

## Hydrographic characteristics and circulation in the Caribbean Sea during April and May 1990

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KUMAR, S. P., V. S. N. MURTY, A. A. KHAN, M. A. JONES, A. B. WAGH, and B. N. DESAI. 1991. Hydrographic characteristics and circulation in the Caribbean Sea during April and May 1990. *Caribb. Mar. Sci.* 2(1&2): 69-80. The analysis of hydrographic data, collected in the course of the Caribbean Oceanographic Resources Exploration (CORE) Project, revealed the presence of two water masses in the upper 1000-m depth of the Caribbean Sea. A subsurface high saline water mass, termed as subtropical underwater, with a salinity maximum of  $36.8 \times 10^{-3}$  occurred between 100- and 200-m depths, while the Antarctic intermediate water with a salinity minimum of  $35.06 \times 10^{-3}$  occurred between 700- and 800-m depths. The so-called plume area, off the west coast of Jamaica, is characterized by the spreading of isotherms and isohalines (between 250- and 500-m depths) associated with a subsurface high velocity core and a current shear. A lens of low salinity water ( $<33.5 \times 10^{-3}$ ) originating from the Amazon River discharge, with a vertical extent of up to 50 m depth was observed east of  $60^\circ$  W between Tobago and Barbados. Strong upwelling was recorded offshore along the north coast of Trinidad. Upwelling tendencies were also observed along the Guyana coast. The observed saline front north of Trinidad indicated the presence of freshwater discharge from the Orinoco River. The near-surface circulation showed a general north-westward flow off the Guyana coast (Guyana Current) and westward flow through the passages of the Lesser Antilles. An anticyclonic gyre existed east of  $60^\circ$  W between Trinidad and Barbados. The southern limit of the North Equatorial Current was evident at  $14^\circ$  N entering the Caribbean Sea through the passage between St Lucia and Martinique.

L'analyse de données hydrographiques, obtenues au cours du Projet d'Exploration des Ressources Océanographiques des Caraïbes (CORE — Caribbean Oceanographic Resources Exploration Project), a découvert l'existence de deux masses d'eau dans la profondeur supérieure de 1000 mètres de la Mer des Caraïbes. L'on a découvert entre des profondeurs de 100 et 200 mètres une masse d'eau de haute salinité au-dessous de la surface, laquelle a été classée comme sous-eau subtropicale, à un maximum de salinité de  $36,8 \times 10^{-3}$  tandis que l'eau intermédiaire de l'Océan Antarctique à un minimum de salinité de  $35,06 \times 10^{-3}$  se trouvait entre des profondeurs de 700 et 800 mètres. La région qualifiée de plume, près du littoral ouest de la Jamaïque, est définie par l'élargissement d'isothermes et d'isohalines (entre des profondeurs de 250 et 500 mètres) ce qui est associée à un centre de haute vélocité au-dessous de la surface et une réduction du courant. A l'est de  $60^\circ$  O entre Tobago et la Barbade l'on a constaté une lentille d'eau à salinité basse ( $<33,5 \times 10^{-3}$ ) venant de l'écoulement du fleuve Amazone, à une longueur verticale de profondeur de jusqu' à 50 mètres. L'on a constaté une turbidité importante près de la côte du nord de la Trinité. L'on a remarqué aussi une tendance à la turbidité le long de la côte de Guyane. Le front de salinité constaté au nord de la Trinité a signalé l'existence d'un écoulement d'eau fraîche débouchant du fleuve Orinoco. La circulation près de la surface a révélé un cours général vers le nordouest près de la côte de Guyane (le courant guyanais) et un cours vers l'ouest par les passages des Antilles Mineures. Un gyre anticyclonique existait à l'est de  $60^\circ$  O entre la Trinité et la Barbade. La limite du sud du Courant Equatorial du Nord a été fort évident à  $14^\circ$  N débouchant dans la Mer des Caraïbes par le passage entre Sainte Lucie et la Martinique.

El análisis de datos hidrográficos, obtenidos durante el Proyecto de Exploración de Recursos Oceanográficos del Caribe (CORE — Caribbean Oceanographic Resources Exploration Project), descubrió la existencia de dos masas de agua en la hondura superior de 1000 metros del Mar Caribe. Se desveló entre honduras de 100 y 200 metros una masa de agua de alta salinidad por debajo de la superficie, la que se calificó de subagua sub tropical, con un máximo de salinidad de  $36,8 \times 10^{-3}$ , mientras que el agua intermedio del Océano Antártico con un mínimo de salinidad de  $35,06 \times 10^{-3}$  se encontraba entre honduras de 700 y 800 metros. El área llamada pluma, cerca de la costa oeste de Jamaica, se caracteriza por la extensión de isoterms e isohalinas (entre honduras de 250 y 500 metros) relacionado con un centro de alta velocidad por debajo de la superficie y una disminución de la corriente. En el este de  $60^\circ$  O entre Tobago y Barbados se observó un lente de agua de baja salinidad ( $<33,5 \times 10^{-3}$ ) originando de la descarga del río Amazonas, con una extensión vertical de hondura de hasta 50 metros. Se notó una turbencia importante cerca de la costa norte de Trinidad. Además se averiguó una propensión para la turbencia a lo largo de la costa de Guyana. La frente de salinidad observada en el norte de Trinidad señaló

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la existencia de una descarga de agua fresca desde el río Orinoco. La circulación cerca de la superficie reveló un curso general hacia el noroeste cerca de la costa de Guayana (la corriente guayanesa) y un curso hacia el oeste pro pasajes de las Antillas Menores. Un giro anticiclónico existía en el este de 60° O entre Trinidad y Barbados. El límite sud de la corriente Ecuatorial del Norte fue evidente en los 14° N desaguando en el Mar Caribe pro medio del pasaje entre Santa Lucía y Martinica.

### Introduction

The Caribbean Sea, a semi-enclosed ocean basin, is influenced by the freshwater discharge from the rivers of the South American continent, particularly the Amazon and Orinoco, and the equatorial current system of the Atlantic Ocean. These rivers discharge fresh water at the rate of  $210\,000\text{ m}^3 \cdot \text{s}^{-1}$  which amounts to about 30% of the world's annual freshwater discharge into the Atlantic Ocean (Ryther et al. 1968).

There have been several studies aimed at understanding the general circulation and water characteristics of the Caribbean Sea in relation to the Guyana Current and the North Equatorial Current. Gade (1961) reported that these currents separate while entering the Caribbean Sea across the Antilles. Fukuoka (1965) calculated the geostrophic circulation in the southern Caribbean Sea but failed to obtain a detailed synoptic picture of the current field due to the wide separation between the stations. The volume transport calculations by Johannessen (1968) revealed an inflow of  $24 \times 10^6\text{ m}^3 \cdot \text{s}^{-1}$  between Barbados and Tobago. Later Stalcup and Metcalf (1972), based on direct current measurements during March–April, 1970, found that higher influx of water into the Caribbean Sea takes place through the Grenada and St Vincent passages and lower influx through the Dominica Passage. The geostrophic calculation of Febres Ortega and Herrera (1976) in the neighbourhood of the Lesser Antilles indicated that the main inflow towards the Caribbean Sea is between the islands of St Vincent and Dominica ( $21.5 \times 10^6\text{ m}^3 \cdot \text{s}^{-1}$ ).

Although offshore conditions are generally well known, the characteristics and circulation of waters of the Exclusive Economic Zones (EEZs) of the Caribbean islands are poorly known. Under the Caribbean Oceanographic Resources Exploration (CORE) Project, studies were carried out in the EEZs of the islands of the Greater and Lesser Antilles by a joint team

of Indian and Caribbean scientists to develop a deeper understanding of the general hydrographic characteristics and circulation in the Caribbean Sea, to identify the water masses, delineate the areas of upwelling, and the effect of freshwater discharge from the Amazon and Orinoco rivers on the general circulation.

### Sampling Stations and Methods

The hydrographic survey was carried out in four legs (Map 1, p. 4): Leg I: Jamaica–Belize–Jamaica; Leg II: Jamaica – the Bahamas – Barbados; Leg III: Barbados – Trinidad and Tobago; Leg IV: Trinidad and Tobago – Guyana. The survey commenced on 14 April 1990 ending on 24 May 1990. Twelve hydrographic stations were occupied in Leg I, 8 in Leg II, 12 in Leg III, and 13 in Leg IV. Altogether 45 hydro-graphic stations were occupied at which data on temperature and salinity with depth were collected through hydrocast and MICOM STD operations. Water samples collected with Nansen bottles were analyzed using a Guildline Autosal (model 8400A). The conversion of conductivity to salinity was carried out using the modified Unesco formula (Anon. 1981). Using the processed data, vertical sections and horizontal maps of property distributions (temperature, salinity, and  $\sigma_t$ ) and current structure were prepared. Temperature–salinity (T–S) diagrams were drawn to identify the water masses.

### Results and Discussion

For convenience in presentation, data from Leg I are used to produce vertical sections while data from Legs II, III, and IV are used to produce horizontal profiles of the various parameters.

#### *Thermal Structure along Belize–Jamaica Section; Leg I*

The thermal structure along this section (Fig. 1) showed an isothermal layer of about 60 m in thickness at the central region which thinned to

less than 40 m off Belize and Jamaica. Surface waters off Belize were  $0.5^{\circ}\text{C}$  warmer than those off Jamaica. The isothermal layer was followed by a thermocline which extends up to about 800–1000 m. Strong temperature gradients ( $5 \times 10^{-2}^{\circ}\text{C} \cdot \text{m}^{-1}$ ) were observed in the upper thermocline (above 400 m depth) while weak gradients ( $1.5 \times 10^{-2}^{\circ}\text{C} \cdot \text{m}^{-1}$ ) prevailed in the lower thermocline. An interesting feature noticed west of Jamaica is the spreading of isotherms between 100 m and 600 m (at Station 9) at approximately the centre of the so-called plume area.

#### *Salinity Structure along Belize–Jamaica Section; Leg 1*

The central region of the section (Fig. 2) was characterized by a lens of low salinity ( $<36.2 \times 10^{-3}$ ) in the upper 50 m. The salient feature of the salinity structure was the presence of a subsurface high saline core ( $36.8 \times 10^{-3}$ ) between 100- and 200-m depths. This high saline core lay between 100 and 170 m off Belize and deepened to 250 m towards the east. As noted in the thermal structure, salinity distribution also showed spreading of isohalines (at Station 9) between 100 and 600 m. The elevation of isohalines above 350-m depths to the upper layers thereby reduced thicknesses in the so-called plume area. Another noteworthy feature was the occurrence of low saline water with salinity  $<35.06 \times 10^{-3}$  between 700- and 800-m depths.

#### *Geostrophic Currents along Belize/Jamaica Section; Leg 1*

The computed geostrophic currents (Fig. 3) showed a weak ( $<5 \text{ cm} \cdot \text{s}^{-1}$ ) southerly flow between stations 4 and 5 and between stations 6 and 7. A broad relatively strong ( $18 \text{ m} \cdot \text{s}^{-1}$ ) northerly flow could be seen between stations 5 and 6.

It is interesting to note a subsurface high velocity core ( $20 \text{ cm} \cdot \text{s}^{-1}$ ) in the depth interval 250–400 between stations 7 and 11 within the plume area, west of Jamaica. The subsurface high velocity core and the associated current shear above and below was responsible for the observed spreading in the thermal and saline fields west of Jamaica.

It was discernible from the geostrophic currents that, in general, the flow was north-westward/westward with meanders within the Belize–Jamaica section of the Caribbean Sea. When the flow reached the Belize coast it bifurcated into northern and southern branches. The southern branch of the flow which flows along the coast of Honduras could be seen between stations 4 and 5. The northern branch of the flow which enters the Yucatan Channel and reaches the Gulf of Mexico could be seen between stations 5 and 6.

#### *Water mass structure*

To understand the water mass characteristics in the Caribbean waters, T–S diagrams were drawn and a typical diagram is presented (Fig. 4). It is evident from the T–S curve that there exists a subsurface high saline water mass with a salinity maximum of  $36.8 \times 10^{-3}$  and with temperatures between 22 and  $23^{\circ}\text{C}$ . This water mass occurred in the depth interval between 100 and 200 m, and lay at 240 cl/t surface. This is referred to as subtropical under-water (Rodriguez 1974). Below this, there was another water mass with a salinity minimum of  $35.06 \times 10^{-3}$  and temperature of  $6\text{--}7^{\circ}\text{C}$ . This water mass occurred at a depth of 700–800 m along 40–60 cl/t surface. This is the Antarctic intermediate water mass which enters the Caribbean Sea through the Grenada Passage after being carried by the Guyana current (Fukuoka 1970).

#### *Thermo-haline Characteristics of Waters between St Lucia and Guyana*

Surface temperature varied between  $27.5^{\circ}\text{C}$  and  $28^{\circ}\text{C}$ . Warm waters ( $<28^{\circ}\text{C}$ ) prevailed in the region north of  $10^{\circ}\text{N}$  and east of  $60^{\circ}\text{W}$  (Fig. 5). Colder waters ( $<27.5^{\circ}\text{C}$ ) were found between Trinidad and Grenada and offshore of Guyana. The surface salinity field (Fig. 6) showed a saline front north of Trinidad with a difference of about  $2.5 \times 10^{-3}$  over a distance of about 40 km. Between Tobago and Barbados (east of  $60^{\circ}30'\text{W}$ ) the waters were less saline ( $33.5 \times 10^{-3}$ ). West of  $60^{\circ}30'\text{W}$ , surface salinity increased to above  $35 \times 10^{-3}$ .

At 50-m depths a strong thermal front was seen north of Trinidad (Fig. 7) with colder

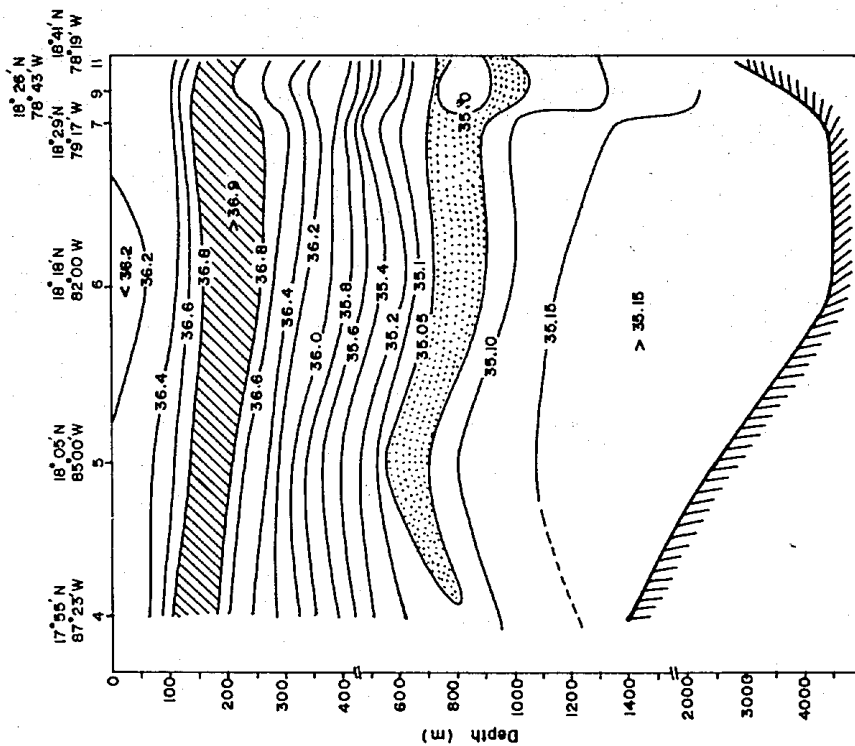


FIG. 2. Salinity structure along Belize-Jamaica section (Leg I).

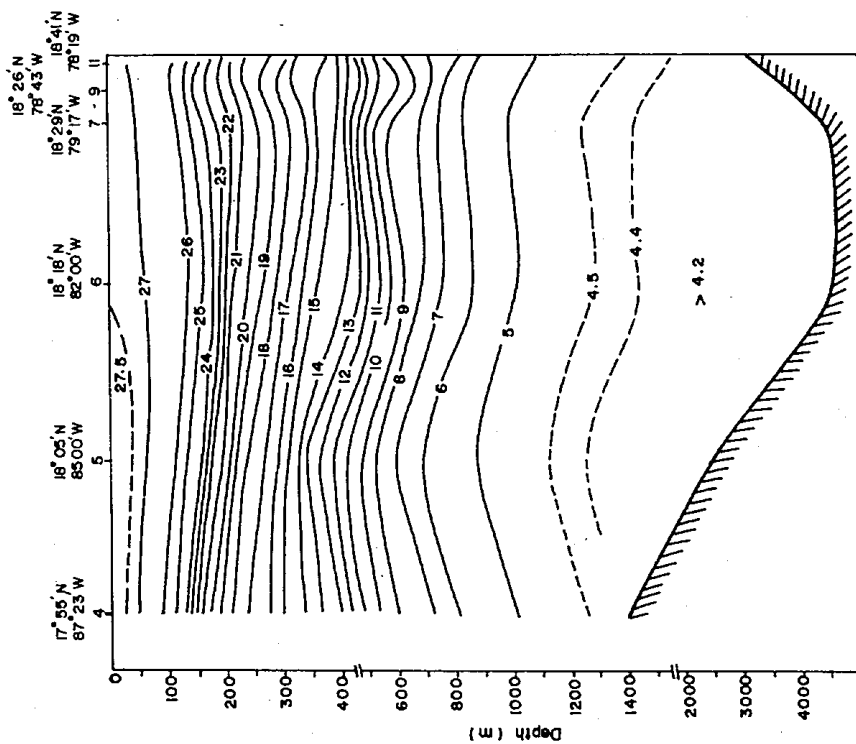


FIG. 1. Thermal structure along Belize-Jamaica section (Leg I).

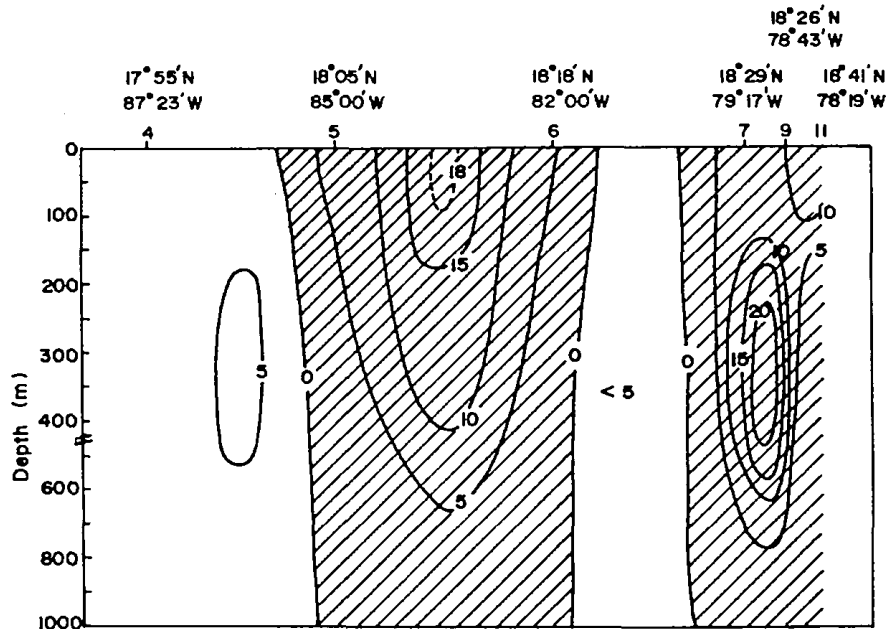



FIG. 3. Geostrophic current ( $\text{cm} \cdot \text{s}^{-1}$ ) structure along Belize-Jamaica section (Leg 1).  Northerly flow.

waters ( $<22^{\circ}\text{C}$ ) close to the coast and warmer waters ( $<27^{\circ}\text{C}$ ) north of it. A temperature difference of  $4^{\circ}\text{C}$  existed over a distance of 40 km. Warm waters were observed east of  $60^{\circ}30' \text{W}$  between Tobago and Barbados. On the Guyana coast, inshore waters were warmer than offshore waters. To the north-west of Tobago and Grenada and east of Barbados, salinity was less than  $35.5 \times 10^{-3}$  (Fig. 8). The saline front observed at the surface north of Trinidad could be seen extending up to 50-m depths but with a weak gradient.

At 100-m depths, a conspicuous cold water pocket ( $20^{\circ}\text{C}$ ) was observed between Grenada and Tobago and a cold water band between St Lucia and Barbados (Fig. 9). A region of warm water ( $>26.5^{\circ}\text{C}$ ) was noticed east of  $60^{\circ} \text{W}$  between Trinidad and Barbados. On the Guyana coast, colder waters were seen in the offshore region. Salinity distribution (Fig. 10) showed high saline waters ( $37.0 \times 10^{-3}$ ) east of St Lucia while in the rest of the region salinity was below  $36.5 \times 10^{-3}$ .

At 200-m depths the cold water band observed at 100-m depths persisted between St Lucia

and Barbados (Fig. 11). Warmer waters ( $>19^{\circ}\text{C}$ ) were seen south of Barbados. The salinity distribution pattern at this level was similar to that at 100-m depths. It varied from  $37.3 \times 10^{-3}$  north of St Lucia to  $35.8 \times 10^{-3}$  off Guyana (Fig. 12).

#### Topography of $20^{\circ}\text{C}$ Isotherm

The topography of the  $20^{\circ}\text{C}$  isotherm, representative of mid-thermocline, is presented in (Fig. 13). This can be used to deduce the near-surface flow pattern in this region. It may be seen that a north-westward flow occurs along the Guyana coast which flows into the Caribbean Sea. A part of this flow deflects towards the east when it encounters the Barbados coast, forming an anticyclonic gyre between  $11^{\circ} \text{N}$  and  $13^{\circ} \text{N}$  east of  $60^{\circ} \text{W}$ . The ridge structure ( $<125 \text{ m}$ ) between St Lucia and Barbados demarcates the southern limit ( $14^{\circ} \text{N}$ ) of the North Equatorial current, which flows into the Caribbean Sea through the passage between Martinique and St Lucia.

In general, the South Equatorial Current carrying the high saline south Atlantic central water crosses the equator near the coast of

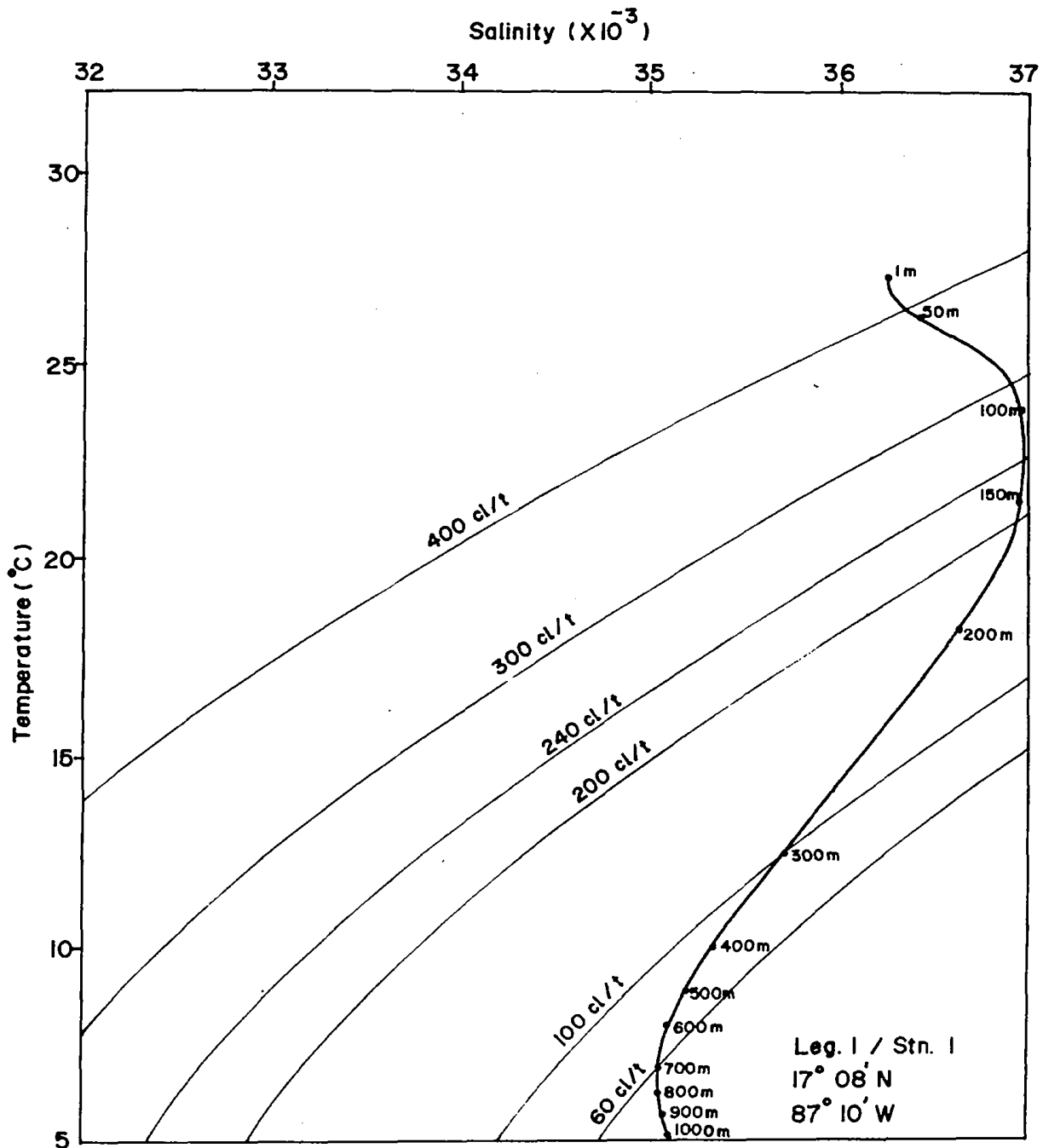


FIG. 4. A typical T-S diagram in the Caribbean Sea.

Brazil and a part flows north-westward forming the Guyana Current. This north-westward flow continues further and enters the Caribbean Sea. At the same time the southern part of the

North Equatorial Current flows into the Caribbean Sea north of St Lucia and further west through the passages of the Greater Antilles (Windward Passage, Anegada Passage).

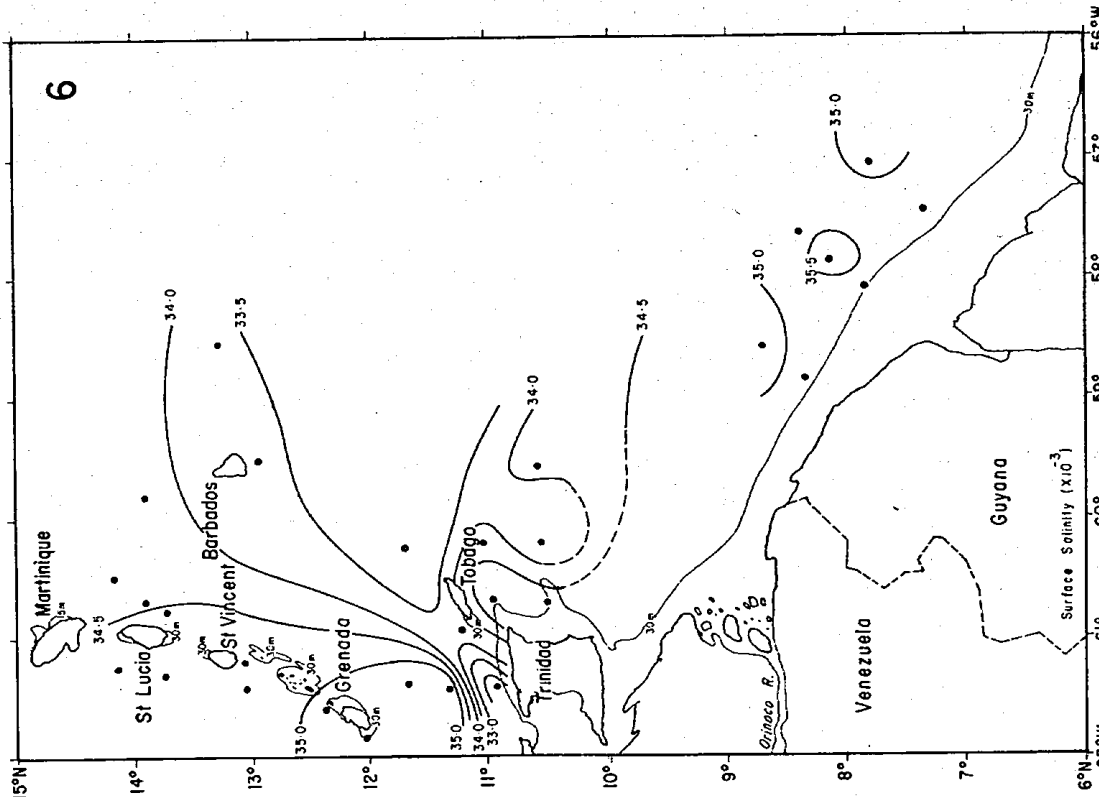


FIG. 6. Surface salinity distribution between St Lucia and Guyana.

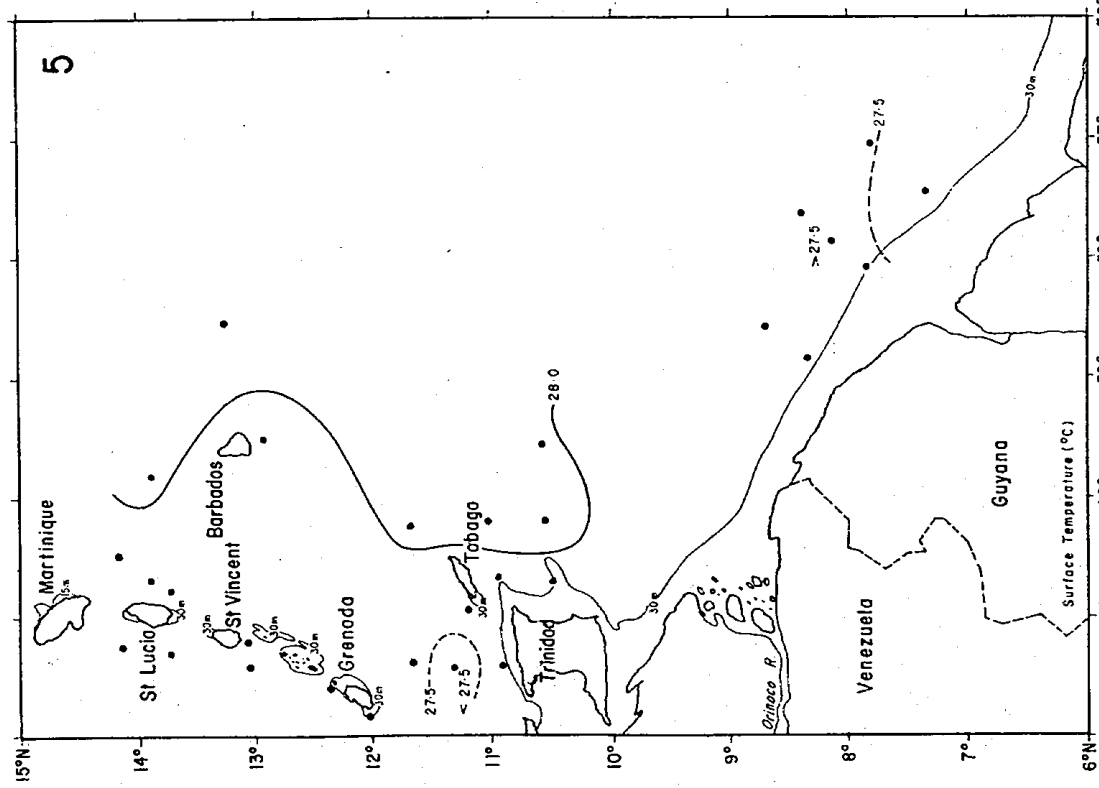


FIG. 5. Surface temperature distribution between St Lucia and Guyana.

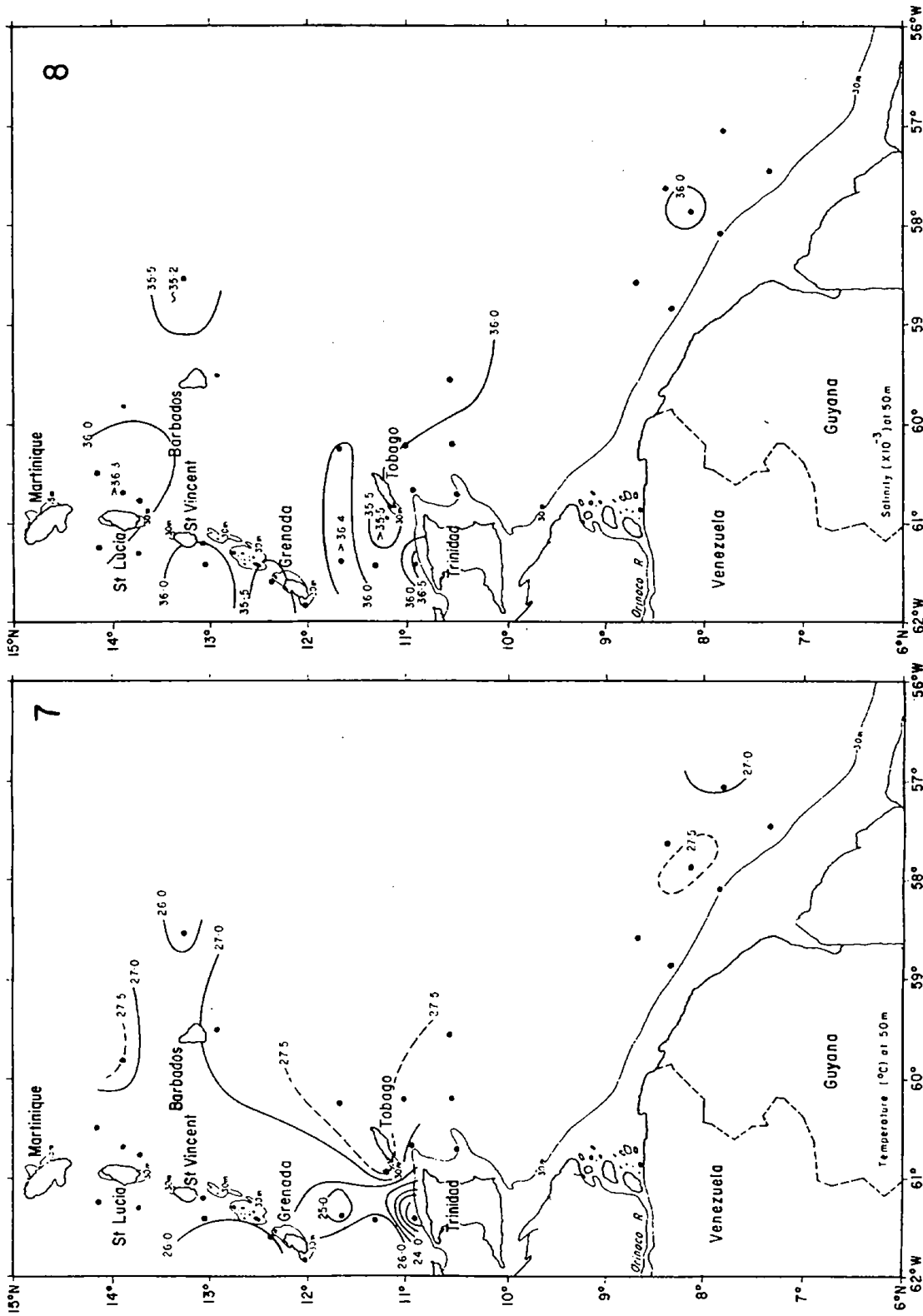


FIG. 8. Salinity distribution at 50-m depths between St Lucia and Guyana.

FIG. 7. Temperature distribution at 50-m depths between St Lucia and Guyana.



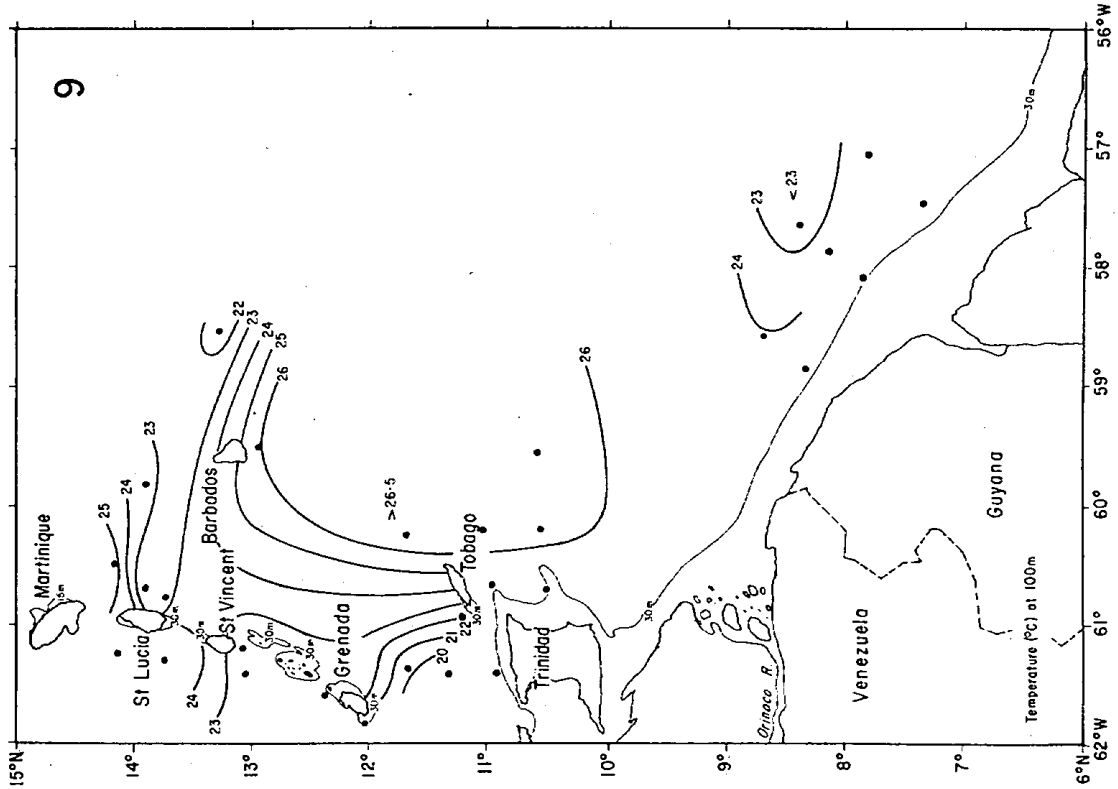
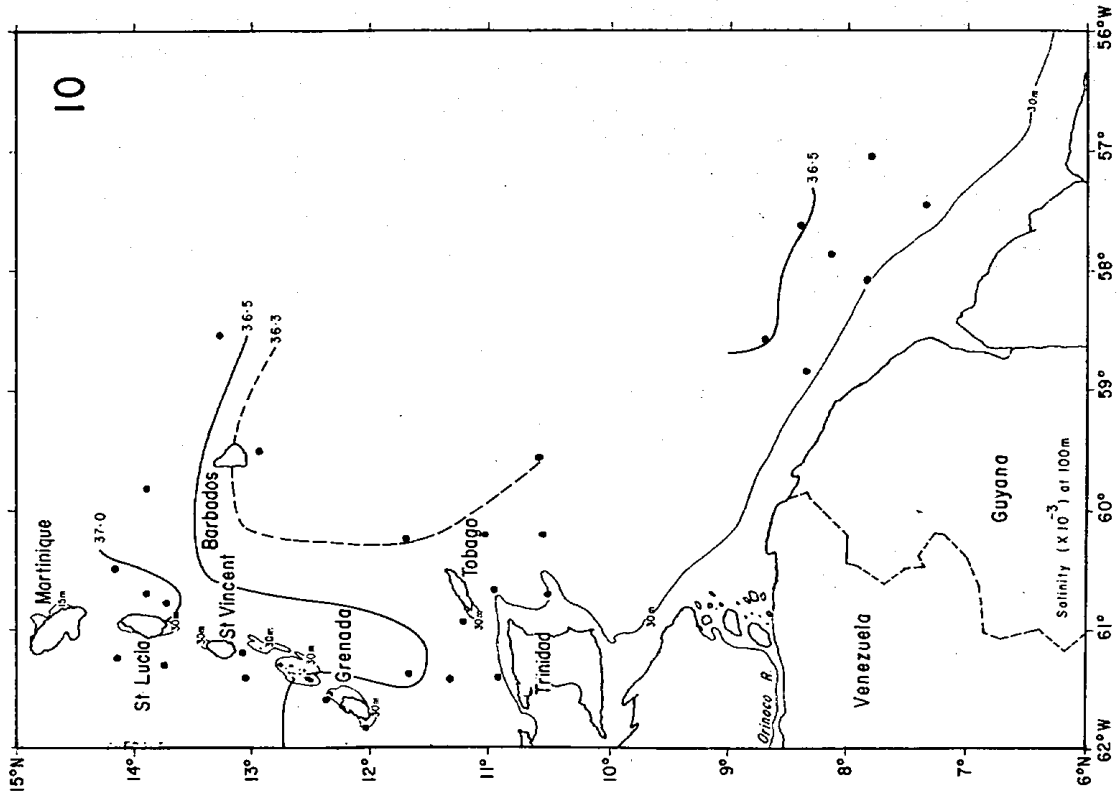


Fig. 10. Salinity distribution at 100-m depths between St Lucia and Guyana.

Fig. 9. Temperature distribution at 100-m depths between St Lucia and Guyana.

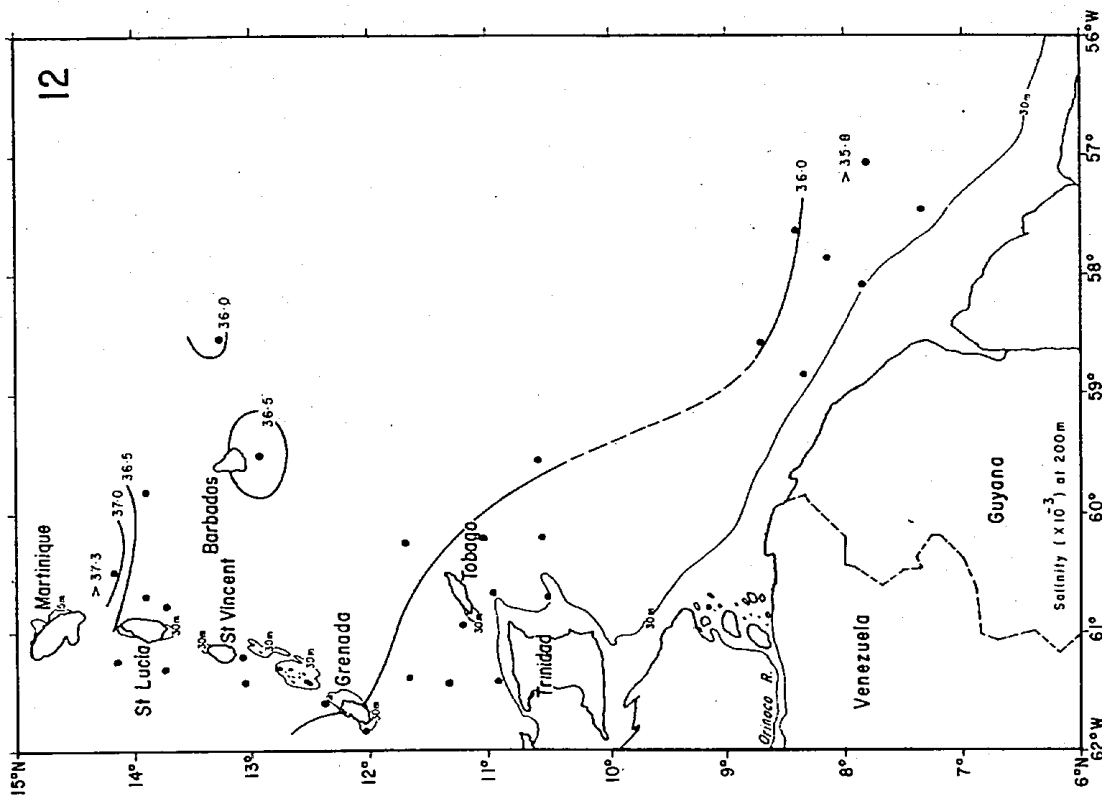


Fig. 12. Salinity distribution at 200-m depths between St Lucia and Guyana.

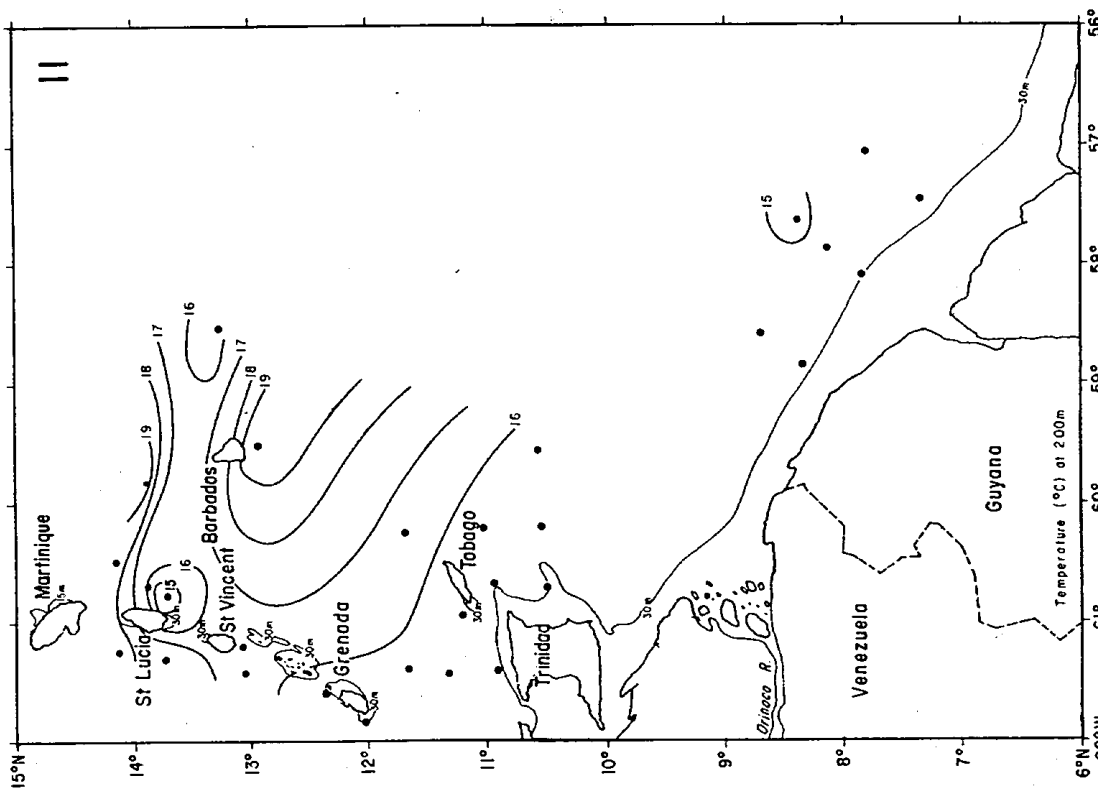


Fig. 11. Temperature distribution at 200-m depths between St Lucia and Guyana.

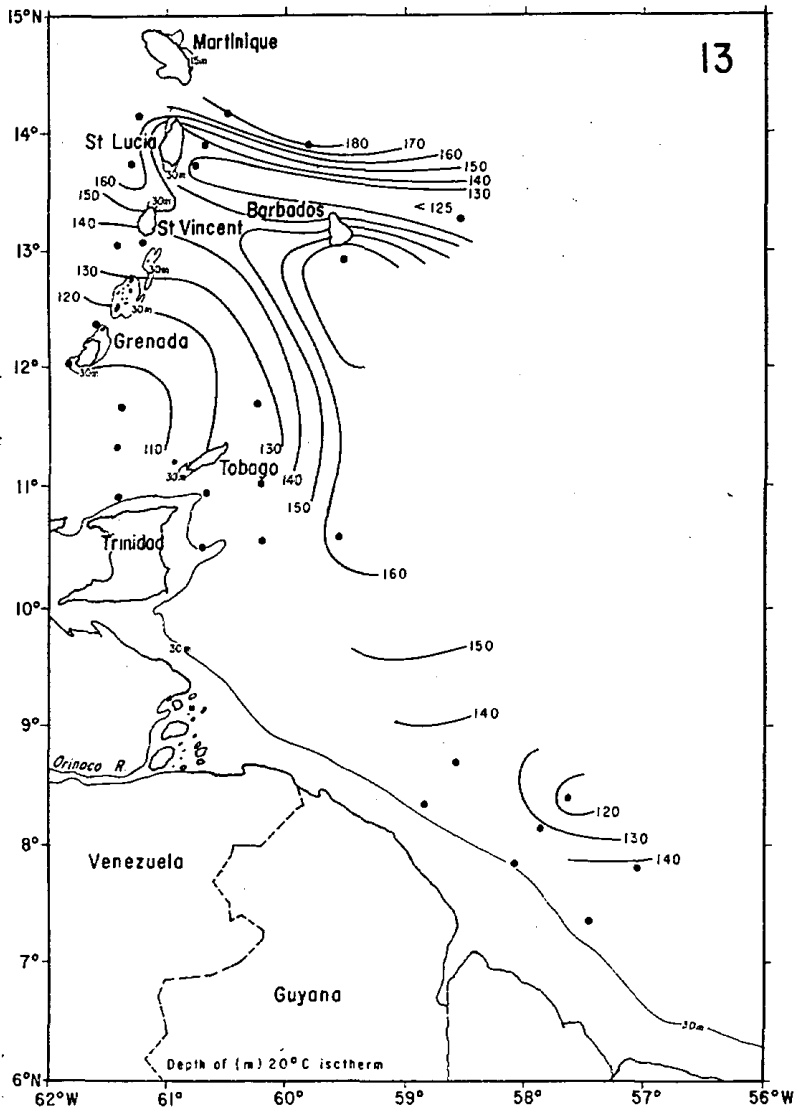


FIG. 13. Topography of 20°C isotherm and derived flow pattern.

In the present study, the cold ( $27.2^{\circ}\text{C}$ ) and high saline water ( $>36.0 \times 10^{-3}$ ) off the coast of Guyana indicates the north-west flowing Guyana Current. This current has potential to induce upwelling along the coast. The northward decrease of salinity at the surface and a patch of low saline waters ( $<33.5 \times 10^{-3}$ ) between Tobago and Barbados east of  $60^{\circ}\text{W}$  indicate the presence of a lens of low salinity water originating from Amazon River discharge. This is further supported by the observed high silicon content in this area

(Rajendran, pers. commun.). The vertical extent of the lens is up to a 50-m depth as could be seen from the low salinity pocket at this depth east of Barbados (Fig. 8). The tongue of low salinity water ( $<32.5 \times 10^{-3}$ ) north of Trinidad shows the presence of freshwater discharge from the Orinoco River which is carried north of Trinidad through the Gulf of Paria under the influence of the prevailing north-westward current. This gives rise to the observed saline front at the surface, north of Trinidad. However, the low salinity water seen at the surface

does not penetrate deeper as could be seen from the high saline waters at 50-m depths (Fig. 8). This high saline water is brought from the subsurface depths under the influence of strong up-welling in this region. The observed thermal front is the manifestation of the upwelling (Fig. 7). However, the high stratification caused by the freshwater discharge from the Orinoco River does not allow the isopleths to rise to the surface even under strong up-welling conditions.

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