BRAZIL/U.S.
WORKSHOP ON PHYSICAL OCEANOGRAPHY

3–6 August 1987

Ocean Process Analysis Laboratory
Institute for the Study of Earth, Oceans and Space
University of New Hampshire
Durham, NH 03824 U.S.A.

Brazil/US Workshop on Physical Oceanography

3-6 August 1987

Ocean Process Analysis Laboratory
Science and Engineering Research Bldg
University of New Hampshire
Durham, NH 03824

Sponsored by:

National Science Foundation/International Programs
Conselho Nacional de Desenvolvimento Cientifico e Tecnologico
Institute for the Study of Earth, Oceans and Space
Ocean Process Analysis Laboratory
Tinker Foundation, Inc.
Center for International Perspectives

Cover photograph: An infrared image on the southwestward flowing Brazil Current (light) near the Brazil coast between 20°S and 30°S. The mingling of the colder (dark) shelf water and the tropical water is occurring over the continental slope between the 200m and 1000m isobaths. (provided by N. Garfield, URI)

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I. Introduction

The first Brazil/U.S. Workshop on the Physical Oceanography of the South Atlantic Ocean resulted from a growing mutual interest in studying a complex and exceedingly interesting part of the world's ocean. Dave Evans, while at the University of Rhode Island, (now at the Office of Naval Research) and Sergio Signorini and, later, A. Mascarenhas (University of Sao Paulo) made the first effort to convene such a workshop several years ago. The purpose was to broaden Brazilian/U.S. interest in studies of the Brazil Current. Finally in 1986, Mascarenhas and W. Brown (University of New Hampshire) were able, with the support of D. Evans, to convince the U.S. National Science Foundation International Programs and Brazil's CNPq and others of the merit of such a workshop.

On 3 August 1987 the first Brazil/U.S. Workshop was convened at the University of New Hampshire for four days of exchange and planning. Despite last minute uncertainty about travel funds, five Brazilians were joined by 25 U.S. physical oceanographers (see Table 1) for four days of interaction (see Appendix A for participant addresses). Two days of technical talks were followed by two days of planning discussions. At the end of the week, the Brazilians visited Woods Hole Oceanographic Institution before returning to Brazil. Table 2 details the Schedule of Events.

After some brief introductory remarks, Belmiro Castro (IOUSP) presented an overview of Brazilian physical oceanograhy. Participant talks followed. The extended abstracts of these talks appear in the next section. The final section contains summaries of the general discussions which occurred on Tuesday afternoon and Wednesday morning, as well as, the more focussed discussions of Wednesday afternoon.

Table 1. A list of registrants for the first Brazil/U.S. Workshop on Physical Oceanography at the University of New Hampshire 3-6 August 1987

Robert Beardsley (U.S.)

Reinaldo Boneto (Br.)

Janice Boyd (U.S.)

Wendell S. Brown (U.S.)

John Bruce (U.S.)

Belmiro Mendes de Castro Filho (Br.)

Douglas Evans (U.S.)

David Evans (U.S.)

Charles Flagg (U.S.)

Manuel Fiadeiro (U.S.)

Wayne Geyer (U.S.)

Newell Garfield (U.S.)

Yoshimine Ikeda (Br.)

James D. Irish (U.S.)

William Johns (U.S.)

Bjorn Kjerfve (U.S.)

Thomas Lee (U.S.)

Richard Limeburner (U.S.)

Joao A. Lorenzzetti (Br.)

Affonso da Silveira Mascarenhas, Jr. (Br.)

Jerry Miller (U.S.)

Dennis W. Moore (U.S.)

Frank Muller-Karger (U.S.)

David Musgrave (U.S.)

Thomas Orvosh (U.S.)

Dick Ou (U.S.)

Neal Pettigrew (U.S.)

Phil Richardson (U.S.)

Raymond Schmitt (U.S.)

Robert H. Weisberg (U.S.)

Table 2. Schedule of Events
Brazil/U.S. Physical Oceanography Workshop

3-6 August 1987

*Sponsored by
National Science Foundation (U.S.A.)
and Conselho Nacional De Desenvolvimento Cientifico e Tecnologico (Brazil)

Sun, 8/2

5:00-9:00 PM	Registration, Undergraduate Apartment Complex (UAC) Lounge (603-862-1779)

Mon, 8/3

8:05 AM	Campus Shuttle pickup in front of UAC Community Building
8:15 AM	Breakfast, Philbrook Dining Hall
8:30 AM	Late Registration, Science and Engineering Research Building (SERB) Room 142
9:00 AM	Welcoming Comments, Ocean Process Analysis Lab (OPAL) Conference Room, SERB 136 - Dr. James Morrison, Associate Vice President for Research - W. Brown, Co-convenor - A. Mascarenhas, Co-convenor
9:15 AM	Talks, OPAL Conference Room, SERB (Moderator—B. Castro) - Physical Oceanography in Brazil . . . . . B. Castro - Brazil Current Measurement . . . . A. Mascarenhas, D. Evans
10:45 AM	Break

*Additional support by:
Institute for the Study of Earth, Oceans and Space (UNH)
Ocean Process Analysis Laboratory (UNH)
Tinker Foundation, Inc.
Center for International Perspectives (UNH)

Table 2. continued

11:00 AM	Talks resume, OPAL Conference Room, SERB 136 (Moderator—A. Mascarenhas)
	- Satellite AVHRR Imagery of the Brazil Current During 1985 . . . . N. Garfield, D. Evans
	- The NECC as Measured by SEQUAL/ FOCAL Drifters. . . . . P. Richardson
	- Meridional Transports in the South Atlantic . . . . Y. Ikeda
	- Tropical Atlantic Finestructure . . . . R. Schmitt
1:00 PM	Lunch, Philbrook Dining Hall
2:15 PM	Talks resume, OPAL Conference Room, SERB 136 (Moderator—D. Evans)
	- Circulation Field off NE Brazil in 1985, and Comparison with Historical Patterns . J. Boyd
	- Large Scale Eddy Caracteristics and Variability in the Western Atlantic Near Equatorial Waters . . . . J. Bruce
	- The NBC Retroflection as Traced from Space with the Coastal Zone Color Scanner . . . . F. Muller-Karger
	- Equatorial Upper Ocean Response to Trade-Winds Forcing Observed Using Moored Current Meters During the SEQUAL Experiment . . . . R. Weisberg
3:45 PM	Break
4:00 PM	Talks resume, OPAL Conference Room, SERB 136 (Moderator—J. Lorenzzetti)
	- Low-Frequency Variability on the Brazilian Continental Shelf . . . . . . B. Castro
	- Dynamics of Amazon Plume . . . . W. Geyer
	- Estuary and Lagoon Systems in Brazil . . B. Kjerfve
6:00 PM	Dinner, Philbrook Dining Hall
8:00 PM	Brazilian Reception, UAC Lounge
Tue, 8/4	
8:05 AM	Campus Shuttle pickup in front of UAC Community Building
8:15 AM	Breakfast, Philbrook Dining Hall

Table 2. continued

9:00 AM	Talks, OPAL Conference Room, SERB 136 (Moderator—C. Flagg) - Variability of the North Brazil Coastal Current . . . . C. Flagg - Physical Oceanography in AMASSEDS . . R. Beardsley - An Overview of "North Brazil Shelf Study" (NOBRASS) . . . . J. Lorenzzetti - The North Brazil Experiment (NOBREX) . . . W. Brown
11:00 AM	Break
11:30 PM	Talks resume, OPAL Conference Room, SERB 136 (Moderator—N. Pettigrew) - Boundary Current Separation and Equatorial Outflow. . . . . D. Ou - Meridional Oscillations Driven by Zonal Winds in a Trapezoidal Equatorial Basin . . . . D. Moore
1:00 PM	Lunch, Philbrook Dining Hall
2:30 PM	Talks resume, OPAL Conference Room, SERB 136 - Doppler Current Profiling from Moored Subsurface Floats . . . . . . N. Pettigrew - The Description of an Inexpensive, Internally Recording CTD . . . . J. Irish - On the Development of Oceanographic Instrumentation in Brazil . . . . . . R. Boneto
4:00 PM	Break
4:30 PM	General Group Discussion, OPAL Conference Room, SERB 136 (Moderator—A. Mascarenhas) Issues concerning Brazilian/U.S. Collaboration
7:00 PM	Banquet, New England Center

<u>Wed, 8/5</u>

8:05 AM	Campus Shuttle pickup in front of UAC Community Building
8:15 AM	Breakfast, Philbrook Dining Hall
9:00 AM	General Group Meetings, SERB 136
10:30 AM	Break

Table 2. continued

11:30 AM	Smaller Group Meetings
1:00 PM	Lunch, Philbrook Dining Hall
	Written Reports
4:00-5:00 PM	Oral Summary, OPAL Conference Room, SERB 136 (Full Group)
6:00 PM	Dinner, Philbrook Dining Hall
<u>Thu, 8/6</u>	
8:05 AM	Campus Shuttle pickup in front of UAC Community Building
8:15 AM	Breakfast, Philbrook Dining Hall
	Preliminary Plan for Cooperative Research
	- Written Reports
1:00 PM	Lunch, Philbrook Dining Hall
	- Planning for Existing Research Initiatives
	- Planning for Next Workshop
6:00 PM	Dinner, Philbrook Dining Hall
<u>Fri, 8/7</u>	
8:15 AM	Breakfast, Philbrook Dining Hall
	Field Trip to Woods Hole Oceanographic Institution (Principally for interested Brazilians)

Physical Oceanography In Brazil

Belmiro Castro
Institute of Oceanography
University of Sao Paul
Sao Paulo - Brazil

There are more than 30 institutions throughout Brazil conducting marine research with the country's premier oceanographic institution in the Instituto Oceanografico da Universidade de Sao Paulo (IOUSP). About 20 faculty work in the Institute's Division of Marine Biology, and fifteen in the Division of Physical Oceanography, both of which offer master's and doctoral programs in their respective disciplines (see Appendix B). The faculty of the Division of Physical Oceanography includes eight physical oceanographers, three chemical oceanographers, two geological oceanographers, one meteorologist, and one specialist in remote sensing. The Institute's three coastal research laboratories provide saltwater access, and offshore work is conducted aboard a seagoing research vessel and two support boats. Instrument development and maintenance is provided at IOUSP within the Oceanographic Instrumentation Laboratory, staffed by three engineers and two technicians.

In nearby Sao Jose dos Campos, the Instituto de Pesquisas Espaciais (INPE, part of the Ministerio de Cienciae Tecnologia) conducts an active physical oceanography program within its Department of Meteorology and Oceanography (DMO). INPE has the facilities to receive and process data from a suite of satellites including LANDSAT, GOES, NOAA, and METEOSAT, and a SPOT receiving and processing station is nearing completion. Airplane remote sensing capability is provided by a twin-engine Bandeirantes aircraft.

Brazil also has three other institutions involved in physical oceanographic research, all in the south: Diretoria de Hidrografica e Navegacao in Niteroi, Instituto de Estudos do Mar Paulo Moreira in Arraial do Cabo, and Fundacao Universitaria do Rio Grande.

Brief Overview of Physical Oceanographic Institutions

- There are more than 30 institutions doing marine research in Brazil

- Physical Oceanography:
  IOUSP - Instituto Oceanografico da Universidade de Sao Paulo
  INPE - Instituto de Pesquisas Espaciais (Sao Jose dos Campos, SP)
  DHN - Diretoria de Hidrografie e navegacao (Niteroi, RJ)
  IEMAPM - Instituto de Estudos do Mar Paulo Moreira
  (Arraial do Cabo, RJ)
  FURG - Fundacao Universitaria do Rio Grande (Rio Grande, RS)

- IOUSP
  - Division of Marine Biology - 20 faculty
  - Division of Physical Oceanography
    - 8 Physical Oceanographers
    - 3 Chemical Oceanographers
    - 2 Geological Oceanographers
    - 1 Remote Sensing
    - 1 Meteorologist
  - Main Resources
    - 3 Coastal Research Stations
    - 1 Oceanographic Ship
    - 2 Boats
  - Graduate Courses (M.Sc., Ph.D)
    - Biological Oceanography
    - Physical Oceanography
  - Oceanographic Instrumentation Laboratory
    - 3 Engineers
    - 2 Technicians

- Instituto de Pesquisas Espaciais - INPE (Space Research Institute)
  - Ministerio de Ciencia e Tecnologia
    - INPE
      - Departamento de Meteorologia e Oceanografia (DMO)

  Facilities:
  - LANDSAT - receiving & processing stations
  - SPOT - Station being concluded
  - NOAA, GOES, METEOSAT - receives & processes
  - One twin-engine BANDEIRANTES aircraft

II. Workshop Abstracts

Brazil Current Measurements

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and

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Introduction

Two apparent anomalies in our conceptual model of global circulation--the computed equatorialward heat flux in the South Atlantic and the very low transport associated with the Brazil Current compared with that expected from the wind stress distribution--motivated the increased interest in the general circulation of the South Atlantic Ocean. The first anomaly may be due to the lack of closely spaced modern observations, including current and transport measurements. The second one is probably correlated to insufficient knowledge of the thermohaline circulation. In order to fulfill this need and to achieve a better knowledge of the Brazil current dynamics, eight oceanographic cruises has been performed since 1982 as part of a cooperative program between the Oceanographic Institute of the University of Sao Paulo, Brazil, and the School of Oceanography, University of Rhode Island, U.S.A., through Dr. David Evans.

In order to focus the work, some questions were asked:

i) How much (if any) transport gets past Abaolhos seamounts (~20°S)?
ii) Does the transport of the Brazil Current increase downstream?
iii) How strong is the transport in the supposed recirculation region?
iv) Does the AAIW flow north or south along the western South Atlantic boundary?
v) Is the Brazil current between 19°S and 32°S characterized by meanders and eddies or by "straight" streamlines?
vi) Is the reported northward flow offshore of the Brazil Current always present or only apparent due to unresolved eddies and other sampling problems?

Results

Even now, the role of the seamount chain near 20°S on the behavior of the Brazil Current flow is unclear. As pointed out by Evans et al. (1983), "any flow from the north must either turn due east for nearly 530 km before returning to the boundary, or flow through one of the narrow deep passages and/or up onto the continental shelf."

Local measurements of velocity profiles performed during April 1983 at one of those passages (Figure 1) did not furnish evidence that a great part of Brazil Current would flow through those passages only. Dynamical computations from hydro casts yielded approximately 3.8 Sv (6.8 Sv) flow through the channel in the banks relative to 500 m (1000 m). PEGASUS velocity profiles taken at TC-1 show NW/SW flow sandwiched between SW flow in the upper and lower part of the profile. The northward component would seem to indicate that AAIW moves northward along the boundary.

Results of the PEGASUS profile section off Cabo Frio indicates at the most inshore position (TC-6, 200 m depth) an almost barotropic flow toward SW with a SE flow next to the bottom in some profiles. The other two positions (TC-4 and TC-5) show a mean direction in the upper 500 m toward SW, meanwhile down to 1000 m the direction is NE. At the two outermost positions (TC-3 and TC-2) the profile exhibits a complex structure and in general the mean horizontal velocity upper 600 m is SW/NW, turning toward southwestward as the depth increases.

An XBT temperature section at Cabo Frio was examined. Table 1 below shows the values of transport of volume and heat using different methods for the Cabo Frio section (24^{o}S).

To verify the downstream increase of volume and heat, an XBT and PEGASUS section was performed at 31^{o}S (see Figures 2 and 3). The results are listed in Table 2.

The PEGASUS station I is the outermost station. It shows a surface flow of 10-15 cm/s toward the SW with a much stronger signal (40 cm/s) to WSW between 200 and 700 m.

The profile at station II shows average speeds between 40 and 50 cm/s throughout the profile, with maximum speeds of 75 cm/s. The direction is nearly constant. At station III the speed profile is strongly sheared in the upper 250 m. The upper 250 m flow is toward the SW while between 250 and 650 m the flow is around N. Below 650 m it swings to a SE direction. At the shallowest station the speeds are reduced to about 35 m/s directed toward south in the upper 150 m. Between 250 and 500 m there is a second maximum of approximately 20 cm/s directed SW to WSW between 250 and 500 at 20 cm/s. Below 600 m a relatively weak flow directed toward NE.

Concerning the transport calculation, since we did not sample far offshore enough, the transport estimates must be viewed as lower bounds. Our estimate using the vertically averaged velocity normal to the section was 16.7 Sv directed toward 230^{o} true. The geostrophic transport estimated using the PEGASUS temperature data and a T-S relationship derived by Miranda (1981) with reference level at 800 m was 11.2 Sv.

The examination of the temperature field sampled by XBT at 31^{o}S show a strong baroclinic signal indicating the Brazil Current core. The geostrophic velocity field computed with respect to 600 m show a core of maximum velocity (80 cm/s) that agree well with the PEGASUS data. We can also notice the fact that we have missed the bulk of the current in choosing the PEGASUS site.

The tables below show values of transport of volume and heat using different methods for the Cabo Frio section (24°S) and Tramondai section (31°S). The PEGASUS data show that the 0 cm/s isotach actually slopes strongly across the section. Using the observed zero speed depth from the PEGASUS, produces nearly identical transports from both geostrophic and direct methods.

Table 1. Southward transports @ 24°S section.

PEGASUS	PEGASUS temperature [level of no motion @ 800 m]	XBT [level of no motion @ 750 m]
6.0 Sv	5.5 Sv	2.0 Sv

Table 2. Southward transports @ 31°S section.

PEGASUS	PEGASUS temperature [level of no motion @ 800 m]	XBT [level of motion @ 750 m]
16.7 Sv	11.2 Sv	9.7 Sv

Transport of heat through XBT section 7.3×10^{14}W

The temperature field sampled by XBT's show a much stonger baroclinic signal along the 31°S than along 24°S. Also at 31°S the baroclinicity extends deeper than at 24°S, indicating a possibility of recirculation regime. The temperature sections at Cabo Frio (24°S) exhibit eddy-like features, introducing noise in the geostrophic calculation.

References

Evans, D.L.; S.R. Signorini; L.B. Miranda (1983). "A Note on the Transport of the Brazil Current". Journal of Physical Oceanography., 13(9), 1732-1738.

Miranda, L.B. (1982). "Análise de Massas de Agua de Platoforma Continental e da Regiao Oceânis Adjacente": Cabo de Sao Tomé (RJ) a Ilha de S. Sebastiao (SP); Tese de Livre docencia, Instituto Oceanografico da U.S.P., 210pp.

Evans, D.L.; S.R. Signorini (1985). "Vertical Structure of the Brazil Current", Nature, 135,6014, 48-50.

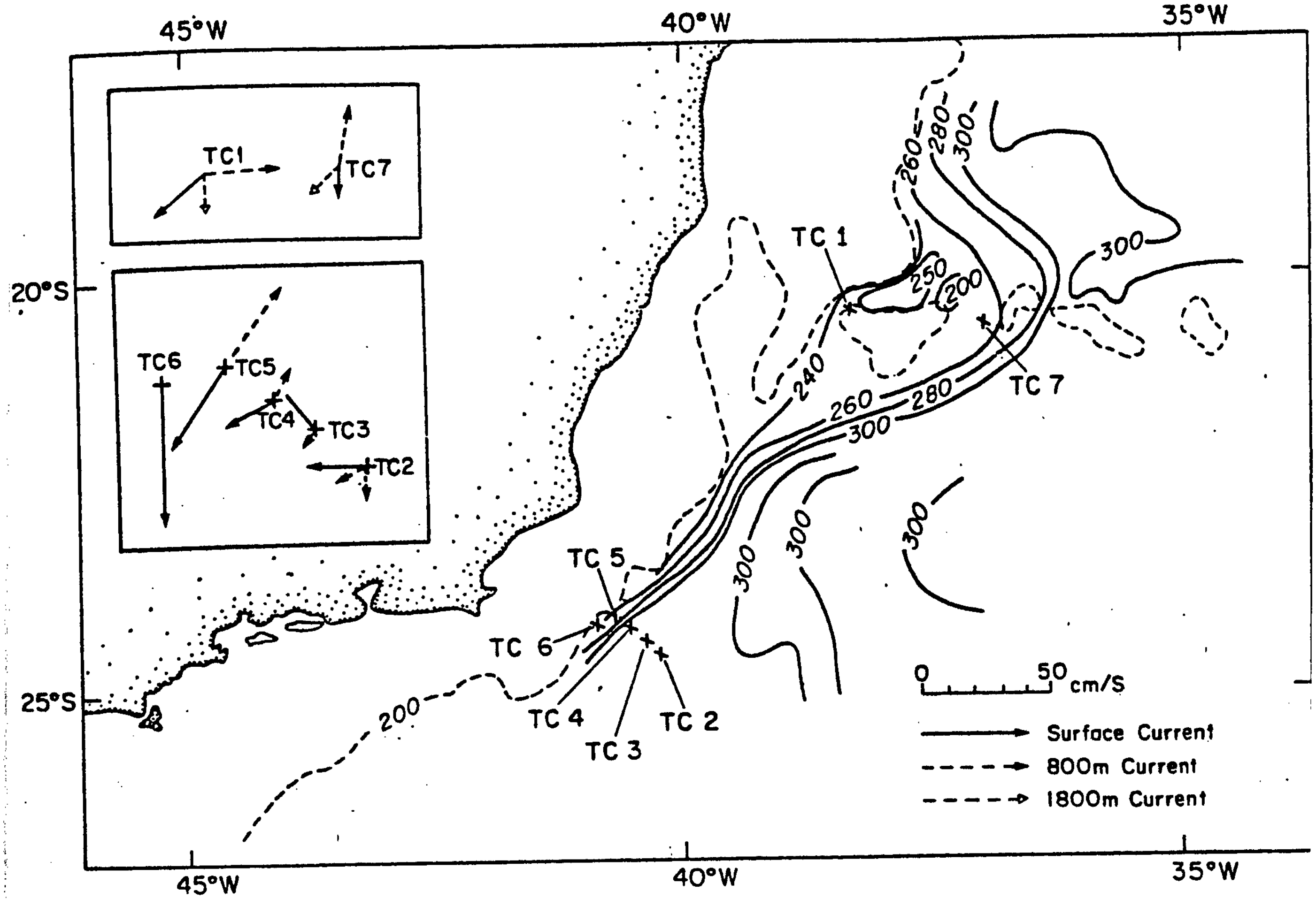

Figure 1. Area surveyed in April 1983 showing the 15°c isotherm depth. and mean velocity vectors at depths characteristic of surface, intermediate and deep water. From Evans et. al. (1985).

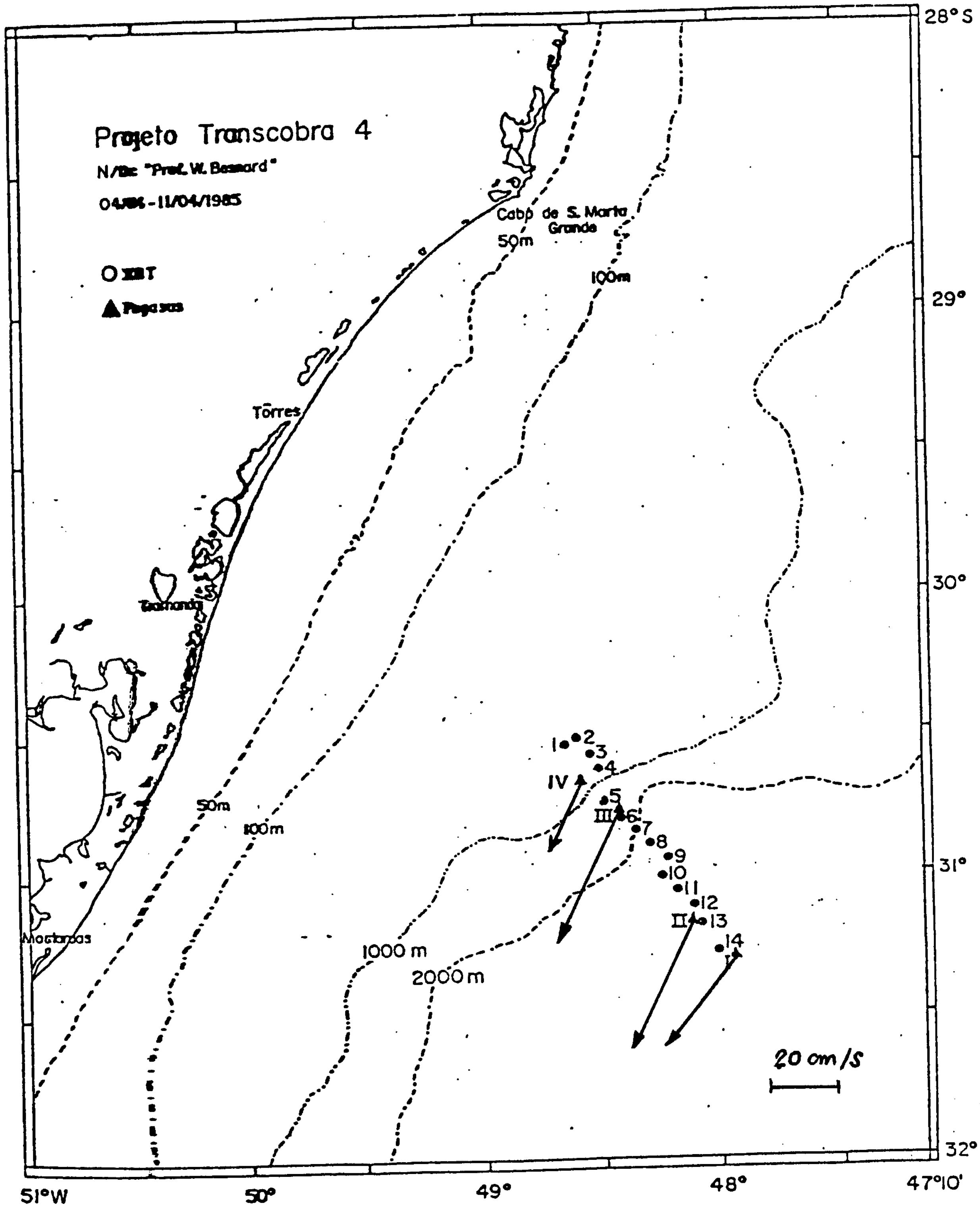

Figure 2. Area surveyed during April 1985 cruise. The PEGASUS current vectors represent mean values in the upper 800m. The stations III and IV have flow reversals at 250m and 400m respectively.

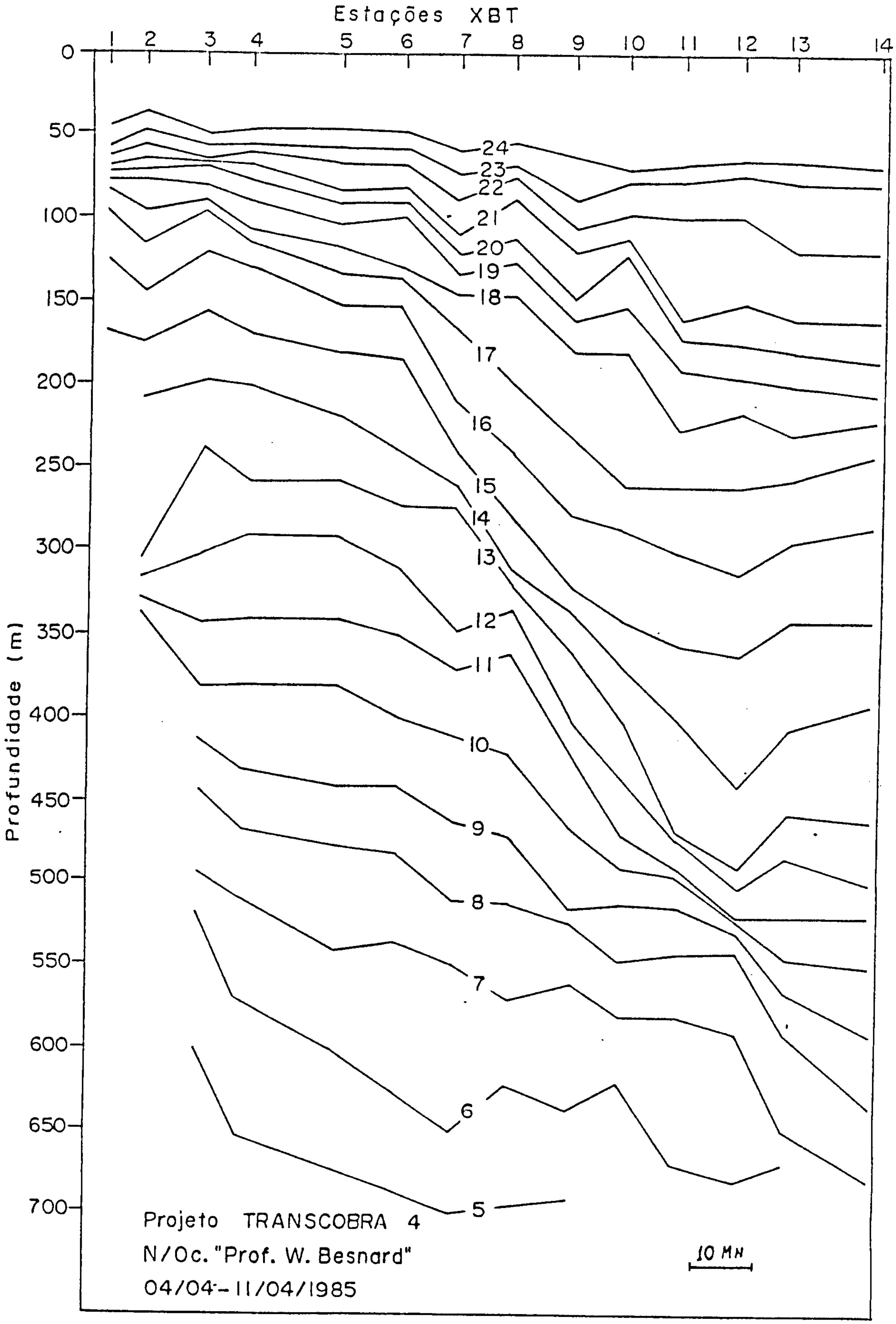

Figure 3. XBT temperature section along 31°S during April 1985 cruise.

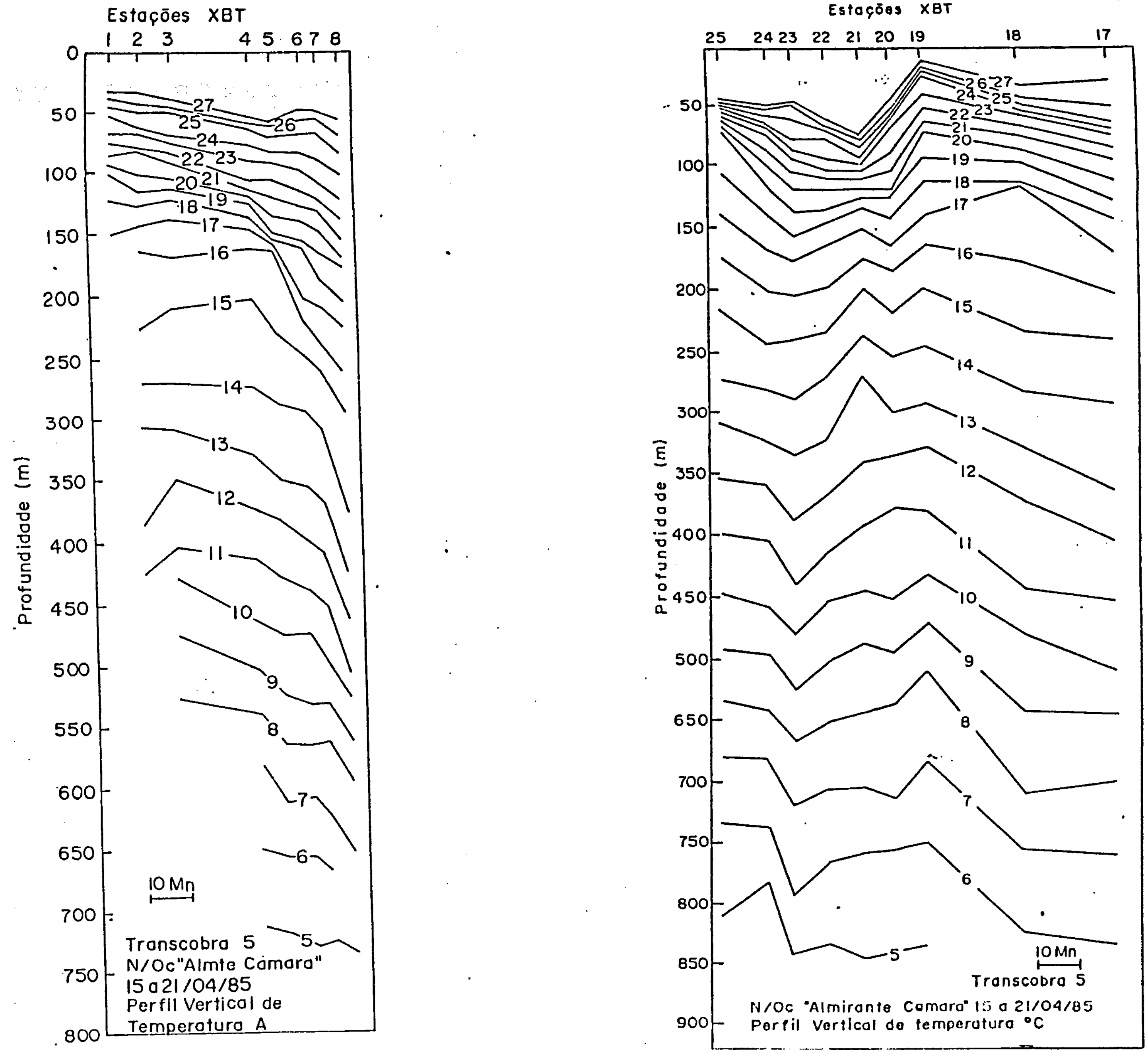

Figure 4. XBT temperature section along the transponder line (~24°S)

Satellite AVHRR Imagery of the Brazil Current during 1985

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and

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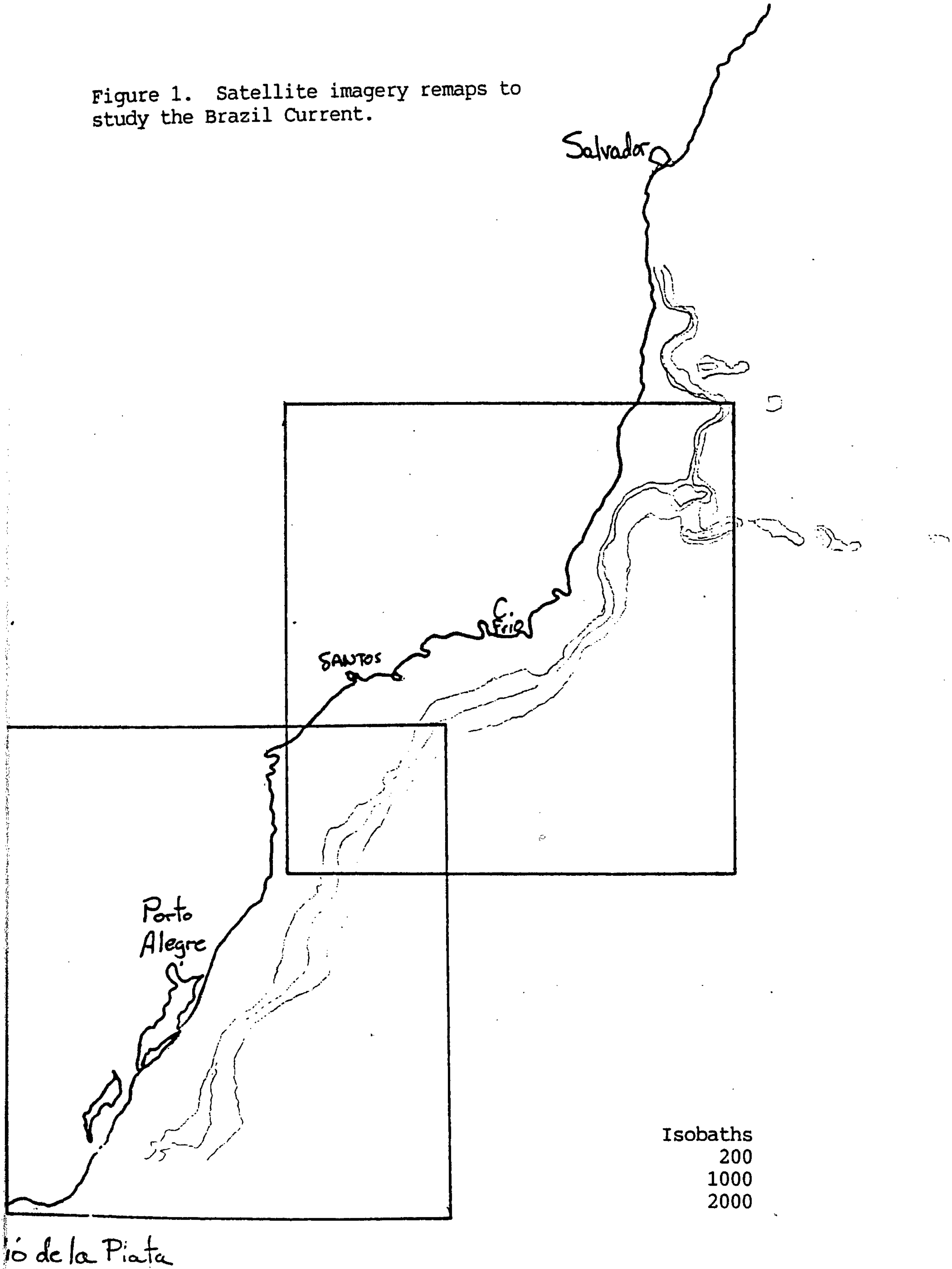
Narragansett, RI 02882

Through a cooperative effort between the University of Rhode Island (URI) and the Instituto de Pesquisas Espaciais (INPE) high resolution (1 km) infrared satellite imagery is archived at URI. The data are received and recorded on magnetic tape at the INPE tracking facility. Using the University of Miami developed software, the data are processed at URI to produce sea surface temperature images with 2 km resolution for two areas of the south Brazilian coast (Figure 1). These data are being used as part of a joint project between URI and the Instituto Oceanografico, Universidade Sao Paulo (IOUSP) to study the Brazil Current.

The satellite data successfully address many of the initial questions posed by the project. The Brazil Current is usually observed as a continuous feature between 21° and 31°S. The warmest signature of the Brazil Current is generally found near the shelf break with an apparent significant transport over the shelf inshore of the 200 m isobath. South of Cabo Frio where the bathymetry turns sharply to the west, the Brazil Current often displays a semi-permanent meander, or a bimodal structure. When the current meanders offshore, it it generally "reattaches" to the shelf break farther south. Inshore, around Cabo Frio and north to Cabo de St. Thome, the imagery reveals the intense intermittant coastal upwelling. The cold upwelled water can either move south on the shelf parallel to the Brazil Current or move offshore, and be incorporated into the Brazil Current. It appears that this location may be the generation area for many of the eddies and meanders seen farther south. South of 31°S, the 1985 data indicates that Malvinas Current waters may have intruded north on the shelf, inshore of the Brazil Current.

With the three-year time series of infrared satellite imagery of the Brazil Current now available, the data are being used to determine statistics of the front and eddies. Techniques for inferring the motion, using the imagery alone and in conjunction with other data sets, are a major objective of this component of the project.

Figure 1. Satellite imagery remaps to study the Brazil Current.



The NECC as Measured by SEQUAL/FOCAL Surface Drifters

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The seasonal variation of currents in the equatorial Atlantic was studied with drifters as part of the SEQUAL and FOCAL experiments. During 1983-1985, 30 freely drifting drogued buoys were launched in the North Equatorial Countercurrent (NECC) and 23 in the South Equatorial Current (SEC). In addition, continuously recording current meters were moored for 20 months at depths from 20 to 300 m near the center of the NECC, at 6N, 28W. These measurements are the longest series ever obtained in this current and provide information about its seasonal and interannual variations and zonal, meridional, and vertical structure.

The seasonal cycle of the NECC is very regular from year to year. Each year the NECC starts up in May-June. It flows eastward across the Atlantic 28W, and flowing into both the Guinea Current and North Equatorial Current. It disappears or reverses from about January-June west of 18W. Some near-surface water of the NECC is inferred to downwell and flow equatorward toward the Equatorial Undercurrent.

The South Equatorial Current flows into the North Brazil Current, which, during spring, continues up the coast into the Caribbean. During fall, however, the whole North Brazil Current retroflects, or turns back on itself, between 45-50W, forming the western NECC. The retroflection establishes a meander pattern in the NECC that slowly propagates westward during fall at a speed of 4 cm/sec. The meanders have a displacement of about 300 km in latitude, a wavelength of 900 km, and meridional velocity fluctuations up to 100 cm/sec. The swift currents and time-dependent meanders in the western NECC cause a high eddy kinetic energy, ~2400 cm2/sec2, equivalent to that of the energetic part of the Gulf Stream. See Richardson, P.L. and G. Reverdin, Journal of Geophysical Research, 92:C4, 3091-3708, for more details.

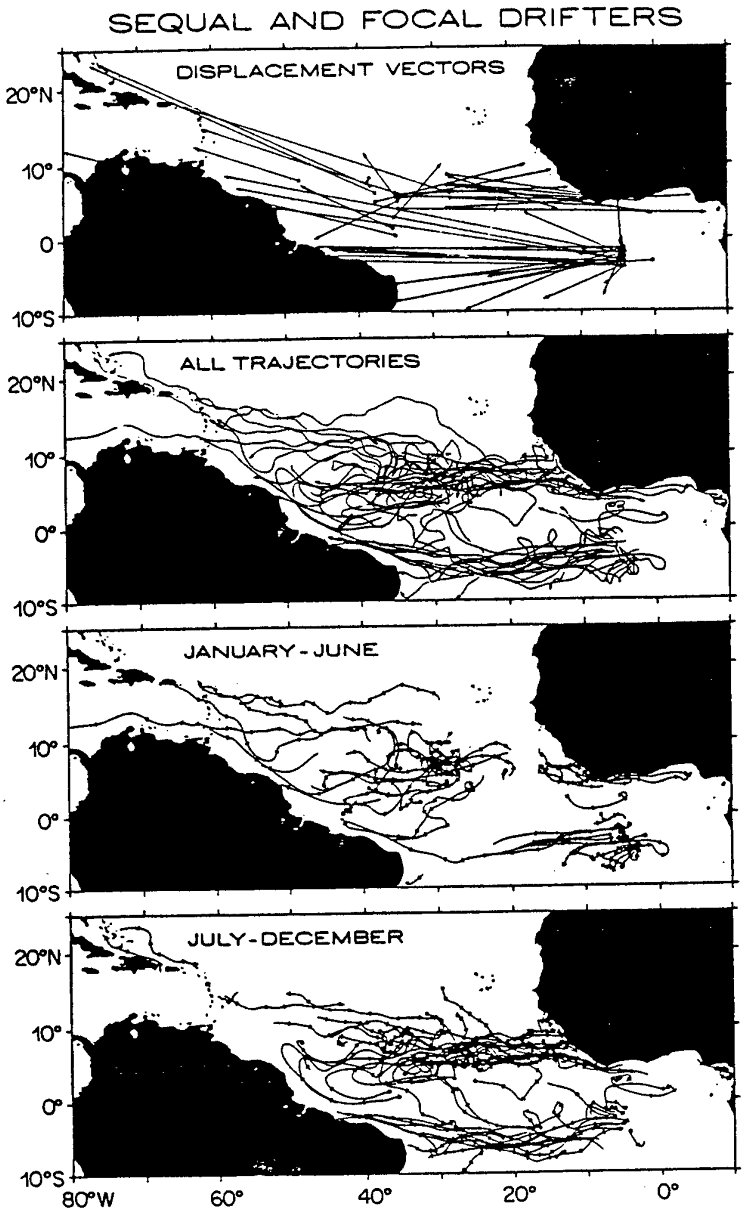

Figure 1: Summary of drifting buoy trajectories. (A) Total displacement vectors from launch (dot) to final position (arrowhead) of SEQUAL drifters launched north of the equator and FOCAL drifters south of the equator. (B) All SEQUAL and FOCAL trajectories superimposed. Trajectories were smoothed with a 10-day filter to remove high-frequency oscillations. (C) Trajectories during spring (January through June) when the NECC disappears west of 20W. Arrowheads are spaced at 10-day intervals. (D) Trajectories during fall (July through December) when the NECC flows eastward across the Atlantic into the Guinea Current.

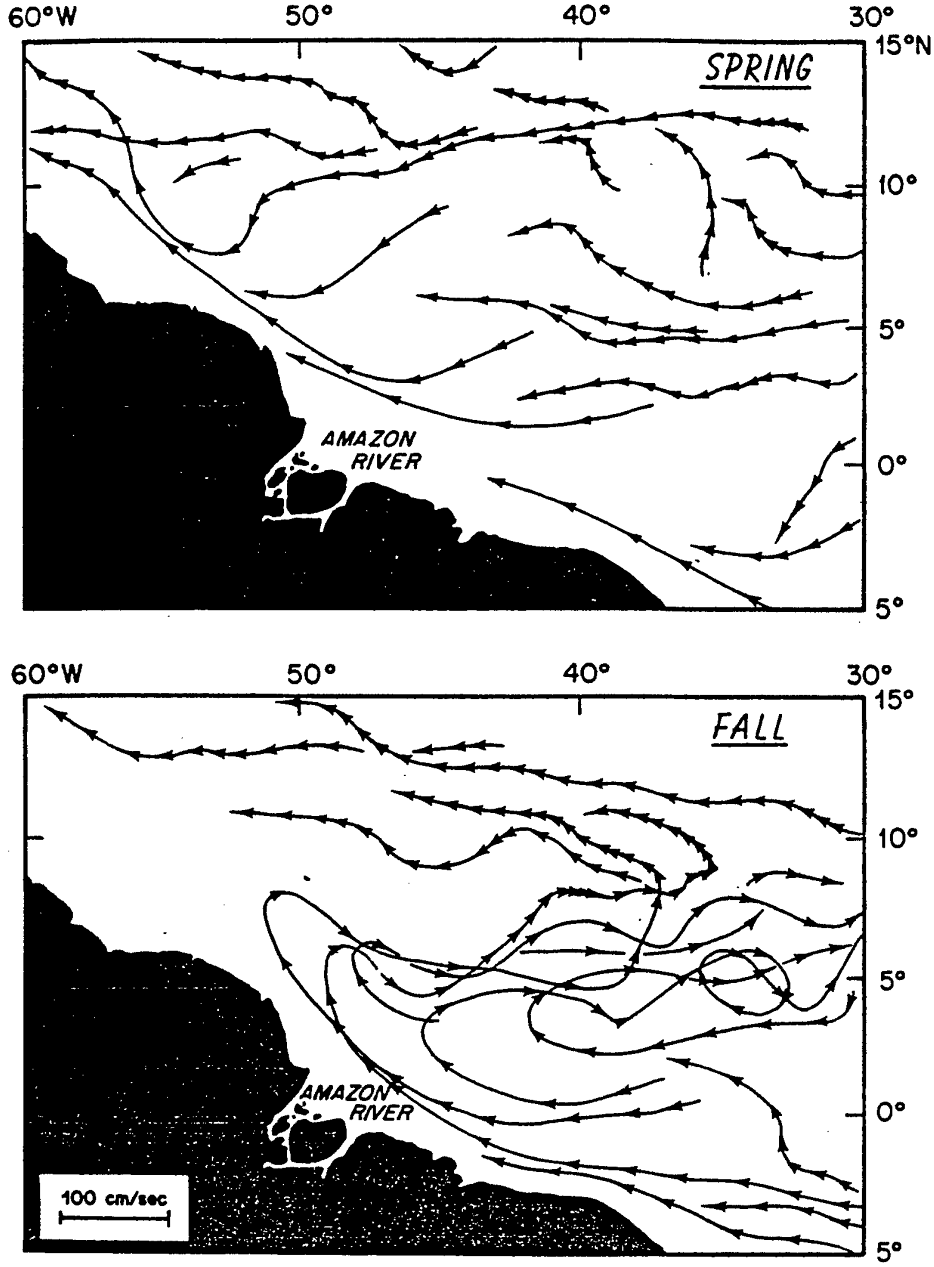

Figure 2: Composites of freely-drifting buoy trajectories from 1983-1986. Top panel shows trajectories for the first half of the year. Lower panel shows the latter half of the year. Arrowheads are spaced at five-day time intervals. Trajectories were smoothed slightly to eliminate high frequency oscillations and some trajectories were omitted to reduce clutter. The drifters were tracked by Service ARGOS.

Meridional Transports in the South Atlantic

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University of Sao Paulo, IOUSP

M. R. Stevenson
Institute of Space Science, INPE

In order to study the meridional flux of heat and salt in the water column across the South Atlantic, the following experiment is being submitted to the Brazilian funding agencies:

- To conduct hydrographic surveys along two transects across the Atlantic Ocean at the latitude of 24^{o} S (216 stations) and 32^{o} S (232 stations), see Figure 1. Along 24^{o} S and 32^{o} S, the station separation will be 15 nautical miles with every other station being a CTD cast with an XBT drop between them. The CTD casts to the bottom will be performed in order to have a picture of the water masses distribution along those transects. In the western and eastern boundary regions, PEGASUS profiles will be performed.

- A meridional XBT section has been made from 35^{o} S to 63^{o} S, since 1984, Figure 2. This section was made using the R/U "Prof. W. Bernard" from I.O.U.S.P. on her way to or back from the the Antarctic. The spacing between the drops is 20 nautical miles, but inside the frontal zones the station separations were reduced to 10 nautical miles. Those data are being reduced and analysed together with oceanographers from Institut fur Meereskund ander Universitat Kiel. It is our intention to continue this program on a yearly basis.

- Another proposal (submitted) is to conduct hydrographic surveys in the subpolar gyre (see Figure 3) and the simultaneous deployments of satellite tracked buoys developed at the INPE.

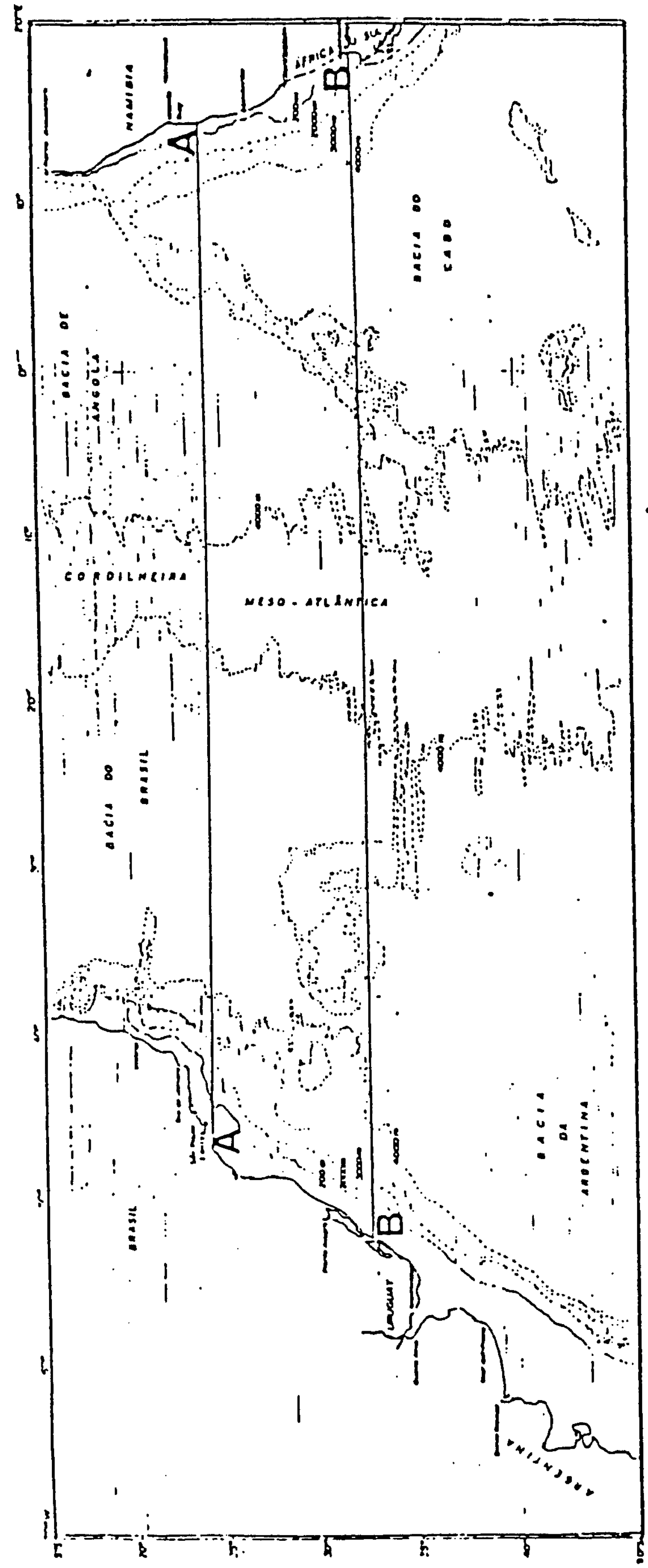
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Figure 1

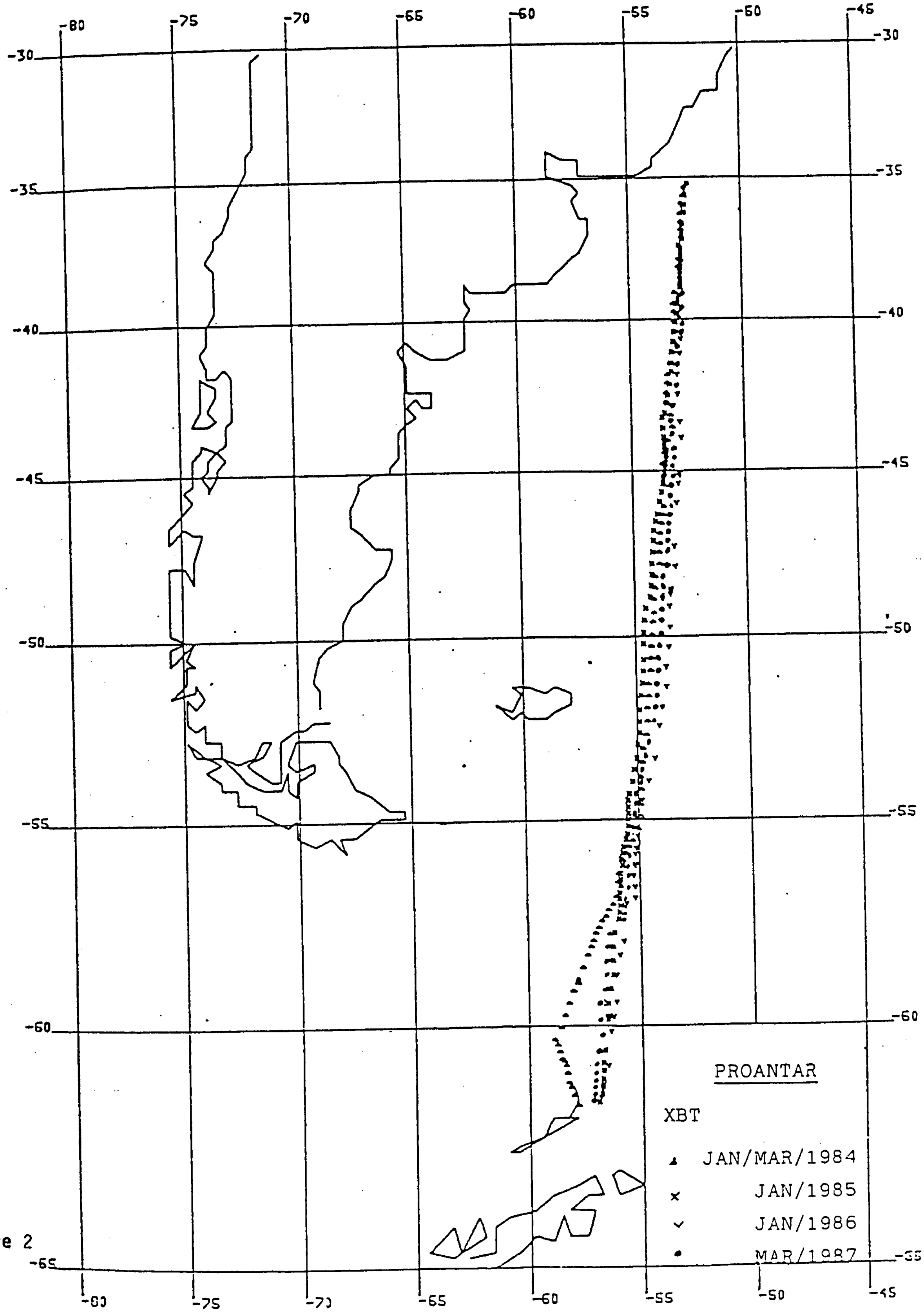

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Figure 2

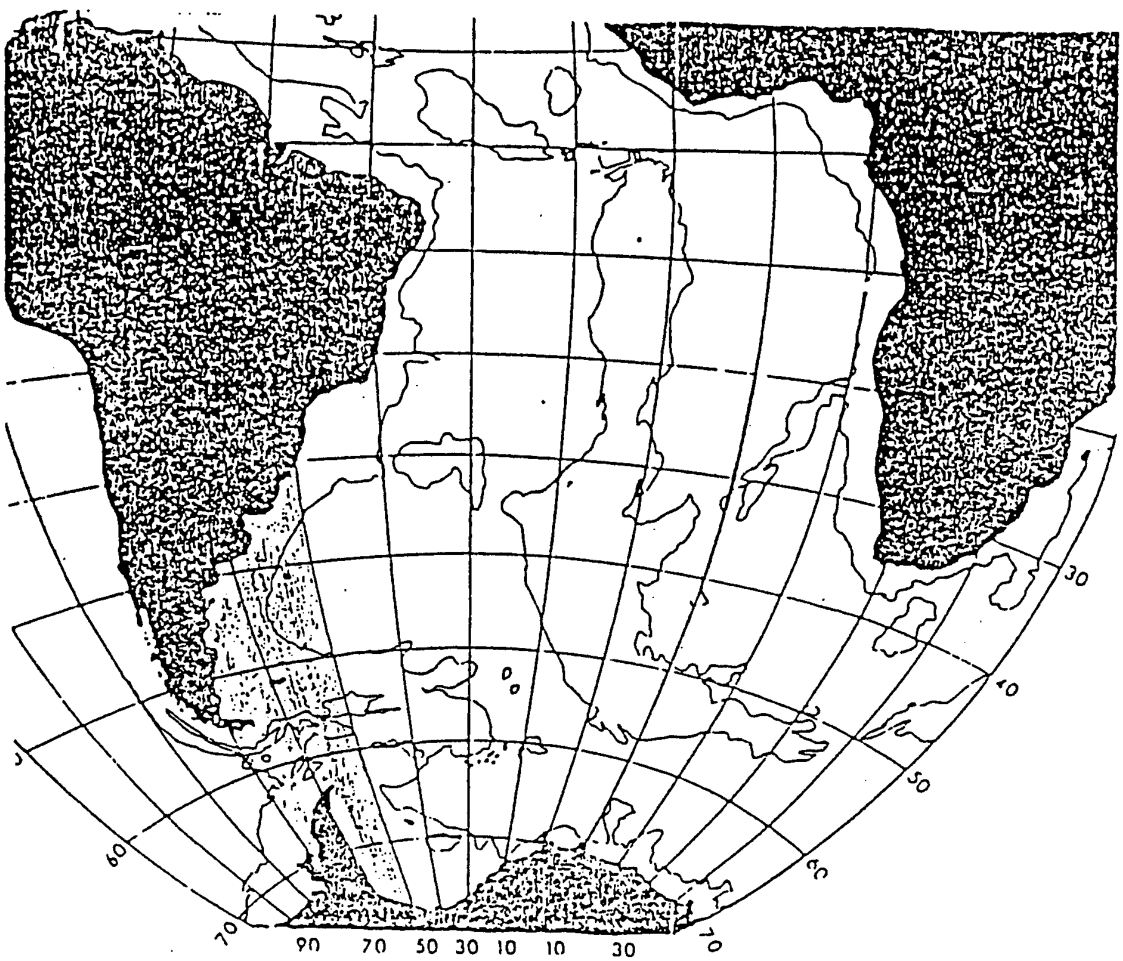

Figure 3

Tropical Atlantic Finestructure

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During the spring and fall of 1985, an intensive study was carried out of the prominent thermohaline staircase found in the western tropical North Atlantic. The program C-SALT (Caribbean -Sheets and Layers Transects) employed wide area AXBT surveys, shipboard hydrographic surveys, a mooring and intensive fine and microstructure sampling. The staircase consisted of about 10 subsurface mixed layers, 5-30 m thick, which were separated by high gradient interfaces or sheets, typically 1-5 meters thick. The layers are found midway between the salinity maximum at 150 m and the salinity minimum at 800 m, where the density ratio drops below 1.7. The density ratio controls the intensity of salt fingering, which becomes most vigorous as it approaches 1.0.

The layers were horizontally coherent for up to 500 km, over which significant changes in the temperature, salinity and density can be seen. Layers get warmer, saltier and denser to the north and west, with a well defined heat/salt ratio. This horizontal density ratio is close to that expected for a vertically divergent salt finger flux. Direct evidence for salt fingers was found in narrow band thermal microstructure on the interfaces and fine-scale convective plumes in the mixed layers. Microstructure measurements yield an estimate of the vertical salt diffusivity near 1×10^{-4} m^2 s^{-1}, indicating that the staircase region is an important site for water-mass conversion in the main thermocline. The region is also rich in mesoscale eddies, including a lens of Antarctic Intermediate Water. The water-mass properties of the lens indicate an origin near the retroflection region of the North Brazil Current. This raises questions about the structure and time variability of a possible western boundary current in the Antarctic Intermediate Water off the coast of Brazil.

Circulation Field off North East Brazil in 1985, and Comparison with Historical Patterns

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Large-Scale Eddy Characteristics and Variability in the Western Atlantic Near Equatorial Waters

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Several near-synoptic surveys by the U.S. Naval Oceanographic Office using expendable bathythermographs (XBT) from aircraft (1983) and ships of opportunity (1980-1985) reveal near-equatorial large-scale eddies (approximately 400 km across). The eddies are associated with the North Brazilian Coastal Current (NBCC), the North Equatorial Counter Current (NECC), and the North Equatorial Current (NEC) in the water off the northeast coast of South America. These features show considerable spacial and seasonal variability; however, most observations suggest that the basic circulation pattern tends to be a year-round characteristic of the region.

In general, the northwestward NBCC in part turns offshore anticyclonically at 4^oN-6^oN, forming a large eddylike flow which supplies water eastward to the NECC at 3^oN-6^oN and to the Equatorial Undercurrent (EUC). The NBCC also turns offshore near 8^oN-10^oN, forming another anyicyclonic eddy to the north. The airborne surveys were obtained during the periods of seasonal extreme, March and September. During northern autumn the mean thermocline depth within the interior of the eddies deepens as much as 80 to 90 m relative to spring depths and the horizontal gradients associated with the eddy boundaries tend to intensify. The volume transports associated with the northern eddy (0-400 dbar rel. to 800 dbar) during February - May are on the order of 10 to $14 \times 10^6 m^3 sec^{-1}$, whereas during late northern summer and autumn, they are closer to 25 to $30 \times 10^6 m^3 sec^{-1}$ with comparable increases in the western NECC.

A further airborne survey during March 1985 (Boyd and Perkins, 1985) indicates that the NEC, in part, may turn cyclonically within part of the region in which the northern eddy was observed during 1983. The eddy appeared to be much closer to the South American coast during 1985, suggesting strong interannual variability.

Reference:

1. Boyd, J.D. and H.T. Perkins (1986) "AXBT Measurements Off the Northeast Coast of South America", Spring 1985. Report 1123, NORDA, NSTL, MS 39529-5004

2. Boyd, J.D. (1986) "AXBT Measurements Off the Northeast Coast of South America", Fall 1985. Report 171, NORDA, NSTL, 39529-5004.

The NBC Retroflection as Traced from Space with the CZCS

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A time series of Coastal Zone Color Scanner (CZCS) images was examined for changes in the horizontal distribution of phytoplankton in the western tropical Atlantic. Thirty-two images were combined into seasonal composites for the period January, 1979 to December, 1982. Concentrations of pigments (chlorophyll a plus phaeopigments) were estimated using the methods outlined by Barale, et al. (1986).

The CZCS images revealed that the Amazon plume, which contained high concentrations of phytoplankton, veered offshore between about June and early January (fall) each year. From mid-January to May (spring), the Amazon plume flowed along the coast toward the Caribbean. These changes were associated with seasonal changes in the circulation of the western Atlantic.

Off the delta, Amazon water always flowed to the northwest adjacent to the coast; very little water flowed to the southeast. The plume was usually contained shoreward of the 60 m isobath between the delta and about 3N, flowing parallel to the North Brazil Current (NBC). The meandering plume extended offshore at least 1,500 km between 6 and 11N, with a width of 300-500 km. The crest of the retroflection was near 12N, 52W. A second crest was located near 11N, 43W. The wavelength of the quasi-stationary meanders was about 730 km. Pigment concentrations decreased from 5 mg m^{-3} or higher nearshore to between 0.5 and 1 mg m^{-3} eastward of 50W. The continuity of the Amazon plume offshore indicated that the retroflection of the North Brazil Current (NBC) was complete.

During fall of 1980 and 1981, the Amazon plume also flowed offshore, but the dispersion patterns were more complex. In both years, large portions of Amazon water leaked to the northwest before reaching the retroflection. In fall 1980, the loop of the Amazon plume showed almost complete closure around an eddy centered at 8N, 51W (internal diameter was 250 km). A similar eddy in fall 1981 was centered at 7N, 51W (internal diameter was about 390km). The 1980 and 1981 temperature sections by Bruce (1984) show eddies of identical proportions.

Drifters tracked during fall of 1983-1986 in the NBC generally took about 18 days to reach 45W after they crossed the mouth of the Amazon (Richardson and Reverdin, 1987). About half of the drifters continued eastward in the NECC, while the other half crossed into the North Equatorial Current (NEC) and drifted westward north of 10N. Likewise, some Amazon water in the NECC subsequently reached Africa (c.f. global composite for December 1981 by G. Feldman, NASA-GSFC), while some detrained from the NECC into the NEC. Little detrainment ocurred into the SEC.

During each spring, the retroflection weakened or vanished and the large eddies became less obvious. In spring 1979, the retroflection elongated to the north without vanishing (see CZCS composite for May 1979, Esaias et al., 1986). During spring 1980, the surface expression of the retroflection vanished, and dispersed over the whole region south of 14N. The steady flow of drifters to the west throughout the region in spring indicated that much of the Amazon water that was carried offshore during fall eventually drifted back west.

The CZCS images also revealed that the circulation north of 6N, 56W is very variable over shorter periods. There appeared to be large (> 100 km) waves traveling northward along the coast and other large anticylonic eddies (100 to 300 km diameter) east and southeast of Trinidad in October, November, and December every year. Southward intrusions of low-pigment NEC water ocurred both in spring and fall. Unfortunately few hydrographic data were available to help explain these patterns.

The local processes that caused the offshore movement of the Amazon plume are still unclear. A possible mechanism is a progressive reversal in the onshore-offshore direction of the slope of the surface of the NBC. Between the equator and 2N, the surface of the NBC probably sloped upwards toward the coast, impeding the offshore dispersal of the plume. Between about 2 and 5N, the slope of the NBC may have reversed. In this region, the topography of the thermocline is approximately featureless (Bruce, 1984; Bruce et al., 1985), and the NBC starts moving offshore (Flagg et al. 1986). Thus, the sea surface may have progressively sloped downward near the coast and upward offshore. Amazon water probably starts moving offshore just north of the inflection point, and is subsequently entrained into the surface waters of the NBC and carried toward the retroflection.

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Acknowledgements: Special thanks to Charles McClain, NASA-GSFC, for general guidance. Support was provided by NASA Graduate Student Researcher's Program grant No. NGT 21-002-822.

Equatorial Upper Ocean Response to Trade-Wind Forcing Observed Using Moored Current Meters during the SEQUAL Experiment

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The Seasonal Response of the Equatorial Atlantic (SEQUAL) Experiment and the Francais Ocean et Climat dans l'Atlantique Equatorial (FOCAL) Program were designed to provide a basin-wide and synopic set of measurements for studying the annual variations in the upper ocean currents and temperatures of the equatorial Atlantic Ocean. The field program encompassed 1983-1985 with several measurements presently continuing. Two reprint volumes and one set of related papers have been published describing the observations and modelling studies: These are (1) Geophysical Research Letters, 11, Aug. 1984 (25 papers); (2) Journal of Geophysical Research, 91 and 92, June 1987 (24 papers); and (3) Nature, 322, July 1986 (7 papers). The Introduction to (2) by E.J. Katz (1987) provides an overview of the programs and a time line of all measurements made.

The SEQUAL Experiment included the deployment of surface moored current meters. These measurements showed the annual evolution of the upper ocean current and temperature variability along the equator which is reported on here. The thermocline evolved with distinctive temporal and longitudinal patterns, the essence of which may be described using a forced linear response model (Weisberg and Tang, 1987, JGR, 92, 3709-3727). Temperature within the mixed layer (or sea surface temperature), however, is not simply related to the thermocline response. The equatorial undercurrent with maximum eastward speed between 50 m to 100 m showed relatively constant speed over the year while migrating vertically with the thermocline. The vertically integrated volume transport (including the surface South Equatorial Current) varied in a complicated manner primarily due to current fluctuations occurring above 100 m depth. The meridional velocity fluctuations were dominated by annually modulated wave packets of approximately 25 day periodicity. Due to surface current instability, these waves are generated in late boreal spring through early summer when the South Equatorial Current is most strongly developed. Their dynamics are nonlinear and they derive their energy primarily from the meridional shear of the surface currents.

The attached figures (from Weisberg et al., 1987, JGR, 92, 5061-6075) show the means and variations (at time scales greater than 10 days) observed in the horizontal velocity and temperature from March 1983 to October 1985 on the equator at 28 W.

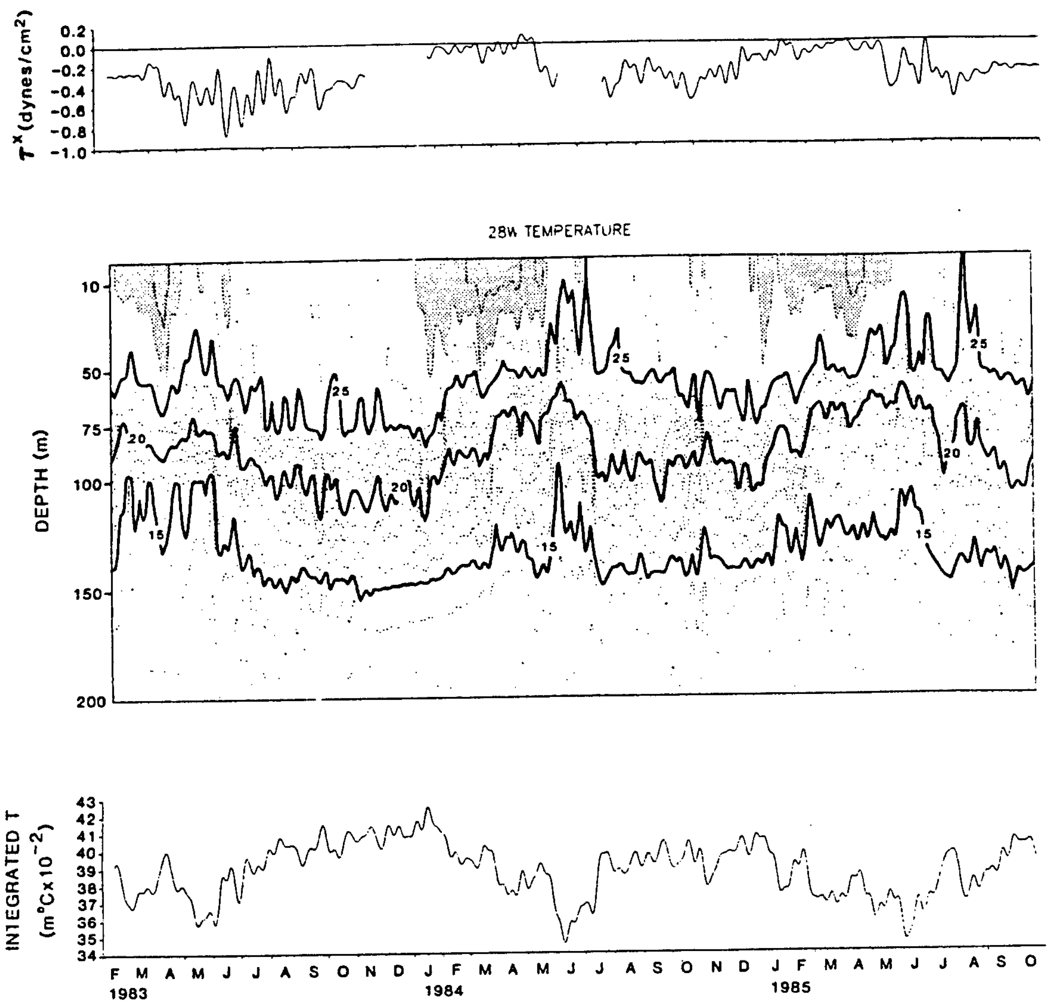

Fig. 5a

Fig. 5. Isotherm or isotach depths and vertically integrated temperature or volume transport per unit width as a function of time computed using temperature and velocity component time series low-pass filtered to exclude fluctuations at time scales shorter than 10 days. (*a*) Temperature with a contour interval of 1°C along with a similarly low pass–filtered zonal wind stress component time series from SPP courtesy of S. Garzoli (temperatures above 27°C are highlighted by stippling). (*b*) East component with a contour interval of 20 cm/s (regions of westward flow are stippled). (*c*) North component, with a contour interval of 20 cm/s (solid lines denote the zero contour, short-dashed lines denote southward flow, and long-dashed lines denote northward flow).

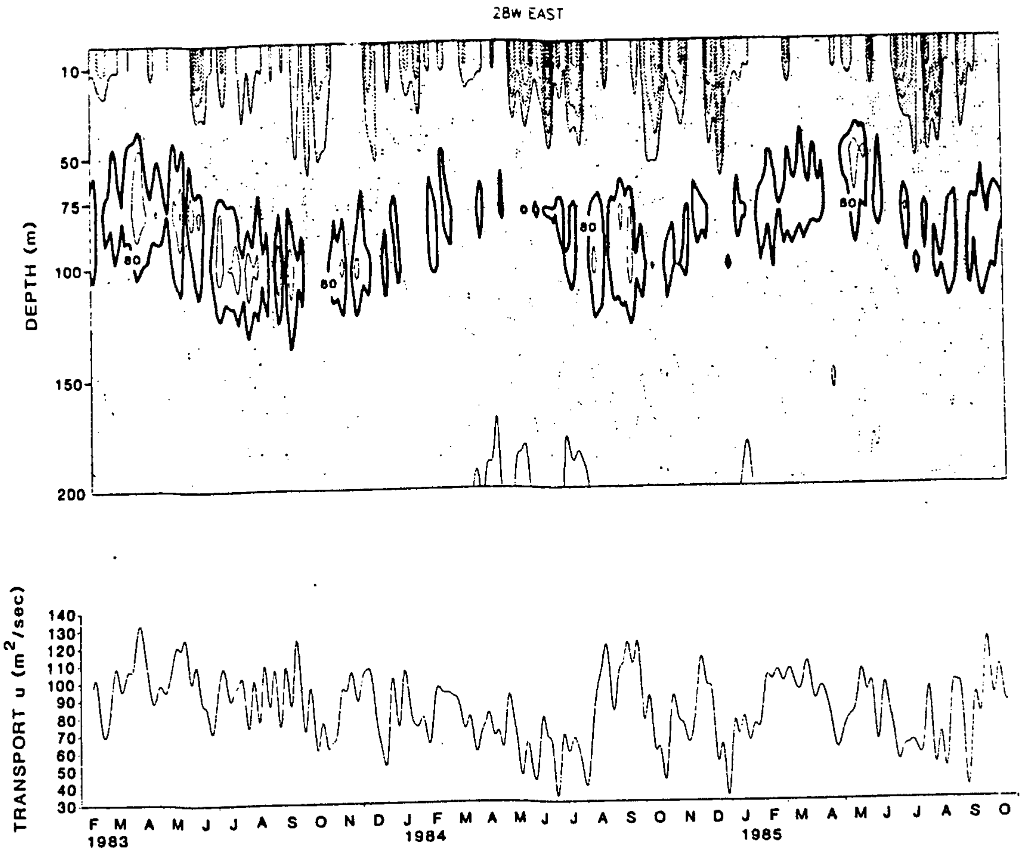
28W EAST
DEPTH (m)
TRANSPORT u (m^2/sec)
F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O
1983
1984
1985

Fig. 5b

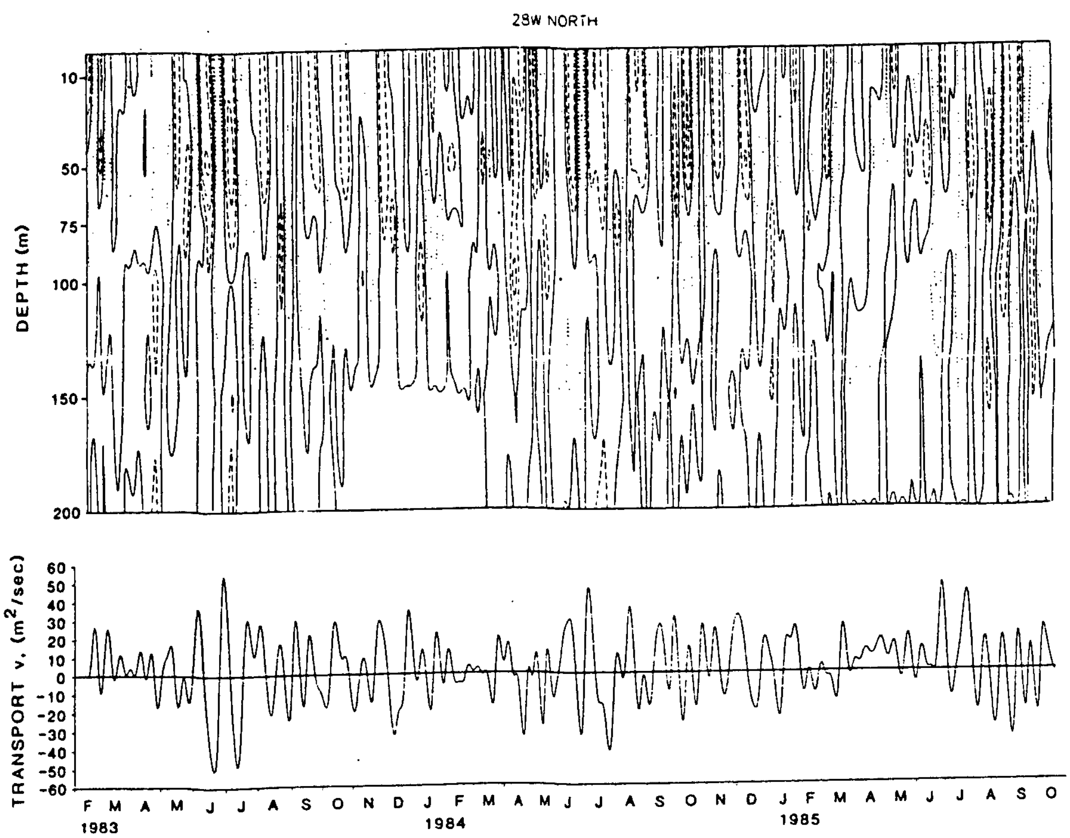
28W NORTH
DEPTH (m)
TRANSPORT v, (m^2/sec)
F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O
1983
1984
1985

Fig. 5c

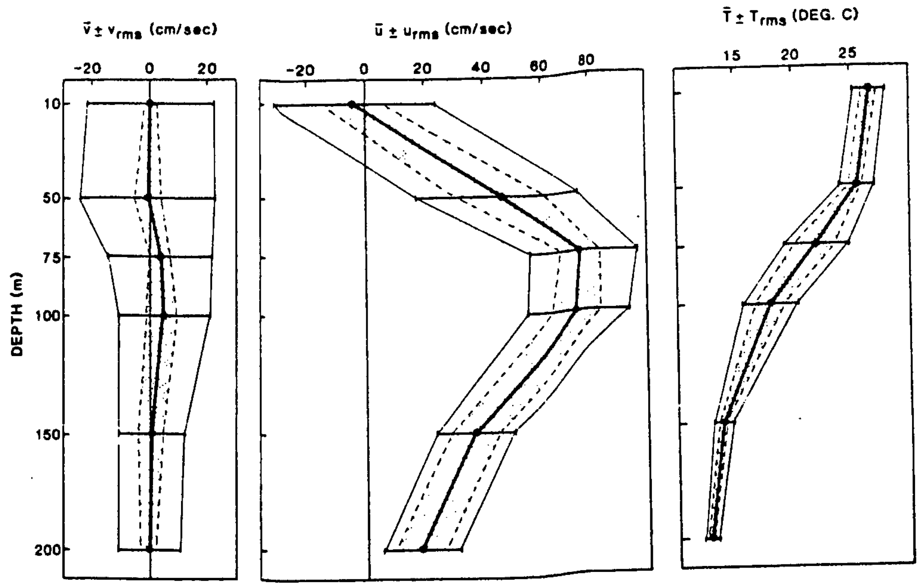

Fig. 2. Mean values, rms deviations, and 90% confidence (stippled) intervals for the means as a function of depth computed from velocity component and temperature time series collected over 2.7 years on the equator at 28°W.

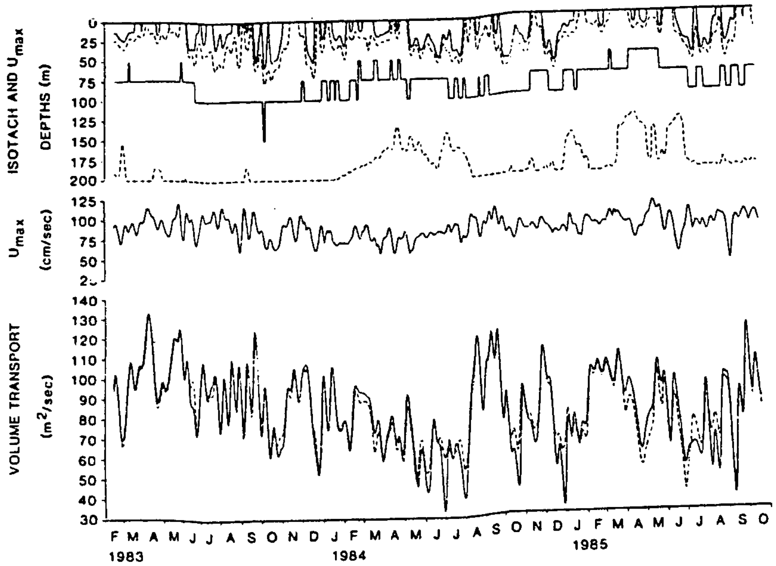

Fig. 6. Zonal current structure over the upper 200-m of the water column based upon east component time series low-pass filtered to exclude fluctuations at time scales shorter than 10 days. (top) Depths of the 0-cm/s (solid line) and 20-cm/s (dashed lines) isotachs computed by linear interpolation and the depth of maximum speed (solid center line). (middle) The speed observed at the depth of maximum speed. (bottom) Vertically integrated volume transport per unit width between the surface and 200-m depth (solid line), between regions of eastward flow only (dashed line), and between the eastward upper and lower 20-cm s isotachs or 200-m (dotted line).

Low Frequency Variability on the Brazilian Continental Shelf

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Subtidal sea level fluctuations in the South Brazil Bight, from Cabo Frio (23°S) to Cabo de Santa Marta (28°40'S), show significant alongshore coherence for periods greater than 3 days. The dominant 9.6-day period signal is characterized by high alongshore coherence and equatorward phase propagation. The dominant perturbation in the wind signal, also with period of 9.6 days, is associated to a clockwise rotating vector that moves equatorward from the south of the bight. Correlations and coherences between wind vector and sea level show that local wind forcing is more important over the south portion of the bight. Modeling of sea level response at Ubatuba (central portion of the bight) for a period of 90 days, using the theory of barotropic continental shelf waves generated by wind forcing, presents results that are similar to the observed response.

Seasonal variability of thermohaline structure off Ubatuba shows a strong signal in the inner shelf water, (waters located between the coast and the 50 m isobath). During winter, vertical stratification is very low and during summer, the waters show a two layer like stratification. Water mass analysis for the two seasons suggest a typical upwelling cross-shore circulation during summer, bringing slope waters near the coast.

Perturbations in the T-S fields found in the outter shelf show characteristics of cyclonic frontal eddies.

Dynamics of the Amazon Plume

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The Amazon River is by far the largest source of runoff in the world ocean, with a discharge of 80,000 - 200,000 cubic meters/second. The discharge is so large that the estuary does not enter the river itself, but rather it extends across a vast portion of the continental shelf, 250 km in the cross-shelf direction and 450 km along the shelf. The broad shelf causes amplification of semi-diurnal tides, with a range of 6 m occurring near the river mouth and cross-shelf tidal velocities of more than 200 cm/sec. Turbulence generation by the tidal currents shoreward of the 10 m isobath is so vigorous as to cause continuous resuspension of sediment and complete vertical mixing of salt, while in the deeper mid-shelf, tidal velocities diminish, sediment falls out of suspension, and the water column is strongly stratified.

The estuary can be divided into three zones, a well-mixed zone in the inner shelf, a frontal zone between the 10 and 20 m isobaths where horizontal gradients of salinity are most intense, and a plume region outside the 20 m isobath in which there is considerable vertical stratification, and the low-salinity water is confined to a relatively thin layer. The seaward limit of the plume extends diagonally across the continental shelf from the mouth of the Amazon at the Equator to 4 degrees N, where it crosses the shelf break. The North Brazil Current flows northwestward along the shelf break at roughly 100 cm/second, possibly contributing to the northwestward deflection of the Amazon plume. The trade winds also may influence the plume structure, with persistent on-shelf stress during the boreal winter and weaker, northwestward stress during the austral winter.

While the dynamics of the Amazon plume have not been investigated in detail, some insight can be gained by simple scale analysis. The cross-shelf dynamics are essentially estuarine, with the baroclinic pressure gradient driving the near-bottom flow inward and the sea-surface gradient driving the near-surface flow outward against the opposing tendency of the on-shore wind stress. The alongshore dynamics are not as well defined; mean gradients are much weaker due to the great alongshelf extent of the estuary, and wind stress makes only a small contribution in the alongshelf direction. The data do indicate a persistent northwestward trajectory of the plume, however, which requires a forcing mechanism. There is likely an along-shelf pressure gradient that makes some contribution, and there may be appreciable Reynolds stress due to eddies along the edge of the North Brazil Current to supply northwestward-directed momentum to the plume. The magnitude and direction of bottom stress beneath the Amazon plume and the adjacent shelf waters have not been clearly defined, although it is likely that bottom stress is a dominant part of the along-front momentum balance. Time-variability of the plume is largely unknown, although the variability of winds, offshore current, river discharge and tidal amplitude undoubtably contribute considerable variability to the plume structure.

Estuary and Lagoon Systems in Brazil

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Variability of the North Brazil Coastal Current

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Long term current measurements were made at about 3.5 degrees North on the upper continental slope between September 1980 and November 1981. Over the 400 meter isobath, nearly continuous current data were collected for the entire period from the near surface and sub-thermocline layers. Shorter term measurements were also made over the 100 and 1200 meter isobaths, approximately 40 kilometers on either side of the main moorings. Based upon a shipboard current profiling survey in December 1980 and Coastal Zone Color Scanner (CZCS) images, the center of the NBCC was located very near the 400 meter moorings. The average velocities in the core of the NBCC were toward the northwest, ranging from about 120 cm/sec near the surface to about 25cm/sec below the thermocline at depths between 200 and 400 meters. The total transport of the NBCC which was composed of three distinct layers, the near surface, thermocline, and sub-thermocline layers, was estimated from the profiling data to be 50 Sverdrups. At that time the thermocline and sub-thermocline layers, carrying some 30 Sverdrups, turned offshore together well to the southeast of the near surface retroflection.

Of the total current variance of the NBCC, 3 to 10 percent was associated with the semi-diurnal tides, 55 to 70 percent with the annual fluctuations, and 20 to 45 percent with fluctuations at intermediate frequencies. The sub-tidal oscillations were strongly polarized along the isobaths with the polarization increasing with depth. Tidal fluctuations were polarized across the isobaths with both the amplitude and polarization increasing onshore. In the near surface, the intermediate frequency motions were typified by surges toward the northwest - sometimes with accelerations of 100 cm/sec in 3 to 4 days - followed by somewhat longer decay periods. These surges may be associated with wandering of the track of the NBCC which has been identified from CZCS photos. These photos suggest a cross-stream movement of perhaps 75 kilometers at 3 to 5 degrees North with considerably less movement southward. The 75 kilometer scale of the NBCC wandering is one half to three quarters of the width of the NBCC itself. The sub-thermocline intermediate period fluctuations are lower frequency than those above the thermocline and there is no significant coherence across the thermocline. In addition, the sub-thermocline currents sometimes reverse toward the southeast with substantial magnitudes. These reversals have been shown to carry water of North Atlantic origin hundreds of kilometers southeastward along the shelf edge.

Physical Oceanography in AMASSEDS

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A Multidisciplinary Amazon Shelf SEDiment Study (AMASSEDS)is a multidiscipinary investigation of physical, geological, and chemical processes within the Amazon dispersal system. There is a complex interplay between shelf circulation and mixing and the geological and geochemical processes occurs over the Amazon subaqueous delta. Vast quantities of sediment and terrigeneous chemical species are carried across the shelf off the delta and their fate depends critically on currents and turbulence on the shelf. As part of AMASSEDS, a physical oceanography component has been developed to address two fundamental problems in coastal physical oceanography, buoyancy-driven flow and low-latitude shelf dynamics. An experimental and theoretical program is proposed to study the freshwater discharge of the Amazon River over the adjacent continental shelf and the physical processes which influence the structure and variability of the Amazon plume and the turbulent mixing of fresh and salt water over the shelf. The field component will use a combination of moored and shipboard measurements and deployments of satellite-tracked drifters to measure and characterize the temporal and spatial structure of the current and water properties over the Amazon shelf on time scales from a few minutes to seasonal and on length scales of a few meters (in the vertical) to 100's of km (in the horizontal). These observations should provide a comprehensive picture of circulation and mixing processes on the Amazon shelf, including the first extended time series of dynamical variables. The theoretical component will construct a numerical model of the regional tidal currents and will use analytical and numerical approaches to model the frontal zone dynamics and low latitude shelf circulation driven by coastal buoyancy and offshore boundary currents. The combined research should lead to a quantitative assessment of the influence of river discharge, wave-, current-, and tide-induced turbulent mixing, boundary (both surface and bottom) stresses, and the North Brazil Coastal Current on the structure and dynamics of the Amazon discharge and the regional shelf circulation.

A proposal for AMASSEDS was submitted to NSF in February, 1987 and was reviewed at the August, 1987 panel. NSF declined the physical oceanography component of the AMASSEDS proposal, but encouraged its resubmission. A revised proposal for physical oceanography in AMASSEDS was submitted in February, 1988. Its focus is on current and water structure variability in the region of high sediment accumulation. We hope that this mid-shelf study can be conducted as part of a combined NOBRASS/AMASSEDS experiment to study the dynamics of the North Brazilian continental shelf.

Overview of the North Brazil
Shelf Study (NOBRASS)

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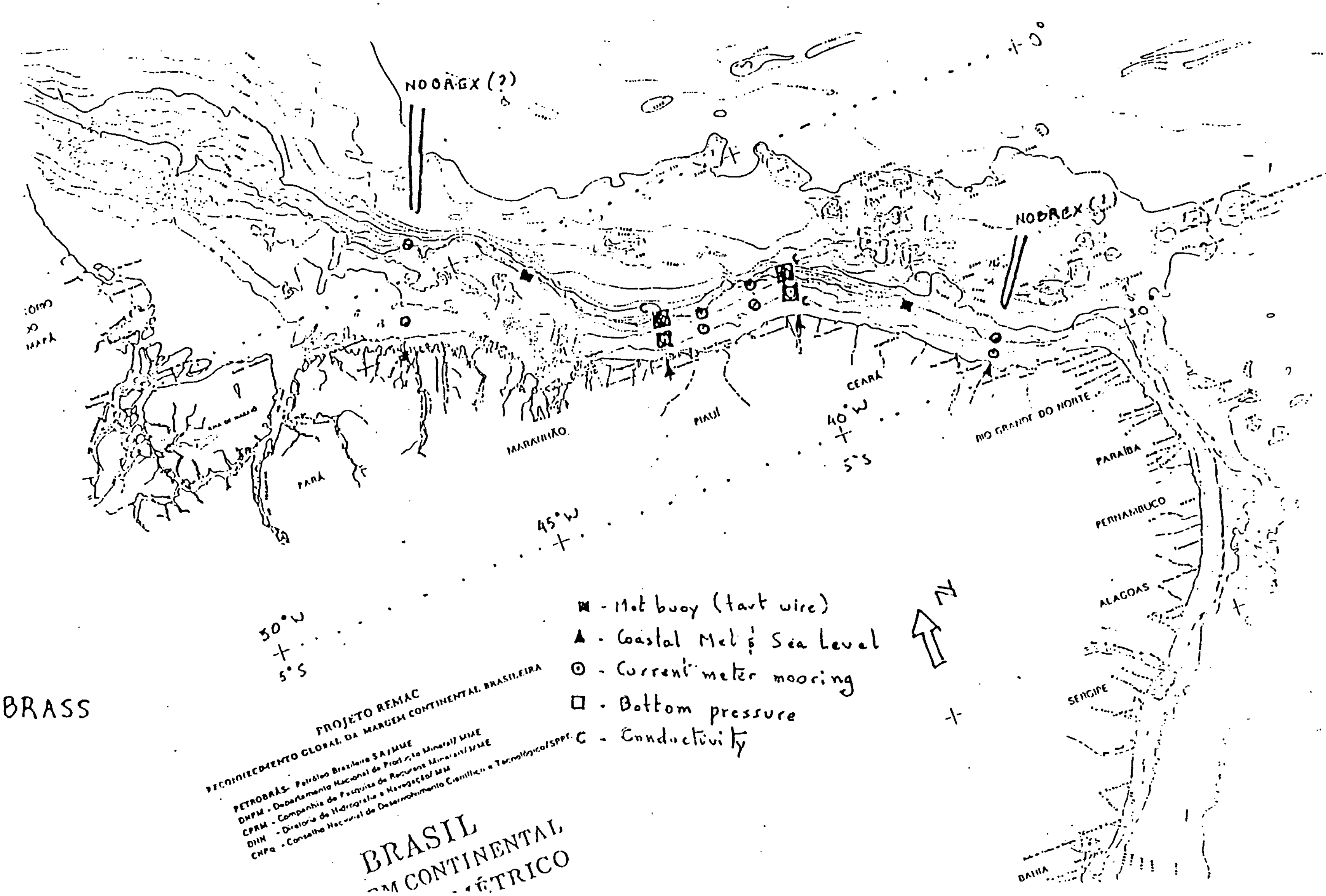
The general objective of NOBRASS is to improve our understanding about the dynamical processes which govern the response of continental shelf waters of the northern coast of Brazil in the region between 35 W and 46 W to its different forcings. Due to its geographical location, the north Brazilian continental shelf offers unique conditions for the development of a comprehensive study of the dynamics of low latitude shelves. The fast decrease of the Coriolis parameter toward the Equator in these low latitude regions should have a major impact on the dynamics of the system, causing its behavior to be significantly different from mid-latitude shelves. In this aspect, it will be of high interest to analyse the propagation and cross-shelf structural characteristics of the continental shelf waves for different sections spaced along the coast. The large scale response of this region to the atmospheric forcing will also be investigated. Thus, we will evaluate what is the fraction of the flow and sea level variability which is coherent with the local wind, as well as, what is the magnitude of the seasonal signal. The influence of the NBCC on the circulation over the continental shelf and on the exchange processes between shelf and deep ocean through meanders and frontal eddies will be investigated. The observational program will consist of the following: a) an array of six offshore mooring lines, each containing two current meter moorings with current meters at three depths; b) four coastal sea-level and meteorological stations; c) two moored met buoys at the shelf break; d) hydrographic; cruises; e) offshore sections using ship board Doppler Acoustic Profilers; f)satellite drifters; and g) reception and use of satellite images. The field work is scheduled for the period of Jan-May/89 and Jul-Nov/90. The NOBRASS project is being organized by physical oceanographers of IOUSP and INPE, Brazil, and of RSMAS, USA. It will be submitted for funding in the US to NSF and in Brazil to CNPq by the end of 1987.


NOBREX (?)
NOBREX (1)
PARÁ
MARANHÃO
PIAUÍ
CEARÁ
RIO GRANDE DO NORTE
PARAÍBA
PERNAMBUCO
ALAGOAS
SERGIPE
BAHIA
40° W
5° S
45° W
50° W
5° S
N
▪ - Met buoy (taut wire)
▲ - Coastal Met & Sea Level
⊙ - Current meter mooring
□ - Bottom pressure
C - Conductivity
PROJETO REMAC
RECONHECIMENTO GLOBAL DA MARGEM CONTINENTAL BRASILEIRA
BRASIL

NOBRASS

The North Brazil Experiment (NOBREX)

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The North Brazil Experiment (NOBREX) is based on the convergence of interest in three classical oceanographic study areas namely the equatorial current system, the global heat and mass balance, and the dynamics and role of western boundary currents. The three areas come together geographically in the North Brazil Current (NBC) which is an especially interesting and relatively unexplored western boundary current, an important link in the equatorial current system, and a major conduit of poleward heat transport. Figure 1 illustrates schematically the relationship of the NBC to the equatorial and western boundary current systems of the Atlantic Ocean.

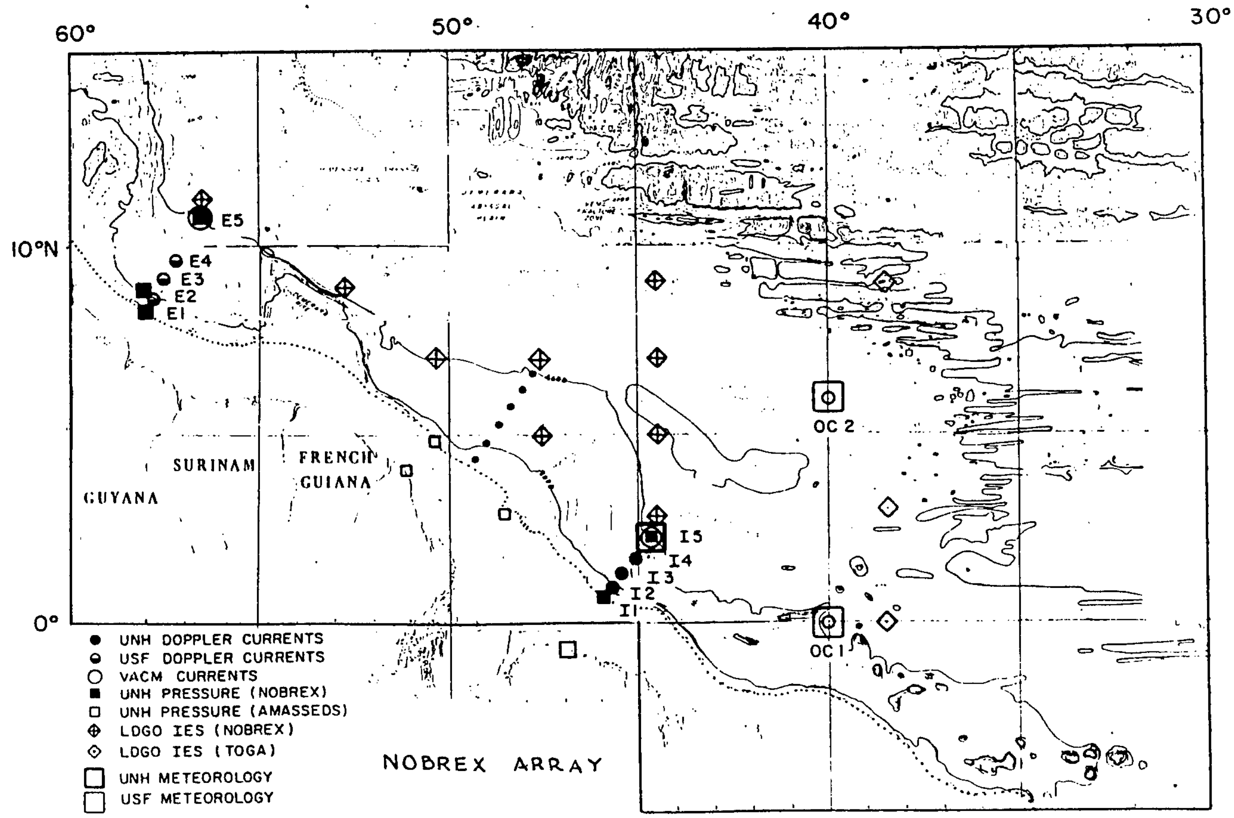
From a global point of view, the goal of NOBREX is to understand how the tropical and subtropical oceans interact, more specifically how the mass balance of their warm water layers is connected. As Figure 1 suggests, tropical/subtropical interactions occur because the equatorial and western boundary current systems are connected by key links such as the NBC. Meridional transport on a rotating planet is, however, limited by vorticity constraints. An important general goal of NOBREX is to discover what limitations there are on the meridional transport of warm surface waters by low latitude western boundary currents.

Past studies have outlined the role of the NBC as a collector of South Equatorial Current waters and suggested that it feeds the Equatorial Undercurrent, the North Equatorial Countercurrent and the Guiana Current. However, this picture is made hazy by seasonal variations and sometimes contradictory data. It is not clear, for example, how fresh Amazon water is mixed into and carried by the NBC, to pass eventually to the seaward side of the NBC.

A number of studies of global heat and mass balance have indicated large transports of both heat and mass across the equator, in the Atlantic resulting in substantial net annual heat transport northward. Models, and what can be surmised from direct observations, suggest that much of the mass transport, and especially the northward heat transport, take place in narrow western boundary currents, the NBC and deeper currents underflowing it. It should be clear that we have to understand these currents and be able to quantify their transports if we want to arrive at reasonable estimates of the basin-wide cross-equatorial transfer of heat and mass.

From a theoretical point of view, the NBC is a boundary current on a beta-plane within which f passes through zero. It has certain similarities to the Somali current during the SW Monsoon, including complexity. The inertial "overshoot" of both these currents across the equator, and their subsequent separation from the coast have been discussed in the literature, but we are far from a full understanding of the controlling factors. The NOBREX field program is intended to provide a much improved data base for subsequent model studies, while related modelling work prior to and parallel with the observations is intended to help in the design of the field experiment and in the interpretation of the data.

The field program is planned for September 1989 through December 1990 and consists of moored array, profiling, float and remote sensing components. The backbone of the moored array are two line arrays of current meters (Doppler Acoustic Profiling Current Meters); one near the equator southeast of the NBC retroflection - the INFLOW - and one to the northwest beyond the retroflection - the OUTFLOW. A continental margin array of pressure moorings links the INFLOW and OUTFLOW ARRAYS. An array of inverted echo sounders, IES, will be used to monitor thermocline depth variability (i.e. baroclinic pressure) in the complex retroflection region. The profiling program consisting of shipboard Doppler Acoustic Current Profiling, airplane AXBT, CTD, and High Resolution Current Profiling will provide important spatial information throughout the region during the NBC retroflection and non-retroflection periods. The float, airplane remote sensing and PEGASUS profiling observations will bridge the time/space scale gap between the moored and shipboard profiling programs.



Boundary Current Separation and Equatorial Outflow

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A minimal model is considered to examine the dynamics of a nonlinear frictional boundary layer on a beta plane. It is demonstrated through scale analysis that the inertial jet will separate from the coast if the transport of the jet does not increase downstream sufficiently rapidly (i.e., a linear function of the downstream distance). Inclusion of baroclinicity will enhance the separation process and also impose an upper bound for the separation latitude. The study is essential in evaluating classical inviscid theories and provides a more complete theory of separation and hence a more flexible dynamical tool for interpreting various separations.

A simple model is used to examine the dynamics of an outflow discharged at the equator. It is found that the flow will be confined to the anti-cyclonic side of a radial boundary in the far field where the beta effect is important. For a weak discharge (with Reynolds number of order 1 or less), the transition to the far field occurs over the Munk's scale which is generally of the order of 100 kilometers or less. The model thus suggests that the Amazon outflow will be deflected to the northwest over the shelf, consistent with observations.

Meridional Oscillations Driven by Zonal Winds In a Trapezoidal Equatorial Basin

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A symmetric zonal wind stress oscillating with period in the range of a few weeks to a few months can drive meridional motions at the equator due to the shape of the western boundary. The portion of the coast of Africa that bounds the western equatorial Indian Ocean is a good example. This coast crosses the equator at an angle of nearly 45 degrees. In a model with no horizontal friction and small vertical friction the boundary condition of no normal flow effectively converts directly forced symmetric disturbances into both symmetric outgoing Kelvin waves and anti-symmetric outgoing mixed Rossby-gravity waves. This model provides a possible mechanism for the generation of observed equatorial meridional motions on these time scales.

Doppler Current Profiling from Moored Subsurface Floats

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Over the past decade, the potential of acoustic Doppler profilers has begun to be exploited for the remote sensing of ocean currents. In addition, these instruments are capable of making current measurements with a combination of range and vertical resolution not feasible with conventional current meter moorings.

The first moored applications of acoustic Doppler profilers utilized them in a bottom-mounted configuration. In these applications, the instrument provided velocity profiles within several hundred meters of the sea floor. In shallow coastal environments, deployment on the bottom may thus provide coverage of the entire water column.

In deep regions, the measurement of upper ocean currents by Doppler techniques requires mooring the instrument up in the water column. As a first step toward the general use of Doppler profilers on moorings, we have installed an upward-looking 154 kHz RD Instruments profiler in the uppermost buoy of a subsurface mooring deployed in the Strait of Gibraltar. Since the profiler points upward from the top of the mooring, the potential problems associated with reflections from mooring components are avoided. This configuration is well-suited to investigations of the detailed structure of flows within the top several hundred meters, and in regions of strong flow, since the extent of the mooring motion may be reduced by deploying the profiler beneath the core of the current.

The performance of the midwater Doppler in the Strait of Gibraltar clearly demonstrates the utility of this technique for obtaining detailed velocity measurements at fixed depths under the most severe conditions.

Microcomputer Revolution
in Remote Instrumentation

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Microprocessor based instrumentation offers many advantages in oceanographic applications: fewer electronic components (decreased size and increased reliability), lowered power requirements (COSMOS circuitry), solid state data storage, software control of sampling (easily altered), power to preprocess data, and direct interface to a PC (to check and initialize the instrument prior to deployment, and after recovery to dump the data, process and display the results). The Ocean Process Analysis Laboratory at UNH has used microcomputers in instrumentation since 1979 for: conditional sampling (data dependent sampling for high frequency events), in situ calculation of derived quantities (such as salinity), data compression (for telemetry), and data telemetry via acoustics and satellite (both ARGOS and GOES). We are developing new general purpose systems for profiling, current meter and telemetering drifter applications.

Currently, we are using an 80C85 based system (an 8 bit processor) with 8 KBytes of scratchpad RAM and 32 KBytes of on board EPROM for program storage. A variety of data storage and sensor interface boards can be plugged into the system to configure it for a particular application. We have been using 64 KByte RAM boards (2 MByte boards are available), and are now testing 256 KByte EPROM boards as a non-volatile storage medium. This system forms the heart of our "Thoughtful CTD", "Smart VACM", and Telemetering Lagrangian Drifter.

The "Thoughtful CTD" is microprocessor controlled, and temporarily stores the data internally in RAM. There is no need for conducting cables and slip rings with their accompanying cost and problems. The system will interface to a variety of sensors, and is rugged and reliable. It connects to a PC for check-out and initializing, and for data dump and processing through a 20 ma SAIL communications link. The system is configured with dual Sea Bird temperature and conductivity sensors, and Vibrotron and Paroscientific pressure sensors. Data resolution (digitizing at 16 Hz) is better than 1 millidegree Centigrade, 0.0001 Siemens/meter and 1 millibar. Up to 16,000 samples are stored in 256 KBytes of RAM, which is satisfactory for shelf work. Power is supplied by either standard flashlight or Lithium batteries for up to 2000 hours of continuous operation.

The CTD has its own operating system and run time "C" library to make program development easier. Software is written and compiled on a PC, then downloaded to the CTD for testing and finally burned into EPROM for deployment. Besides controlling the sampling, the software allows the user to check the data RAM, output data for calibrations, and configure the system and initialize it for each profile. The software also annotates the data file, and checks for data transfer errors. Currently we are working on the "thoughtful" by making the system examine data quality. Data are normalized to temperature, pressure and salinity, and the results from the sensor pairs compared. If the results agree to within a specified amount, then the instrument records the unnormalized data from one suite of sensors. If the data is different, the instrument determines if one sensor is not functioning, then records the other. If they both are reasonable, but the difference is too large, it will record both. If a problem is detected, the system will alert the user and suggest a solution. Since the system is modular, this will probably be to plug in a new sensor.

On The Development of Oceanographic Instrumentation in Brazil

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Development of oceanographic instrumentation in Brazil has been motivated by difficulties in obtaining resources and licences to import oceanographic instruments. Also, acquisition of spare parts for instruments is not easy, thus their maintenance becomes quite hard.

So, in the last few years some universities and research institutes started developing prototypes of instruments for oceanography. In the same way, Brazilian companies have been manufacturing some oceanographic instruments, such as data aquisition systems and echosounders.

Instituto Oceanografico built simple instruments in the beginning, such as nets, bottom and water samplers. In order to have better technical support the Laboratory of Oceanographic Instrumentation (LOI) was created in 1981. LOI maintains instruments and develops and improves prototypes.

Development of prototypes by LOI has resulted sophisticated instruments which are applied in several areas. The most important lines of development are data acquisition and storage systems, communication, positioning and remote controlled acoustics systems, mooring systems and pressure cases for underwater instruments. Those projects have been developed with the following premise: simple ideas and easy building.

In this sense LOI intends to improve the prototypes and has already made plans to develop new ones. New technics, materials and components should be used in the near future. Also, more improved measurement systems might be in plan, such as acoustic/satellite telemetry of oceanographic parameters.

Finally, time should be spent with sensor technology in order to have the problem of development of instruments entirely solved. In parallel, a calibration laboratory must be built permitting research with those sensors as well as periodic calibration of oceanographic instruments normally in operation.

III. Discussion Summaries

General Discussions Concerning Brazil/U.S. Scientific Collaboration 4 August 1987

One of the objectives of the first Brazil/U.S. workshop on physical oceanography was to introduce a majority of the Brazilian physical oceanographers and their U.S. counterparts to each other. The purpose was to promote collaborative research in several areas of mutual interest. One important subject of discussion was how to improve the means by which legitimate collaboration can occur in the future.

The research areas of priority in Brazil are established by consensus under a process guided by Comissao Interministerial Para os Recursos do Mar (CIRM). Presently, the three main areas are:

- regional marine ecologies and ocean resources;
- Antarctic oceanography;
- climate of northeastern Brazil.

The following set of recommendations highlight the main issues raised in that discussion:

- To assure authentic collaboration, U.S. physical oceanographers should involve interested Brazilians at the very earliest stages of planning for research initiatives.
- Establish TELEMAIL mail boxes at the Institute of Oceanography, University of Sao Paulo (IOUSP) and Space Research Institute (INPE).
- Promote a more active exchange between Brazilian and U.S. physical oceanographers.
- Develop a more efficient way to match Brazilian Ph.D. candidates in physical oceanography to relevant research programs in the U.S.
- To facilitate face-to-face interaction, conduct a series of workshops, alternating between the U.S. and Brazil.
- Establish formal cooperative agreements between pertinent Brazilian and U.S. institutions involved in physical oceanographic research.
- Work to improve the intercountry travel visa process.

Discussion: Wednesday afternoon's full group discussion of major issues concerning more extensive Brazil/U.S. collaboration in physical oceanographic research highlighted the need to make early contact with Brazilian counterparts. It was pointed out by B. Castro and J. Lorenzetti that Brazilians have not always been involved in the research planning in its earliest stages. For example, by some appearances the AMASSEDS process did not include Brazilian input before submission to NSF. Beardsley explained the constraints involved and committed the U.S. to a more vigorious effort of direct involvement with the Brazilians in planning future work in the Amazon outflow region of the Brazilian continental shelf.

General Discussion continued

Affonso Mascarenhas proposed a model, based on his collaboration with David Evans (URI), in which scientific hypotheses concerning the Brazil Currents were developed jointly and work tasks were integrated from the start.

Of course making the initial contacts in Brazil (or the U.S.) and developing a dialogue is the key issue here. This workshop has provided an important forum for scientific discussions between Brazilian and U.S. physical oceanographers who were able to attend. A list of those attendees and where they might be contacted appears in Appendix A. A more complete list of Brazilian physical oceanographers and their interests can be found in Appendix B. Presumably some of the workshop discussions will stimulate more vigorous interaction and collaborations in the future months.

- Recommendation: Establish TELEMAIL mail boxes for physical oceanographers at IOUSP and INPE.

Discussion: One of the primary problems concerning Brazil/U.S. scientific cooperation and collaboration are the difficulties of routine communications. The standard mails are slow (2 weeks one-way) and alternate methods such as phone and telex are expensive particularly for Brazilians. TELEMAIL seems to offer an attractive alternative which can be used for direct communication between countries and in addition permits Brazilians to access ocean-related bulletin boards. Frank Muller-Karger (NASA-Goddard, University of Maryland) will explore the possibility of establishing a NASA-supported mailbox at INPE. Wendell Brown (UNH) will explore the possibility of establishing an NSF-supported mailbox at IOUSP.

- Recommendation: Develop a more efficient way to match Brazilian Ph.D. candidates in physical oceanography to relevant research programs in the U.S.

Discussion: In some cases the relatively small number of Brazilian physical oceanographers poses a problem when it comes to identifying an overlap in scientific interests. It is clear that this situation would be improved if more Brazilian students with a commitment to work in Brazil, would choose to pursue Ph.D. degrees at U.S. universities.

With what is presently a very limited research interaction between Brazilian and U.S. physical oceanographers, the logistics of making good matches between potential Brazilian Ph.D. candidates and U.S. scientists with relevant research programs is difficult. The present situation should improve with the increased interaction associated with future major research initiatives, such as NOBREX, AMASSEDS and NOBRASS, that are scheduled to begin in 1989 subject to funding approval. The establishment of TELEMAIL (as recommended above) should facilitate the exchange of information associated with the student application process.

Workshop Discussions
5 August 1987

I. Coastal Oceanography

Participants: Belmiro M. Castro
Joao A. Lorenzzetti
Wayne Geyer
William Johns
Thomas Lee
Jerry Miller
Dick Ou
Neal Pettigrew

Discussion Summary:

Due to its location, the northeast-north Brazilian continental shelf is a natural laboratory for studying low latitude shelf dynamics. Some key issues related to the low latitude effects or coastal dynamics are not yet well studied. Answers to the following sets of questions concerning different aspects of the problem require a major observational program, complemented by theoretical and numerical modelling efforts. Simple numerical experiments with idealized coastal geometry and bottom topography and simple wind forcing, should shed some light to many of the questions and related issues even before observations are made.

1) Wind driven circulation

The cross-shelf geostrophic balance, which governs alongshelf flow in mid-latitudes, should not be nearly so important near the equator. There are many unanswered questions about the important terms in the momentum balance for low latitude continental shelves. Other questions include: What is the effect on circulation of the changing cross-shelf Ekman Transport due to the rapidly changing Coriolis parameter as the equator is approached? What is the adjustment time for forced circulation at such low latitudes?

2) Free shelf waves

Free continental shelf waves propagate equatorward along a western boundary. What happens in the energy convergence zone at the equator? Are equatorial Kelvin waves generated in such processes? How does the modal structure of such waves change at low latitudes?

3) Equatorial waves

Equatorial Kelvin waves impinging on an eastern boundary transfer energy to the continental shelf waveguide. This energy transfer from the equatorial to the continental shelf waveguide is not, however, possible for a Rossby wave impinging on a western boundary. The fate of the long-wave energy that does penetrate onto the shelf is still not well understood.

4) Other forcing mechanisms.

Besides the wind, the circulation on the north-northeast Brazilian continental shelf is influenced by the following forcing mechanisms: tides, boundary currents and buoyancy. In the higher frequencies, tides are the dominant mechanism. In Fortaleza, CE, the tidal range is about 1 m, increasing to 6 m near the Amazon mouth. This amplification of the tidal amplitude should have a significant influence on the tidal currents, and consequently, in the bottom stress parameterization. The North Brazil Current may influence the shelf in the subtidal frequency band via frontal eddies that intrude into the shelf. In the seasonal band, the north-south excursion of the ITCZ should have a significant impact over the regime of precipitation-evaporation and long-wave radiation, consequently also on the buoyancy forcing of the shelf. Satellite images indicate that most of the Amazon River outflow moves northwestward, and so its buoyancy effect on shelf waters should be restricted to the region located northwestward of the river mouth.

Recommendations:
Some preliminary research could be accomplished by analysing existing historical tidal, hydrographic and meteorological data. In the short-term, ships of opportunity could be used for collecting XBT data as well as for the deployment of low-cost surface satellite tracked drifters. It seems, however, that an extensive data collection program is still necessary for a better understanding of the dynamics of the continental shelf waters off the north-northeast coast of Brazil.

II. Equatorial Atlantic

Participants: R. Weisberg
M. Fiadiero
W. Brown
N. Garfield
D. Moore
J. Boyd
C. Flagg
A. Mascarenhas
Y. Ikeda

Presently there are a number of ongoing research programs in the Equatorial Atlantic including: SECTIONS, TOGA (inc a Ship-of-Opportunity XBT Sections), A French Tide Gauge Program, STACS, Malenas Confluence Program.

Brazilian plans for future research include those of;

- A. Mascarenhas
  - A study of the partition of the South Equatorial Current into the Brazil Current (BC) and the North Brazil Current (NBC) at 5-7^{o}S.

  (a) The plan is to study the NBC in the context of NOBREX with two CTD/PEGASUS across current transects - one southeast of the Amazon and one northwest of the Amazon. The transects will be occupied 5 times using the R/V Besnard to augment NOBREX NSF shiptime. Coastal Sea level and meteorological data will be acquired.

(b) The plan is to study the surface and deep circulation across the entire South Atlantic at 24°S and 32°S. A proposal to CIRM will request funds for stations separated by 15 nautical miles. Two Navy ships and Sea Bird CTD and Plessy STD will be used with hydro bottles to be analyzed for salt, oxygen, fluorocarbons.

CIRM funding for some continued "TRANSCOBRA" PEGASUS work across the continental margin will be requested.

- Ikeda

  A continued study of the connection of the South Atlantic and the Southern Ocean.

  This is done with an annual 90-100 station XBT line from Rio Grande de Sul to Antarctica during Summer January - March on the R/V Besnard.

One of the priority scientific issues in Brazil is to understand the equatorial atmosphere and ocean interaction and to what extent the Atlantic equatorial atmosphere and ocean are responsible for the serious droughts in Northeast Brazil. As physical oceanographers we should interact with meteorologists at INPE who have an interest in the ocean in the NOBREX region. Every effort should be made to callaborate during NOBREX. It would be helpful if Brazilian meteorologists and/or physical oceanographers could help to provide a measure of the atmospheric influence on the ocean. This could happen with studies of satellite information, analysis of ship and coastal observations and use of European Center Analyses of these data.

Mascarenhas works with a private meteorological foundation in Fortaleza who could provide coastal meteorological and sea level monitoring assistance. This contact must be persued in time for NOBREX.

III. U.S./Brazil Joint Modelling Studies

Prepared by Dennis Moore with inputs from Julian McCreary and Joao Lorenzzetti, Aug. 5, 1987. US/Brazil Workshop, Durham, New Hampshire

U.S. Scientists: Pijush Kundu, Julian McCreary, Dennis Moore

Brazilian Scientists: Marcio Vianna

- Drs. Vianna and Moore would like to address the very general problem of

  "Reflection of Equatorial Waves from Ocean Boundaries of Arbitrary Shape".

Dr. Moore has been working on a stream function and Laplace transform formulation of Ris problem. Dr. Vianna has been applying boundary element techniques to the same problem.

- Drs. Kundu, McCreary and Vianna would like to apply a model recently developed at Nova University to study the

  "Seasonal Cycle of the Wind-driven Circulation off the Coast of Brazil".

  This study will investigate the North Brazil Coastal Current, its meanders, eddies and seasonal connection to the North Equatorial Counter Current.

Acknowledgements

This workshop was made possible through the efforts of many people in the Ocean Process Analysis Laboratory. A special acknowledgement is deserved by Frank Smith who did the major share of the coordination and Elaine Drapeau who played a central role in producing this proceeding. The principal funding was provided through the National Science Foundation International Program Grant INT-8703019 and additional support from the Institute for the Study of Earth, Oceans and Space (UNH), Ocean Process Analysis Laboratory (UNH), Tinker Foundation, Inc., and the Center for International Perspectives (UNH).

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Appendix B - Brazilian Physical Oceanographers

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Large and Meso-scale Ocean Circulation
Air-Sea Interaction

Afranio R. De Mesquita (Ph.D.)
Tides
Statistical Data Analysis

Belmiro Mendes De Castro Filho (Ph.D)
Continental Shelf Dynamics
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Joseph Harari (Ph.D.)
Numerical modeling
Tides

- Instituto de Pesquisas Espaciais (INPE)
  (Space Research Institute)

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Satellite Oceanography
Satellite Drifters Development & Use

Marcio Vianna
Semi-Analytical Modeling of Ocean Circulation
South Equatorial Current
Bifurcation of the NBCC & Brazil Current

Joao A. Lorenzzetti
Coastal Dynamics
Numerical Modeling