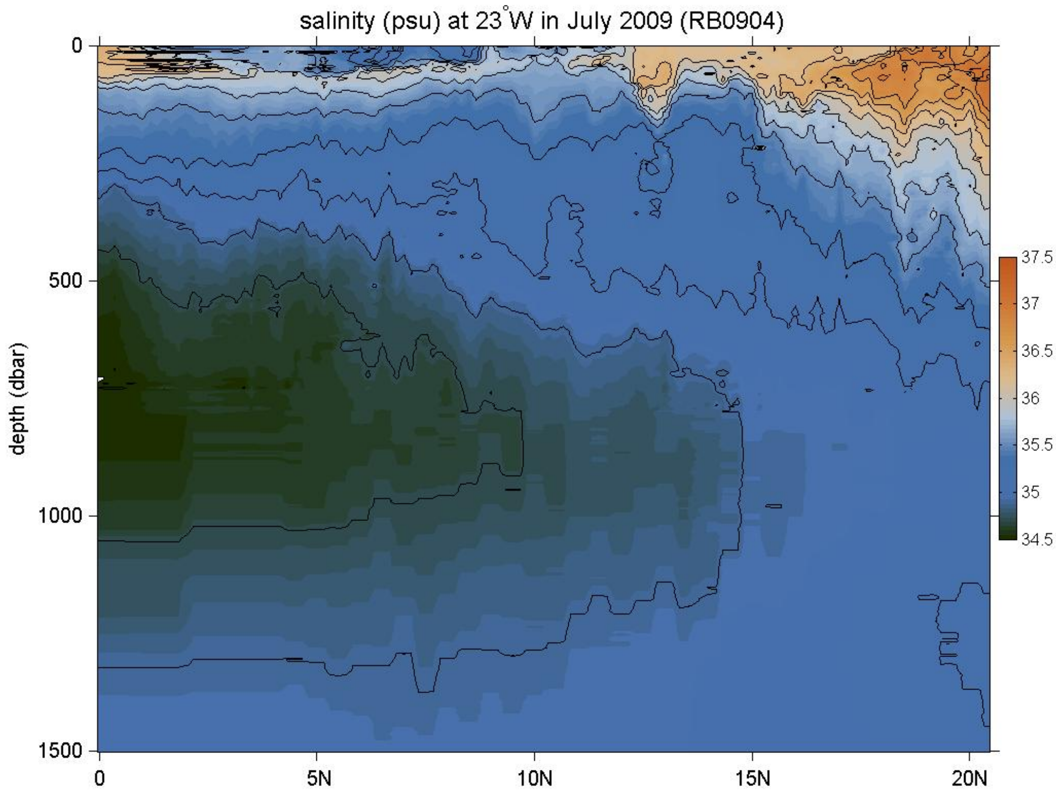

Fig. 9: salinity (psu) vs. depth at 23ºW.

Salinity vs. depth (Fig. 9) shows the increased salinity of the subtropical waters to the north, in the region where increased evaporation-minus-precipitation drives subduction and the production of Salinity Maximum Water (SMW). Tropical SMW is seen beneath the surface, where low salinity is caused by the precipitation associated with the Intertropical convergence zone. At 500—1000 dbar, the signature of northward-flowing fresh Antarctic Intermediate Water dominates the section.

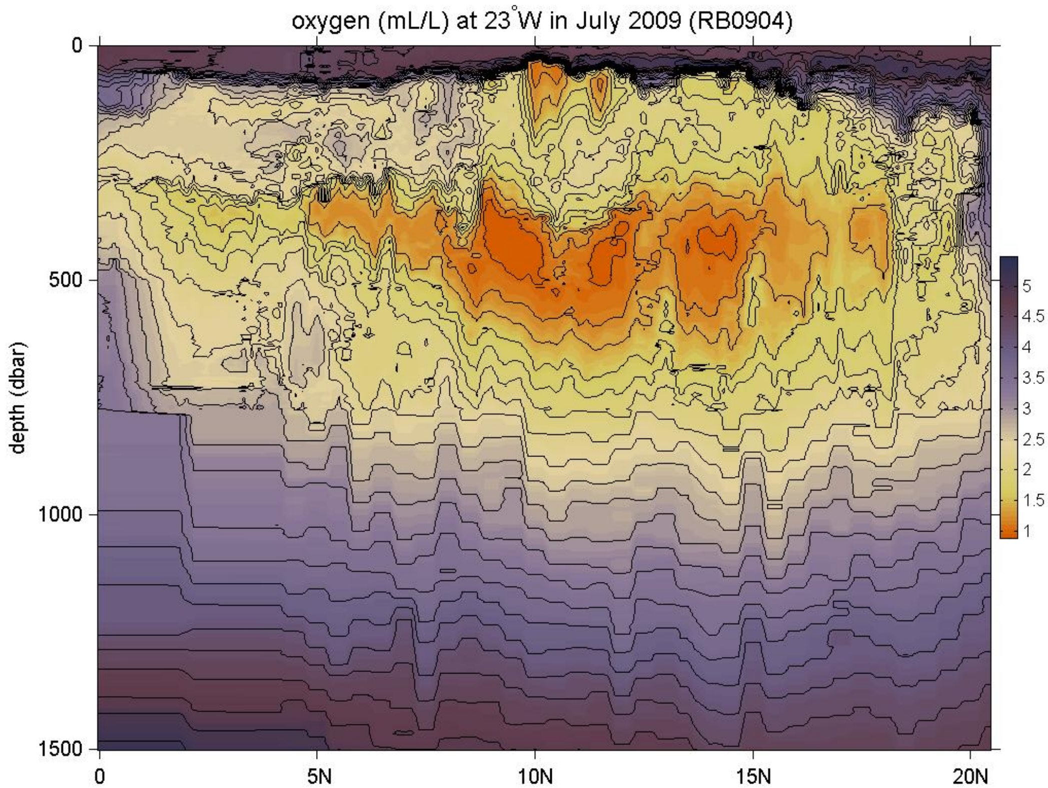

Fig. 10: oxygen (mL/L) vs. depth at 23ºW.

Oxygen vs. depth along 23ºW is shown in Fig. 10. The oxygen minimum water at 400—600 dbar is the most prominent feature of the section. This water is in the stagnant shadow zone of the North Atlantic, not participating in the ventilated thermocline circulation of the subtopical gyre. The abrupt increase in oxygen values north of ~18ºN marks the Cape Verde Frontal Zone, which also marks the boundary between North Atlantic and South Atlantic Central Water (this is shifted far to the north, compared to earlier PNE cruise sections when it is typically found at ~14°N). High oxygen values are also found at depths of 100—250m from the equator to 1ºN. The position of this anomaly corresponds to that of the EUC, suggesting that higher oxygen water has been advected from the west.