GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 21, PAGES 3497-3500, NOVEMBER 1, 2000

Water Masses and Circulation in the Surface Layers of the Caribbean at 66°W

Alonso Hernández-Guerra
Universidad de Las Palmas de Gran Canaria, Canary Islands, Spain

Terrence M. Joyce
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Abstract.
A meridional hydrographic section was made in August-September 1997 at 66°W from the coast of Venezuela to Woods Hole aboard the R/V Knorr. In this report, we concentrate on near surface measurements in the Caribbean. The data show two distinct water masses with different origins. From approximately 14°N to Puerto Rico, Caribbean Surface Water and Subtropical UnderWater with their source in the North Atlantic are found, as previously observed. From Venezuela to approximately 13°N, a less saline water mass with its source in the Tropics and South Atlantic is found. Within the southern portion of the section, two different velocity patterns are observed, namely, an eastward flow with a subsurface maximum near the coast of Venezuela, and a surface intensified westward jet with velocities of 130 cm s^{-1} in midbasin.

1. Introduction

The westward flowing North Equatorial Current (NEC) is the southernmost current of the North Atlantic Subtropical Gyre. It is fed by the Canary Current, which separates from the African coast at approximately 20°N, and the recirculation of the western branches of the Azores Current. The NEC spans the entire North Atlantic. Part of its flow enters the Caribbean through narrow passages [*Wilson and Johns,* 1997] and continues westward as the Caribbean Current. The Subtropical-Tropical Gyre boundary has a seasonal shift at its northernmost position in summer [*Mayer and Weisber,* 1993] and allows water from the South Atlantic to enter the Caribbean.

One important water mass in the Caribbean is the North Atlantic Subtropical UnderWater (SUW) which originates in the central tropical Atlantic. It is found beneath the surface water of the Caribbean at the salinity maximum [*Wüst,* 1964; *Kinard et al.,* 1974; *Metcalf,* 1976]. The formation of fresh surface water above the SUW is a complex process affected by rainfall, runoff and upwelling. An intermediate water mass existing in the Caribbean is the Antarctic Intermediate Water (AAIW) as seen in *Morrison and Nowlin* [1982] and *Joyce et al.* [1999]. Thus, the Caribbean contains water of both North and South Atlantic origin.

In this study we analyze near surface hydrographic, Vessel-Mounted Acoustic Doppler Current Profiles (VMADCP), thermosalinograph, and remote sensing data in the Caribbean for the purpose of describing the water masses and circulation in surface layers of the Caribbean.

2. Data

In August-September 1997, a meridional section at 66°W from Venezuela to Cape Cod (MA, USA) was carried out as part of the World Ocean Circulation

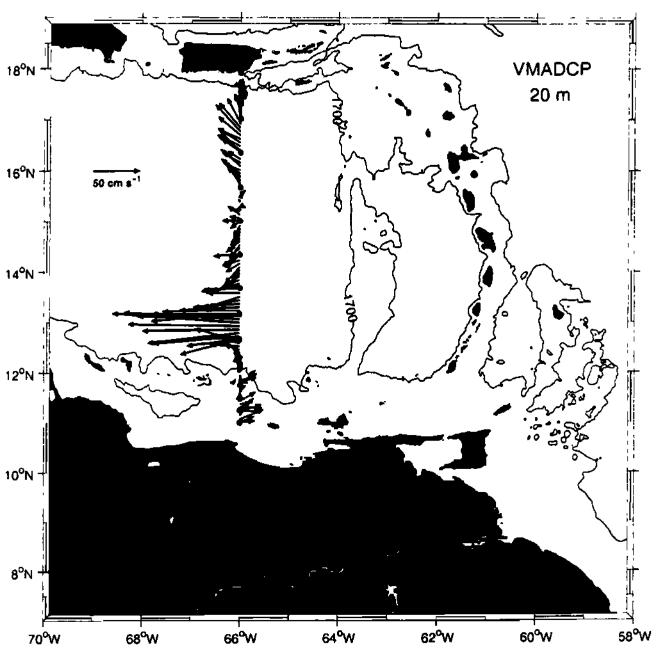

Figure 1. Locations of the CTD stations in this study shown as solid dots. We have also plotted the VMADCP velocity at 20 m depth. Notice the narrow and strong jet with velocities of 130 cm s^{-1} at approximately 13°N. For reference, the 1700 m isobath is shown.

Paper number 1999GL011230.
0094-8276/00/1999GL011230$05.00

Experiment (WOCE) Program. The measurements we will show consist of underway thermosalinograph and Vessel-Mounted Acoustic Doppler Current Profiles (VMADCP) data, hydrographic station data collected in the Caribbean, from Venezuela to Puerto Rico (Figure 1), and remote sensing data.

The station data consist of 22 CTD casts following the methodology described in the WHP technical operations manual [*Joyce,* 1994] . The horizontal resolution of the casts is 3-75 km depending on the bottom topography. Salinity data from the thermosalinograph were compared to salt samples. An offset value of 0.31 was found and added to the data. Temperature values from the thermosalinograph proved to be within acceptable ranges when compared to surface CTD measurements given the spatial variability. The VMADCP data were collected using a 150 KHz narrow band sensor. Navigation was provided by a P-code GPS and gyro heading was adjusted using a four antenna, Ashtech GPS unit.

3. Results and Conclusions

To identify water masses, associated depths and circulation patterns, we will show vertical sections of VMADCP, salinity, potential density, and potential temperature (Figure 2), and potential temperature/salinity diagrams (Figure 3).

In the upper layer (<50 m, Figure 2b), the northern half of the section has fresh water with salinity values less than 35.5. *Wüst* [1964] called this water Caribbean Surface Water and it is thought that it is a mixture of North Atlantic surface waters, Amazon river water, and local freshwater runoff from South America. In the middle of the section, we observe a region of minimum salinity (<34.5) also shown in Figure 3 near the 22 kg m^{-3} potential density isopycnal. The origin of this low salinity water is the Orinoco river, as discussed later.

The next deeper water mass is the Subtropical UnderWater (SUW) [*Wüst,* 1964; *Morrison and Nowlin,* 1982] characterized by the salinity maximum ($\geq$37). This water mass, formed in the central tropical Atlantic where evaporation exceeds precipitation, sinks along σ_θ=25.4 kg m^{-3}, at an approximate depth of 150 m (Figure 2c). This water mass is found in the northern half of the section, from approximately 14°N to Puerto Rico (Figure 2b), forming patches as previously observed by *Morrison and Nowlin* [1982]. The θ/S diagram (Figure 3) shows three different salinity values for this isopycnal: 37.2 corresponding to an area close to Puerto Rico, 37 corresponding to the rest of the northern half of the section and 36.8 near the Venezuelan coast. Although the velocity structure (Figure 2a) shows a strong mesoscale variability along the whole section, we notice that these three different locations correspond to three different velocity patterns. The northern portion of the entire section close to Puerto Rico has a strong westward velocity ($\geq$20 cm s^{-1}), the

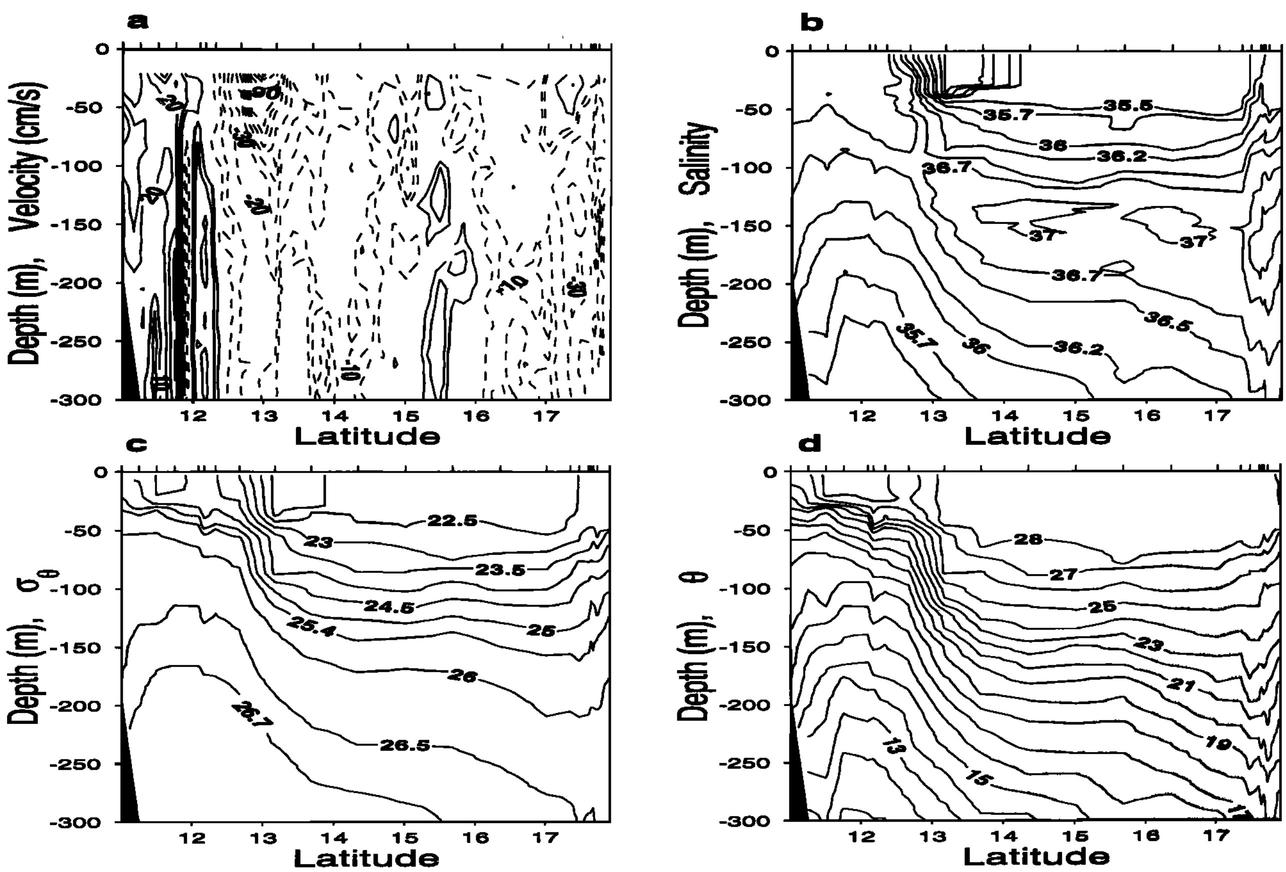

Figure 2. Section of a) VMADCP velocity (cm s^{-1}) (positive eastward), b) salinity, c) potential density, and d) potential temperature for the surface waters (<300 m) for the Caribbean. Station positions are at the top.

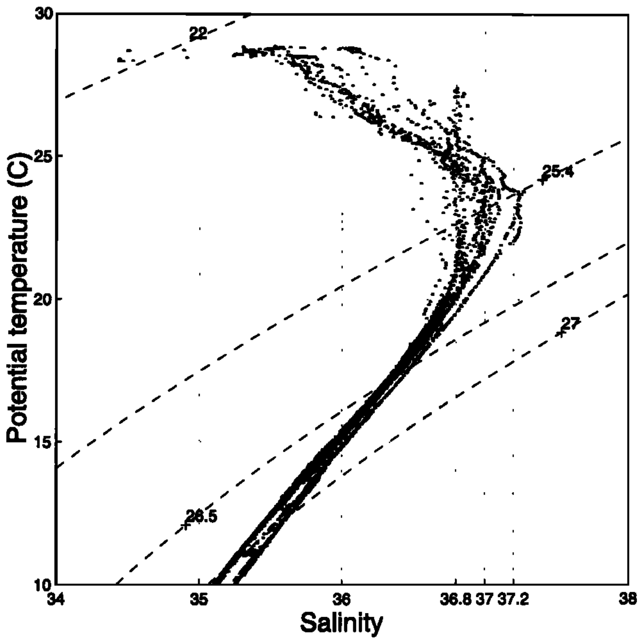

Figure 3. Potential temperature/salinity diagrams for the surface waters (<300 m) of the Caribbean.

central portion has a low and almost uniform westward velocity (≤10 cm s^{-1}) and the flow is eastward near Venezuela. The flow close to Puerto Rico is probably from the Anegada-Jungfern passage because data to the immediate north of Puerto Rico (data not shown here) have similarly high salinity values of SUW.

At 150 m depth, a denser water mass is found from Venezuela to approximately 13°N where the isotherms and the isohalines depict a strong slope (Figure 2b, 2c, 2d). This water mass apparently has its origin in the South Atlantic and is part of the freshest branch of the θ/S diagram for $\theta < 20$°C. With respect to the winds, the COADS data from *da Silva and Levitus* [1994] indicate that the zero wind stress curl position has a seasonal meridional shift with its northernmost position in summer, at about 14 °N. This seasonal shift is about 1° of latitude in the Caribbean and about 10° in the open Atlantic ocean (see also *Mayer and Weisber* [1993]). This results in a seasonal variability in the Subtropical-Tropical Gyre boundary, which demarks a wind-driven connection between the Tropics and the Caribbean. What is surprising is that within this tropical gyre and the zone of upwelled dense water having a South Atlantic character, an eastward current flowing against the mean wind is observed with a subsurface velocity maximum (Figure 2a). This has not been documented in the Caribbean before although a similar flow was previously found by *Wilson and Johns* [1997] at the Grenada Passage where a strong, possible seasonal, time-dependence is suggested. Based on only our data, this eastward flow does not have an obvious explanation. It could be a localized mesoscale event or evidence of a Caribbean coastal undercurrent which is part of a return flow of tropical/South Atlantic waters entering the Caribbean.

Another significant velocity feature observed in this section is a strong westward jet with velocities of 130 cm s^{-1} at approximately 13°N (Figure 1). To further examine this structure, we show the East-West and North-South VMADCP velocity at three different depths (20, 80, and 140 m), the sea surface salinity, and sea surface temperature, these two last measurements from an underway thermosalinograph (Figure 4). Here, the East-West VMADCP velocity (Figure 4a) shows the strongest velocity at 13°N, and also a strong shear from 20 to 140 m depth. The sea surface salinity (Figure 4c) shows a minimum value between 13°N and 14°N. Therefore, the velocity jet is found at the southern boundary of the low salinity feature. Figure 4b shows that there is not any indication of a flow transporting this feature to the north and also that a $v_y < 0$ until 15°N producing a confluence or convergence of water which explains the sharp salinity gradient at the northern boundary of the low salinity structure.

In an attempt to understand the origin of this structure, we have used remote sensing satellite images. Sea Surface Temperature images from the Advanced Very High Resolution Radiometer (AVHRR) were not very useful because they only showed the southern boundary of the structure, which was also seen in the sea surface temperature data from the thermosalinograph (Figure 4d). Another type of satellite data available

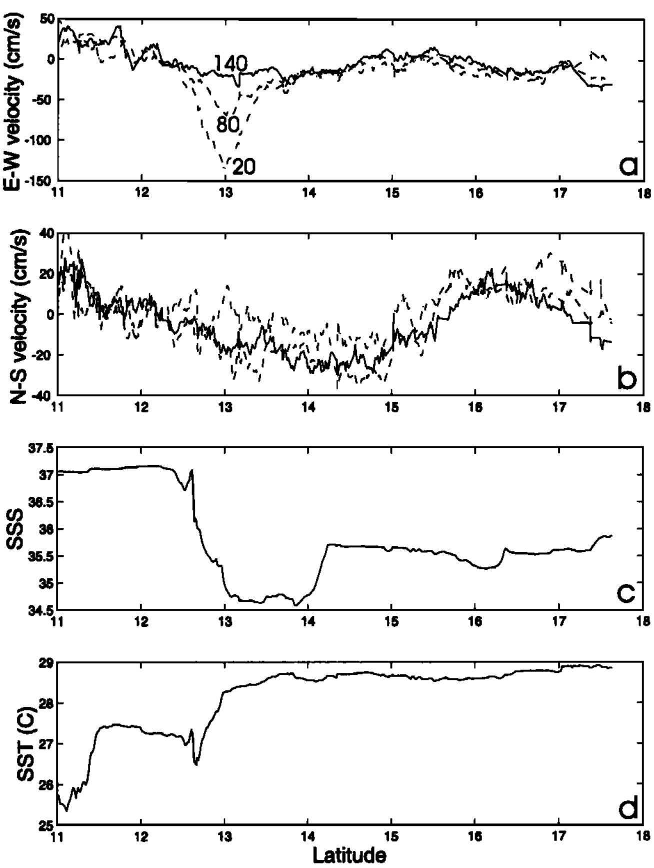

Figure 4. a) East-West VMADCP velocity for three different depths (20, 80, and 140 m), b) North-South VMADCP velocity for the same three different depths (20, 80, and 140 m), c) the sea surface salinity, and d) the sea surface temperature, these two last measurements taken from an underway thermosalinograph with a sampling depth of approximately 5 m.

to us were the ocean color images from the SeaWifs satellite. SeaWifs measures the visible radiation coming from the ocean in several spectral bands from which the chlorophyll concentration may be estimated.

Although this satellite was launched one month later than our cruise, it has been useful for our purposes. Figure 5 shows the binned chlorophyll *a* image from September 22 to 29, 1997. Here, a chlorophyll plume starting at the Orinoco river outflow is clearly seen. According to *Muller-Karger et al.* [1989], who has processed and analysed the whole archive of Coastal Zone Color Scanner (CZCS) data in the Caribbean, the plume formed at the Orinoco River is present during August through November every year. It is over 100 km wide and flows into the Caribbean Sea drifting northwest across the Caribbean, reaching Puerto Rico around October. On this occasion, the Orinoco plume passes through our section represented by the white crosses in the image. Although the hydrographic data and SeaWifs image are one month apart, it seems that the inflow transporting the Orinoco Plume from its source converges at 64°W with the eastward outflow of the Caribbean. This carries the Orinoco plume to the north until the region where the prevailing westward flow is found. Thus this westward jet may be a wind-driven

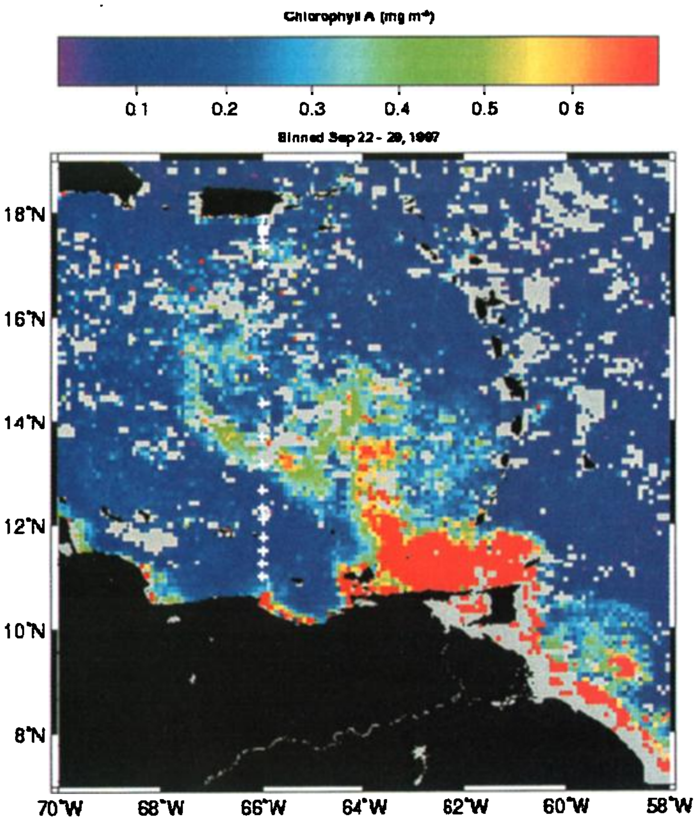

Figure 5. Weekly binned phytoplankton pigment image for the Caribbean region from September 22 to 29, 1997. The white crosses are the station positions for the cruise.

phenomenon which is time dependent and tied to the Orinoco plume. There is no evidence in the available surface drifter (D. Fratantoni, personal communication, 2000) data that this jet is a permanent feature of the Caribbean circulation.

Acknowledgments.
We wish to acknowledge the support of NSF grant (OCE95-29607), the assistance of J. Dunworth-Baker in helping with some of the calculations, and to M. Caruso in providing the SeaWifs image. The first author acknowledges the grant received from the Secretaría de Estado de Universidades, Investigación y Desarrollo (Spain) for his stay at Woods Hole Oceanographic Institution. This is contribution number 10169 of the Woods Hole Oceanographic Institution.

References

da Silva, A. M., and S. Levitus, Atlas of marine data 1994, volume 1: algorithms and procedures, 83 pp., US Dept. of Commerce, December 1994.

Joyce, T. M., WOCE Operations Manual, WHP Office report WHPO 91-1, WOCE Report 68/91, revision 1, Woods Hole, Mass, USA, November 1994.

Joyce, T. M., R. S. Pickart, and R. C. Millard, Long-term hydrographic changes at 52 & 66°W in the North Atlantic Subtropical Gyre and Caribbean, *Deep Sea Res. Part II, 46,* 245-278, 1999.

Kinard, W. F., D. K. Atwood, and G. C. Giese, Dissolved oxygen as evidence for 18°C Sargasso Sea water in the eastern Caribbean Sea, *Deep Sea Res. Part I, 21,* 79-82, 1974.

Mayer, D. A., and R. H. Weisberg, A description of COADS surface meteorological fields and the implied Sverdrup transports for the Atlantic Ocean from 30°S to 60°N, *J. Phys. Oceanogr., 23,* 2201-2221, 1993.

Metcalf, W. G., Caribbean-Atlantic exchange through the Anegada-Jungfern Passage, *J. Geophys. Res., 81,* 6401-6409, 1976.

Morrison, J. M., and W. D. Nowlin, Jr., General distribution of water masses within the Eastern Caribbean Sea during the winter of 1972 and fall of 1973, *J. Geophys. Res., 87,* 4207-4229, 1982.

Muller-Karger, F.E., C.R. McClain, T.R. Fisher, W.E. Esaias, and R. Varela, Pigment distribution in the Caribbean Sea: Observations from Space, *Prog. Oceanogr., 23,* 23-69, 1989.

Wilson, W. D., and W. E. Johns, Velocity structure and transport in the Windward Islands Passages, *Deep Sea Res. Part I, 44,* 487-520, 1997.

Wüst, G., *Stratification and Circulation in the Antillean-Caribbean Basins,* Columbia University Press, New York, 1964.

A. Hernández-Guerra, Facultad de Ciencias del Mar, Universidad de Las Palmas de Gran Canaria, Canary Islands, Spain. (e-mail: alonso.hernandez@fisica.ulpgc.es)

T. M. Joyce, Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA 02543. (e-mail: tjoyce@whoi.edu)

(Received November 15, 1999; revised May 9, 2000; accepted August 17, 2000.)