Some Accurate Surface Features in the Indian Ocean Revealed by Thermosalinograph Measurements

With the help of the officers and crew of ships of opportunity (SOPs), ORSTOM has collected since 1966-67 a unique set of routine surface data, including sea-surface temperature (SST) and sea-surface salinity (SSS) over three oceans. The difficulties of determining SSS led to the installation and use of thermosalinographs aboard SOPs. A pilot experiment was initiated in 1991, and in 1993 a thermosalinograph was installed aboard a merchant ship running along an around-the-world track.

Several papers already have presented results of the ORSTOM SSS experiment for the Pacific (Donguy, 1994) and Atlantic Ocean (Dessier and Donguy, 1994). This note reports on thermosalinograph data from the Indian Ocean. In the Indian Ocean, the SOP (CGM) *Ronsard* moved through Sunda Strait, traveling northwestward to Sri Lanka through the Bay of Bengal; after Sri Lanka, the track was approximatly westward through the Arabian Sea and to Gulf of Aden (Figures 1 and 2).

Data

Three transects are available from SOP *Ronsard*: August 1993 during the SW monsoon (SWM); November 1993 between the SWM and the Northeast Monsoon (NEM); and March 1994 between the NEM and the SWM. Figures 1 and 2 show maps of SST and SSS that have been objectively interpolated from the three transects.

The main SST features in Figure 1 are the following:

- West of 45°E in the southern Red Sea, SST is greater than 30.0°C from August to November and less than 26.0°C starting in March, a seasonal variation that is typical for the northern hemisphere.
- From 45°E to 50°E in the Gulf of Aden, a typical northern seasonal regime also occurs, but the maximum SST (>30°C) lasts only until September and the minimum (<26°C) exists from December to March.
- From 50°E to 65°E in the western Arabian Sea, upwelling off Somalia during the SWM induces an inverse regime with low SST during the northern summer and high SST (>27.0°C) during the northern winter. There is an intense front across the mouth of the Gulf of Aden near 50°E.
- From 65°E to 75°E in the eastern Arabian Sea, an SST maximum occurs during the first part of the year. This warm season is due to light winds before the SWM, which cause an increase in the surface heat flux.
- Between 75°E and 85°E, low temperature occurs during the northern summer (SST <27°C), which is due to coastal upwelling along the Coromandel coast induced by the SWM.
- Between 85°E and 95°E in the southern Bay of Bengal, a monsoonal regime similar to that in the eastern Arabian Sea occurs, with the warm season starting in March.
- Between 95°E and 105°E along the Sumatra coast, the warm season is in July-August, even though the track is in the southern hemisphere. This is likely due to the outflow of warm water from the easternmost Indian Ocean.

The main SSS features in Figure 2 are the following:

- West of 45°E, the southern Red Sea is characterized by SSS of more than 36.5 ppt.
- Between 45°E and 50°E in the Gulf of Aden, SSS is more than 36.0 ppt in the northern summer, less in the northern winter.
- Between 50°E and 65°E in the western Arabian Sea, there is low SSS during the SWM due to the Somali upwelling, and high SSS during the NEM due to the southward advection of northern Arabian Sea water.
- Between 60°E and 70°E, an SSS front, which separates high SSS water in the western Arabian Sea from low SSS water in the eastern Arabian Sea, moves from approximately 60°E in April to 70 °E in October.
- Between 65°E and 75°E in the eastern Arabian Sea, high SSS (>36.5) occurs from July to December, and low SSS from December to May. High SSS could be due to increased evaporation caused by the strong winds of the SWM. Conversely, a low SSS during the NEM is likely caused by advection from the Malabar coast.
- Between 75°E and 85°E, coastal upwelling of Coromandel during the SWM increases SSS to values greater than 35.0 ppt, and there is low SSS during the NEM.
- Between 85°E and 90°E, an SSS minimum occurs in December due to a southward advection of low-salinity water from the Bay of Bengal.
- In the vicinity of 90°E south of Sumatra, an SSS (>34.5 ppt) maximum appears during the NEM.
- East of 95°E, SSS is always less than 34.5 ppt, with a minimum during the NEM due to the presence of the ITCZ.

Comparison with Climatology

SST and SSS climatologies have been prepared by Donguy and Meyers (1995) along the same track. Space-time diagrams from the climatology (Figure 3) may be compared to those from the thermosalinograph (Figures 1 and 2). Most of the major features are present in both data sets, but not with the same intensity in the climatology.

Conspicuous differences in the SST plots are

- Climatological SST is high throughout the Gulf of Aden (45°E-50°E) during the summer, whereas SST from the thermosalinograph shows that it remains cool (<28°C) in part of the Gulf of Aden.

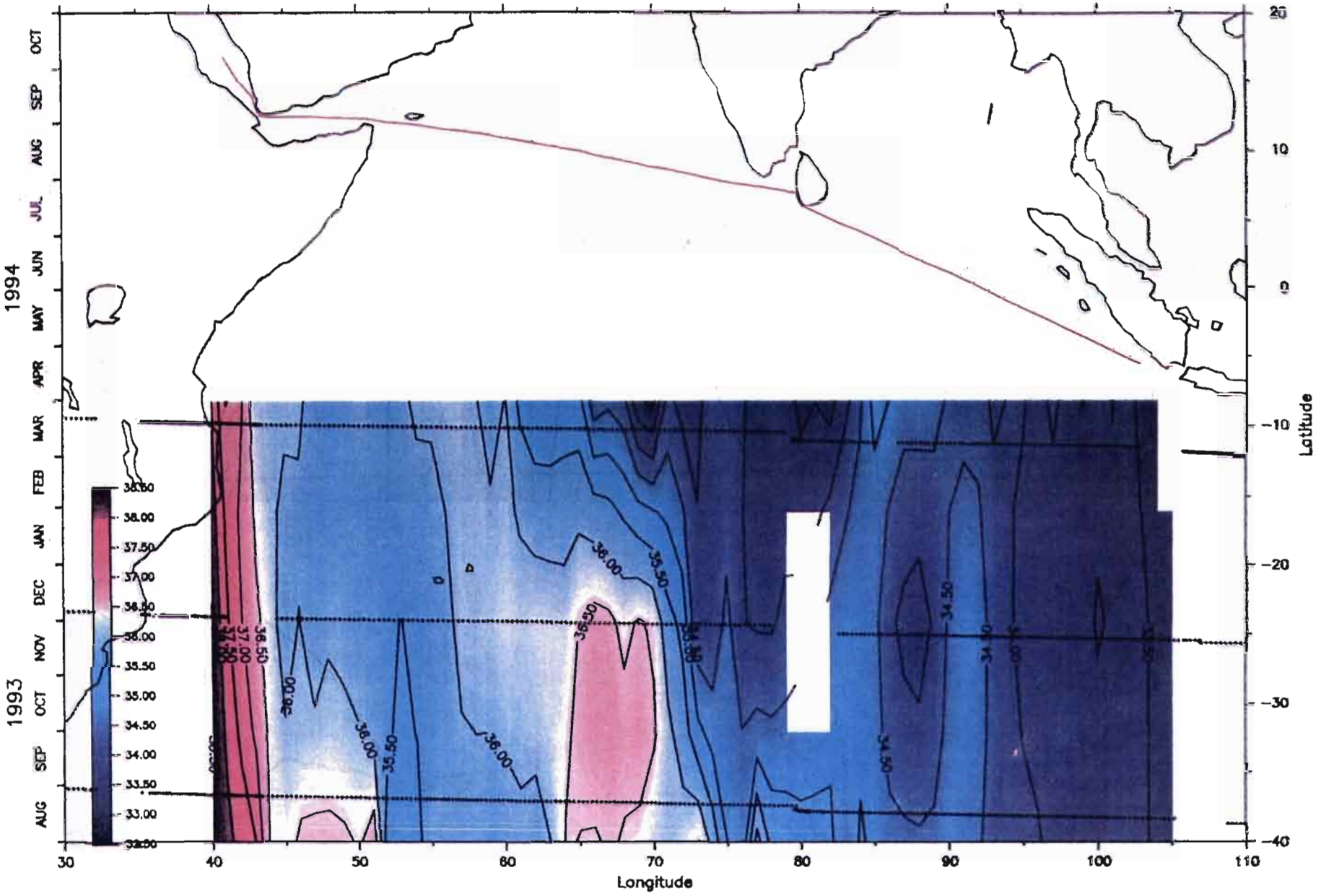

Figure 1 . SST along the Indian Ocean track shown, as determined from the thermosalinograph.

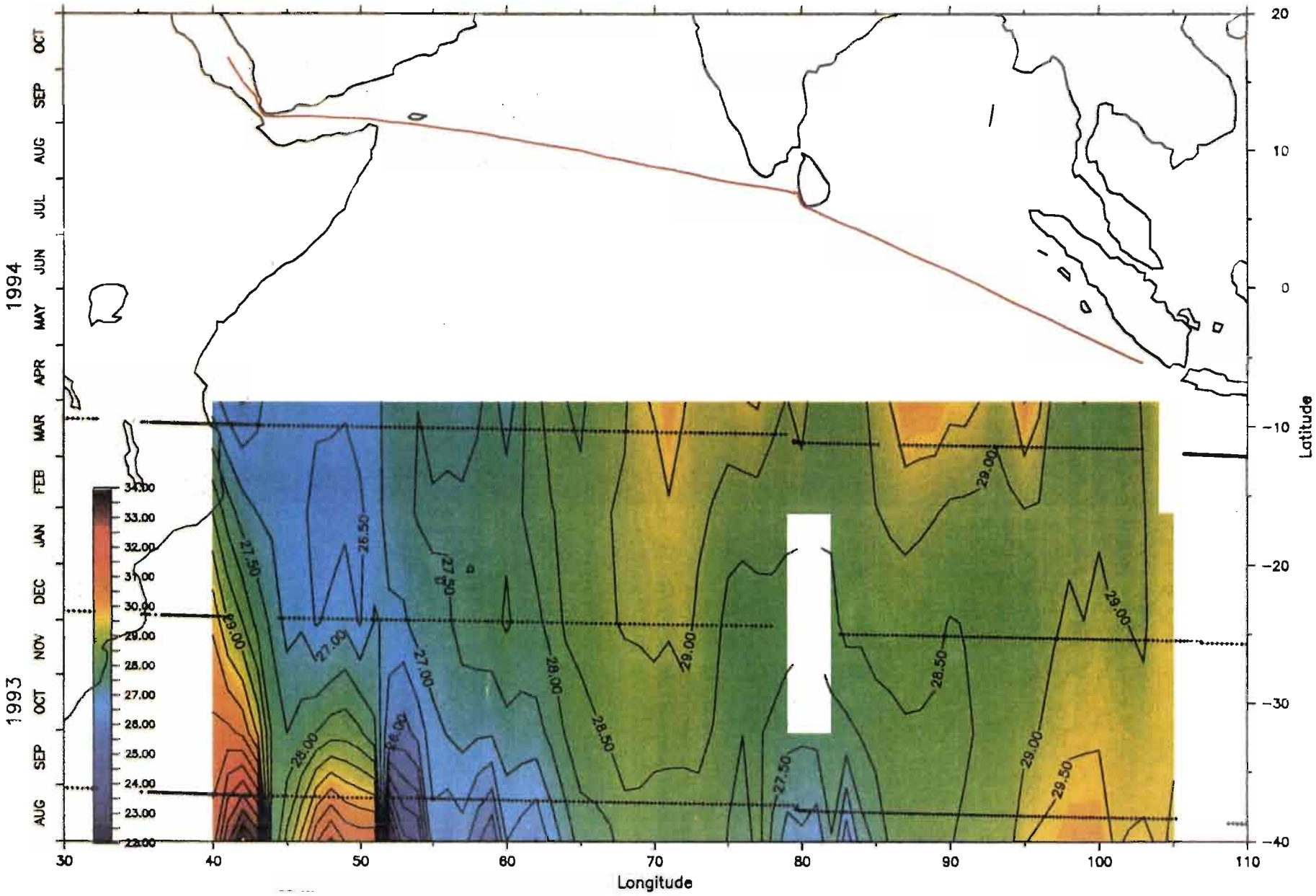

Figure 2. SSS along the Indian Ocean track shown, as determined from the thermosalinograph.

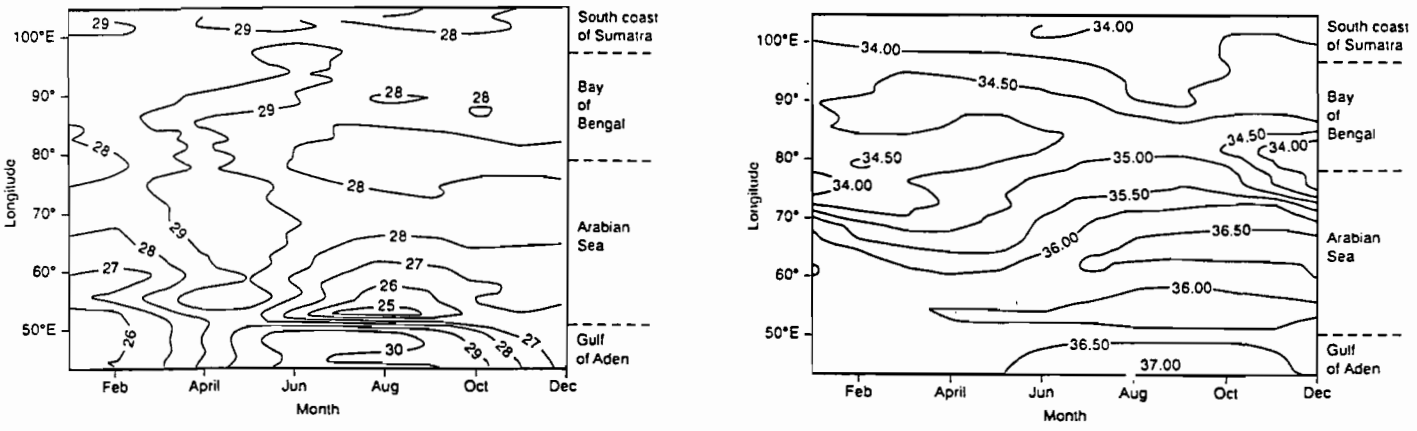

Figure 3. Climatological SST and SSS along the Indian Ocean track shown in Figures 1 and 2.

- The minimum SST at 80°E due to the Coromandel upwelling is larger in the thermosalinograph data (<27°C) than in the climatology (<28°C).

- The climatological SST maximum in the Bay of Bengal (29.5°C) is larger than in the thermosalinograph data (28°C).

A notable difference in the SSS data is

- In the western Arabian Sea, SSS deceases to 35.5 ppt during the SWM in the thermosalinograph data but only to 36.0 ppt in the climatology.

T-S Relationships

Figure 4 shows the T-S relationships taken during August 1993. They differ considerably from those taken on the other two cruises, since it was the time of the SWM, and therefore the time of upwelling along the Somali coast and the Coromandel coast.

In the eastern Indian Ocean (east of 90°E in the Gulf of Bengal), SSS is typically close to 34.0 ppt, and SST is greater than 29.5°C. At 80°E, we find a different water mass due to the Coromandel coastal upwelling, with SST = 27°C and SSS = 35.0 ppt.

West of the Indian peninsula (80°E), the water masses are much more saline. Between 80°E and 60°E, Arabian Sea water with an SSS maximum appears. Typical values of SSS and SST for the water are 36.5 ppt and 28°C, respectively. At this time (during the SWM) this water is isolated from the east by a salinity front and from the west by a temperature front.

West of 60°E, a water-mass appears that is charateristic of the Somali upwelling, with SST = 24°C and SSS = 35.5 ppt.

West of 50°E in the Gulf of Aden, SST and SSS are both high, with SST

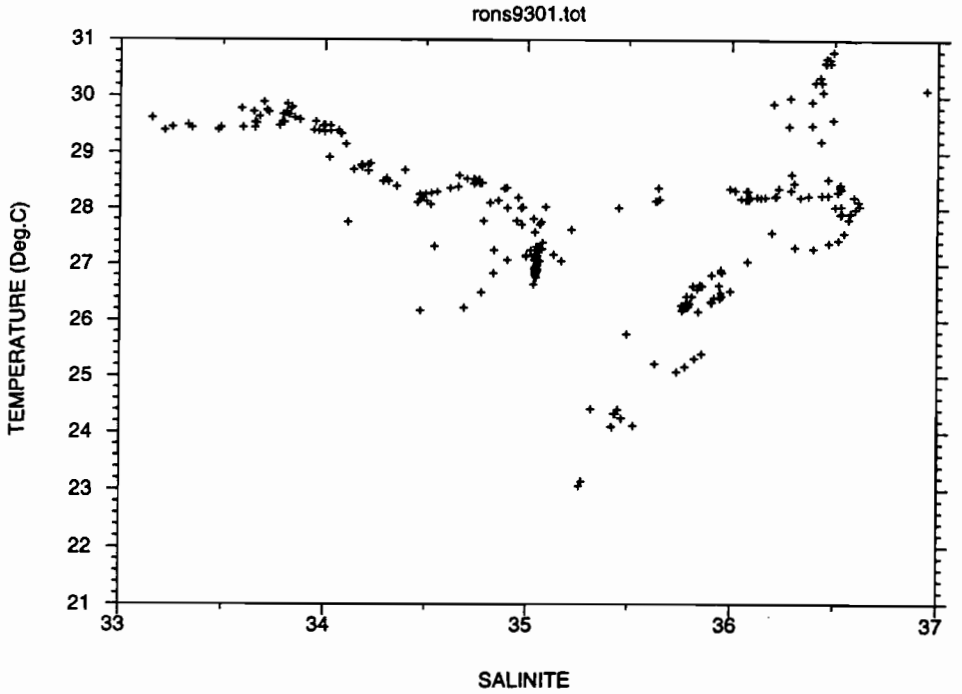

Figure 4. T/S relationships during the cruise of August 1993.

>30°C and SSS = 36.5 ppt. Consequently, between these two water masses there is one of the most prominent fronts in the world: SST changes from 24°C to more than 30°C and SSS from 35.5 ppt to 36.5 ppt.

The T-S relationships for the other two voyages are similar to each other. During the November voyage, the water in the eastern Indian Ocean is almost the same type as during the SWM; water typical of the Coromandel upwelling has disappeared, but the water masses characteristic of the Somali upwelling, Gulf of Aden, and Arabian Sea regimes are still present. During the March voyage, the eastern Indian Ocean water has the same characteristics, except that water in the Gulf of Aden has changed, with SST = 27°C and SSS = 36.0 ppt.

Conclusions

The use of thermosalinographs aboard SOPs may open a new era for understanding SSS fields and their temporal variations. Moreover, the thermosalinograph gives simultaneous values of SST and SSS, and so can determine characteristics of water masses.

References

Delcroix, T., and C. Henin, 1991: Seasonal and Interannual Variations of Sea Surface Salinity in the Tropical Pacific Ocean. *J. Geophys. Res.*, 96, 22135-22150.

Dessier, A., and J.R. Donguy, 1994: The sea surface salinity in the tropical Atlantic between 10°S and 30°N. Seasonal and interannual variations (1977-1989). *Deep-Sea Res.*, 41, 81-100.

Donguy, J.R., 1994: Surface and subsurface salinity in the tropical Ocean. Relations with climate. *Prog. Oceanog.*, 34, 45-78.

Donguy, J.R., and G. Meyers, 1995: Seasonal variations of sea surface salinity and temperature in the tropical Indian Ocean. (Submitted)

C. Henin
Groupe SURTROPAC
Centre ORSTOM
Noumea, New Caledonia
and
J.-R. Donguy
Centre ORSTOM de Brest
BP 70
29280 Plouzane, France

TOGA Notes

Nova Southeastern University
Oceanographic Center
8000 North Ocean Drive
Dania, Florida 33004, USA

JANUARY 1995

TOGA Notes

This is the final issue of *TOGA Notes*. The bulletin has been published quarterly since 1989 by the Nova Southeastern University Press. Its purpose has been to provide a forum for presenting to the scientific community new theories, findings, and announcements concerning TOGA-related issues in a timely way. We trust that the bulletin has served its purpose well, and we thank the many contributors who have made its publication possible. **Dr. Julian P. McCreary** has served as Science Editor and **Ms. Jan Witte** has been the Technical Editor.

Questions concerning the availability of past issues or a possible successor to *TOGA Notes* (retaining the current mailing list) should be addressed to:

Ms. Jan Witte, Technical Editor
TOGA Notes
Nova Southeastern University
Oceanographic Center
8000 North Ocean Drive
Dania, Florida 33004, U.S.A.
Phone: (305) 920-1909;
Fax: 947-8559
E-mail: witte@ocean.nova.edu

CONTENTS

(*continued from page 23*)

Communications concerning the transition from TOGA to CLIVAR should be addressed to:

Valery Detemmerman
Joint Planning Staff for WCRP
World Meteorological Organisation
P.O. Box 2300
CH-1211 Geneva 2, Switzerland
Tel: +41 22 7 30 82 42
Fax: +41 22 7 34 31 81
e-mail: valery@wcrp4.wmo.ch

Communications concerning TOGA CD-ROMs should be addressed to:

Chris Finch, M/S 300-320
Physical Oceanography DAAC,
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109-8099, U.S.A.
e-mail: cjf@shrimp.jpl.nasa.gov

John Marsh, Director
International TOGA Project Office