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Direct observations of velocity and transport in the passages between the Intra-Americas Sea and the Atlantic Ocean, 1984–1996

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Abstract. Shipboard acoustic Doppler current profiler observations of the velocity in the upper 200 m of the water column collected during 1984–1996 using the National Oceanic and Atmospheric Administration R/V *Malcolm Baldrige* are used to examine the velocity structure and transport in the passages between the Atlantic Ocean and the Intra-Americas Sea (IAS). Data were collected during 23 cruises along the following sections: across the Straits of Florida, in the Northwest Providence Channel (NWPC), across the northern passages into the Caribbean Sea (Windward, Mona, and Anegada), across the eastern Caribbean along 63°30′ W, thereby forming a closed quadrangle, and in the Grenada Passage. The Florida Current, the eastern Caribbean, and the Grenada Passage share a similar mean velocity structure characterized by high-velocity, surface-intensified flows with strong vertical and horizontal shears. The northern Caribbean passages (NWPC, Windward, Mona, and Anegada) share a different common mean velocity structure, with subsurface velocity maxima directed into the IAS, and surface-intensified counterflows along one side of each passage. On average, there is a transport balance in the upper 200 m between waters entering and exiting the IAS, with the 16.5 ± 2.4 Sv (1 Sv = 10^6 m^3/s) transport of the Florida Current at 27°N comprised of 0.4 ± 0.8 Sv from the NWPC, 2.2 ± 1.5 Sv from the Windward Passage, 2.8 ± 2.1 and 2.4 ± 2.8 Sv from the Mona and Anegada passages, respectively, and 9.5 ± 4.7 Sv across the eastern Caribbean, for a total of 17.3 Sv. The four passages north of 17°N (from NWPC to Anegada Passage) have a combined transport of 7.8 Sv, nearly half of the transport of the Florida Current in the upper 200 m. Of the 9.5 Sv flowing through the eastern Caribbean between 11°N and 17°N, 4.9 ± 2.6 Sv, or more than half, come from the Grenada Passage. This is significant to the subject of cross-equatorial exchange of mass, heat, and salt, as the Grenada Passage is where the highest transport of waters originating in the southern hemisphere is thought to enter the Caribbean.

1. Introduction

The Intra-Americas Sea (IAS) is the semienclosed body of water comprised of the Caribbean Sea, the Gulf of Mexico, and the Straits of Florida, connected to the North Atlantic Ocean by a number of passages between the islands of the Bahamas, Greater Antilles, and Lesser Antilles (Figure 1). The circulation of the IAS is dominated by the Caribbean and Florida currents. These currents form a major component of the North Atlantic subtropical gyre, leading directly into the Gulf Stream, and as such are an important conduit for mass, heat, and salt fluxes in the Atlantic.

The IAS is a fascinating region from a physical oceanographic viewpoint, with variability on all timescales from synoptic to seasonal, interannual, and decadal, driven by wind and thermohaline forcing. The deep circulation is dominated by sporadic inflow events over the sills of the major Caribbean passages [*Sturges*, 1970], while the upper layer circulation is a throughflow system in which inflows from the passages, including recirculating North Atlantic subtropical gyre waters as well as waters originating in the South Atlantic, pass through the Caribbean and into the southeastern corner of the Gulf of Mexico and eventually exit via the Florida Current. The wind-driven circulation of the Caribbean is dominated by the Trade Winds, which have a strong seasonal component and a wind stress curl field that responds to the seasonal northward and southward migration of the Intertropical Convergence Zone [*Mayer and Weisburg*, 1993].

In addition to its strictly physical oceanographic interest, attention has recently been given to the interconnected nature of the marine and atmospheric environments of the IAS in terms of pollutant dispersal, larval transports, the health of coral reefs, and commercial and recreational fisheries [*Roberts*, 1997; *Ogden*, 1997; *Mooers and Maul*, 1998]. It is becoming apparent that only through the use of focused numerical models of the circulation which can properly simulate the atmospheric and oceanic forcing and the ocean's response on all relevant space and timescales will the models be able to move toward the nowcast/forecast capability that could be used to address the environmental and societal concerns critical to the IAS.

However, the development of effective numerical circulation models requires high-quality and abundant observational data for model verification. For some parts of the IAS, such as the Florida Current, adequate data exist for this purpose. The

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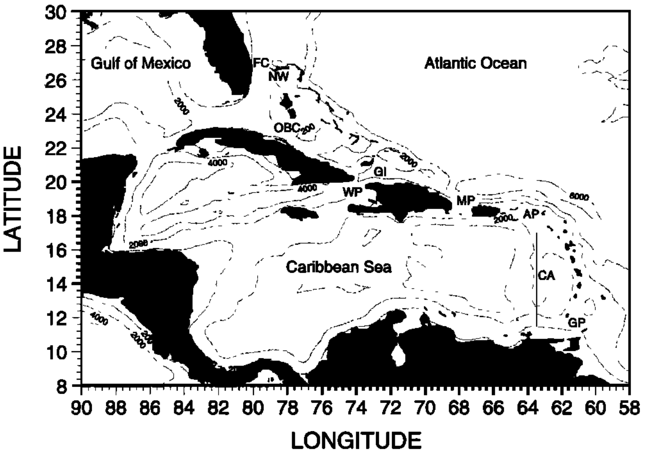

Figure 1. Bottom topography of the Intra-Americas Sea. Transect locations are indicated as follows: FC, Florida Current; NW, Northwest Providence Channel; WP, Windward Passage; GI, Great Inagua Passage; MP, Mona Passage; AP, Anegada Passage; CA, eastern Caribbean; and GP, Grenada Passage. OBC indicates the location of the Old Bahama Channel.

Florida Current is probably the most studied current in the world, from the pioneering physical oceanographic study of *Pillsbury* [1890] which utilized the first current meter to measure the transport of the Florida Current, to more sophisticated studies such as that by *Richardson and Schmitz* [1965] and *Schmitz and Richardson* [1968] using dropsondes. More recently, NOAA's Subtropical Atlantic Climate Study [*Molinari et al.*, 1985] used a combination of shipboard observations, moored current meters and pressure gauges, and a submarine cable to examine the velocity structure and variability of the Florida Current at 27°N and to continuously monitor the transport using the cable [*Larsen and Sanford*, 1985]. The Subtropical Atlantic Climate Study was begun in 1982, and the transport monitoring continues to the present time. Results from this study include determination of a stable mean for the transport of 32.3 ± 3.2 Sv [*Larsen*, 1992] and a better understanding of its seasonal and interannual variability [see, e.g., *Molinari et al.*, 1985; *Lee et al.*, 1985; *Schott and Zantopp*, 1985; *Johns and Schott*, 1987; *Larsen*, 1992; *Leaman et al.*, 1987].

Such is not the case for the other passages of the IAS and for the Caribbean Sea as a whole. Although the Caribbean has been the subject of a number of hydrographic studies, few direct observations of the circulation have been made. Earlier historical studies used hydrographic and tracer data to describe the circulation using either the "core" method [*Wust*, 1964] or geostrophic calculations [*Gordon*, 1967], or in the case of a study by *Roemmich* [1981] using a combination of the two techniques in an inverse calculation. Studies using surface drifters in the Caribbean have also been conducted [*Molinari et al.*, 1981], revealing an ocean environment that is rich with eddies superimposed onto a mean throughflow. A review of the state of understanding of the Caribbean circulation as of the 1980s is given by *Kinder et al.* [1985].

The few direct velocity and transport observations which have been made in the IAS passages include the study of *Schmitz and Richardson* [1991]. They used data collected in 1970 by *Stalcup and Metcalf* [1972] to examine the flow between the islands of the Lesser Antilles and arrived at an estimate of the transport distribution based on the limited data available at that time. More recently, *Wilson and Johns* [1997] conducted a comprehensive study of the inflow to the eastern Caribbean during the Windward Islands Passages Program. Using a cable-lowered acoustic Doppler current profiler (ADCP), they were able to obtain enough direct observations of transport and velocity structure in the southern passages over several years to more closely examine the mean inflow and its variability.

The northern passages to the IAS (Windward, Mona, and Anegada; Figure 1) are the least studied, and few direct measurements of their transport have been obtained. Thus a key motivation for the present study was to utilize direct velocity data collected on a series of NOAA cruises both passing through and directed at the region between 1984 and 1996 to address this deficiency. Direct velocity observations were collected using a hull-mounted ADCP along a number of sections across the passages of the IAS, in the eastern Caribbean Sea, and in the Straits of Florida (Figure 1).

Herein, the ADCP velocity data from these cruises are used to examine the velocity structure in the upper 200 m of the water column and to estimate transports through the Caribbean Sea and the Straits of Florida. We begin with a description of the available observations and data reduction, followed by an analysis of the velocity and transport results for each passage, and a discussion of their significance both compared to earlier transport estimates and in terms of addressing some of the issues mentioned above.

2. Data and Methodology

The eight sections considered herein are located in the Straits of Florida at 27°N and 26°N: the Northwest Providence Channel (NWPC), the Great Inagua Passage (between the Bahamian islands of Great Inagua and Hispaniola), the Mona Passage, the Anegada Passage, the eastern Caribbean Sea, and the Grenada Passage (Figure 1). Ideally, for estimating the transport balance of the IAS, the Great Inagua section would instead have been located across the Windward Passage, between Cuba and Haiti. However, this was not possible because of clearance constraints. Thus flow through the Great Inagua section is comprised of flow into or out of the Caribbean Sea through the Windward Passage and flow into or out of the Straits of Florida through the Old Bahamas Channel and can only be used as a proxy for flow through the Windward Passage. The dates of the 23 cruises used in this analysis and the sections occupied and transports obtained during each passage transect are listed in Table 1.

Shipboard ADCP observations are the primary data source for this study. A shipboard ADCP unit provides nearly continuous coverage of upper ocean currents. The system used for most of the cruises aboard the NOAA R/V *Malcolm Baldrige* was a 150-kHz RD Instruments unit with a hull-mounted transducer. Earlier ADCP units (an Ametek Straza 115-kHz instrument with the same hull configuration) were limited to ~200 m in vertical coverage, although more recent cruises yielded data down to a depth of 350–400 m. Results are therefore presented only for the upper 200 m of the water column in order to use all of the cruise data consistently. Standard data acquisition and processing procedures are described by *Wilson and Routt* [1992], and additional details about the ADCP system, including a discussion of navigational referencing and error estimates, are described by *Wilson et al.* [1994]. After referenc-

Table 1. Cruise Dates, Passage Occupation and Transport

Cruise Dates	F27	F26	NW	GI	MP	AP	CA	GP
Aug. 27 to Sept. 6, 1984	···	···	···	−3.0	···	···	···	···
April 17 to May 17, 1985	18.8	···	···	−3.0	···	···	···	···
Aug. 13 to Sept. 6, 1985	13.1	···	···	−1.0	···	···	−14.2	···
Jan. 13 to Feb. 11, 1986	13.6	···	···	−3.1	···	···	−9.9	···
March 25 to April 22, 1986	···	···	···	−1.4	···	···	−9.7	···
July 15 to Aug. 8, 1986	18.3	···	···	−0.5	···	−4.9	−11.8	···
Oct. 23 to Nov. 7, 1986	19.3	···	···	−1.5	···	−8.4	−1.7	···
Oct. 23 to Nov. 7, 1986*	18.1	···	···	···	···	···	···	···
March 11 to March 23, 1987	13.8	14.2	···	···	···	···	···	···
Sept. 1 to Oct. 1, 1987	···	···	···	···	···	···	···	···
Aug. 22 to Sept. 22, 1989	···	···	−0.5	−5.2	−3.0	−2.4	···	···
June 15 to July 11, 1990	15.5	···	···	···	···	···	···	···
Sept. 7 to Oct. 10, 1990	···	14.5	−1.7	···	0.1	···	···	···
Jan. 8 to Feb. 6, 1991	···	···	···	−1.4	−5.0	···	···	−10.3
June 12 to July 5, 1991	···	···	···	···	···	···	···	−4.0
Sept. 8 to Sept. 23, 1991	···	···	···	···	···	0.9	···	−6.5
Jan. 31 to Feb. 10, 1992	···	13.7	0.4	···	···	···	···	···
Aug. 3 to Sept. 1, 1992	···	···	−0.6	···	···	···	···	···
Aug. 3 to Sept. 1, 1992*	···	···	0.5	···	···	···	···	···
June 1 to June 29, 1993	···	15.8	0.2	···	···	−2.2	···	−3.6
Sept. 16 to Sept. 22, 1993	···	16.3	−1.6	···	···	···	···	···
March 28 to April 8, 1994	···	17.6	−0.1	···	···	−2.2	···	−1.6
July 12 to Aug. 1, 1994	···	15.9	0.1	···	···	−0.3	···	−4.1
March 3 to March 20, 1996	18.2	···	···	···	−4.5	−0.8	···	−5.2
July 15 to Aug. 2, 1996	16.4	···	−1.0	···	−1.7	−1.5	···	−3.8
Mean	16.5	15.4	−0.4	−2.2	−2.8	−2.4	−9.5	−4.9
Standard deviation	±2.4	±1.4	±0.8	±1.5	±2.1	±2.8	±4.7	±2.6
Standard error	±0.8	±0.5	±0.3	±0.5	±0.9	±0.9	±2.1	±0.9

F27, Florida Current at 27°N; F26, Florida Current at 26°N; NW, Northwest Providence Channel; GI, Great Inagua Passage; MP, Mona Passage; AP, Anegada Passage; CA, Eastern Caribbean along 63.5°W; GP, Grenada Passage. Transport measured in Sverdrups.

*More than one occupation of transect was made during cruise.

ing, 15-min averages are computed and form the basis for the velocity results presented below.

Transports for the passages were computed using the following methodology. Velocity data from individual cruises were projected onto standard (i.e., most often occupied) transect locations (requiring in most cases only minor adjustments in position) and the perpendicular and along-transect components of velocity were computed. This velocity was gridded in 2-km bins of along-transect distance and in 10-m depth bins, and the perpendicular velocity component was then integrated horizontally and vertically to produce transport in units of Sverdrups (Sv, where 1 Sv = 10^6 m^3/s). Average transports and standard deviations were obtained by summing the individual gridded transports and dividing by the number of transect occupations. No attempt was made to remove the tidal variability from the observations. However, given enough occupations for each transect, this variability should tend to average out.

3. Results

The results will be presented by passage from northwest to southeast across the IAS in the form of vector maps of the surface and upper 200 m average flow through each passage superimposed upon the bottom topography, and vertical sections of the mean and standard deviation of the northward and eastward velocity components for each passage. Transports perpendicular to the passages are presented for all passage occupations in Table 1, which includes the mean, standard deviation, and standard error for each passage.

3.1. Florida Current at 27°N

The 27°N Florida Current transect is located between Palm Beach, Florida, and Little Bahama Bank (Figure 2). This transect was occupied ten times between April 1985 and July 1996 (Table 1). The average surface and 0–200 m velocities shown in the vector maps show the asymmetrical nature of the Florida Current, with a sharp rise to the velocity maximum on the western side of the Straits, and a more gradual decrease across the middle and eastern side of the channel (Figure 2). The vertical section of northward velocity also shows the asymmetry of the velocity structure, with the maximum velocity found farther offshore with depth. The surface velocity reaches a maximum of over 160 cm/s ~20 km east of the section origin (Figure 2). The standard deviation of the northward flow is highest (±50 cm/s) near the surface on the western side of the current (~12 km from the origin) and is due to lateral meandering of the current core as well as variability of the core velocity. The larger standard deviations on the eastern side of the Straits are in part attributable to variable southward flows also found in an earlier study [*Leaman and Molinari*, 1987]. Both the eastward velocity section and the average velocity vector maps of Figure 2 show that the flow is converging at 27°N; i.e., on average, there is a weak eastward component at the onshore side of the transect, with a stronger (5–10 cm/s) westward component on the offshore side. Standard deviations of the eastward flow component are in the ±5 to 15 cm/s range, highest near the eastern side of the transect in the upper 50–100 m. The average transport at 27°N in the upper 200 m

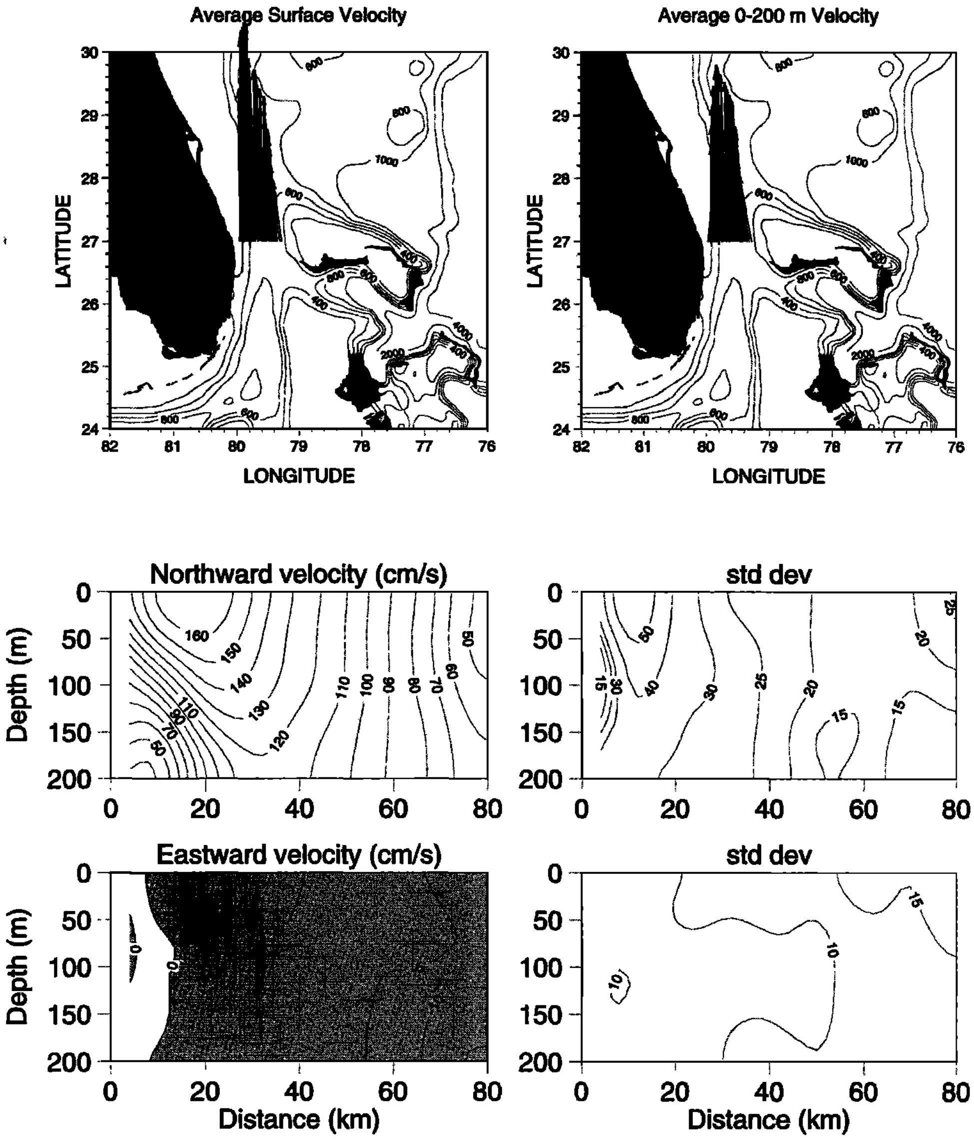

Figure 2. The Florida Current at 27°N: Acoustic Doppler current profiler (ADCP) vector maps of the average surface velocity (left top) and the average 0–200 m velocity (right top). The velocity vectors are scaled such that 50 cm/s equals 1° of latitude. Also shown are vertical sections of ADCP velocity in cm/s for the northward and eastward velocity components (left bottom) and their standard deviations also in cm/s (right bottom). The orientation of the vertical sections is west to east along the transect.

from the 10 section occupations is 16.5 ± 2.4 Sv, with a range of 13.1 Sv in August 1985 to 19.3 Sv in October 1986 (Table 1).

3.2. Florida Current at 26°N

The 26°N Florida Current transect, located between Miami, Florida, and Bimini, Bahamas (Figure 3), was occupied seven times between March 1987 and July 1994 (Table 1). The surface and 0–200 m average velocity vectors (Figure 3) are similar in appearance to the equivalent vectors at 27°N (Figure 2) but show that whereas at 27°N the current was directed slightly west of due north, at 26°N the average flow is directed at a bearing of ~10° eastward of due north. The northward velocity structure (Figure 3) shows a maximum surface velocity mid-channel of over 170 cm/s. A weak counterflow is present below 100 m on the western edge of the section, at a depth of 100–200 m. The standard deviation of the northward velocity reaches a maximum of ±25 cm/s at a depth of 100 m about 200 km along the section, near the high horizontal and vertical shear zone of the onshore edge of the current. The standard deviation is also high (±25 cm/s) near the surface on the offshore side of the channel. The standard deviations of the northward flow are generally smaller at 26°N than at 27°N, indicating that the velocity structure of the Florida Current at 26°N is more consistent from one cruise to the next. This may be due to the local bottom topography, which constrains the current to a relatively narrower channel at 26°N (Figure 3). The vertical section of eastward velocity shows that at 26°N the flow has an eastward component rather than westward, as also observed from the vector maps (Figure 3). On the western side of the channel, there is an area of westward flow at 50–200 m

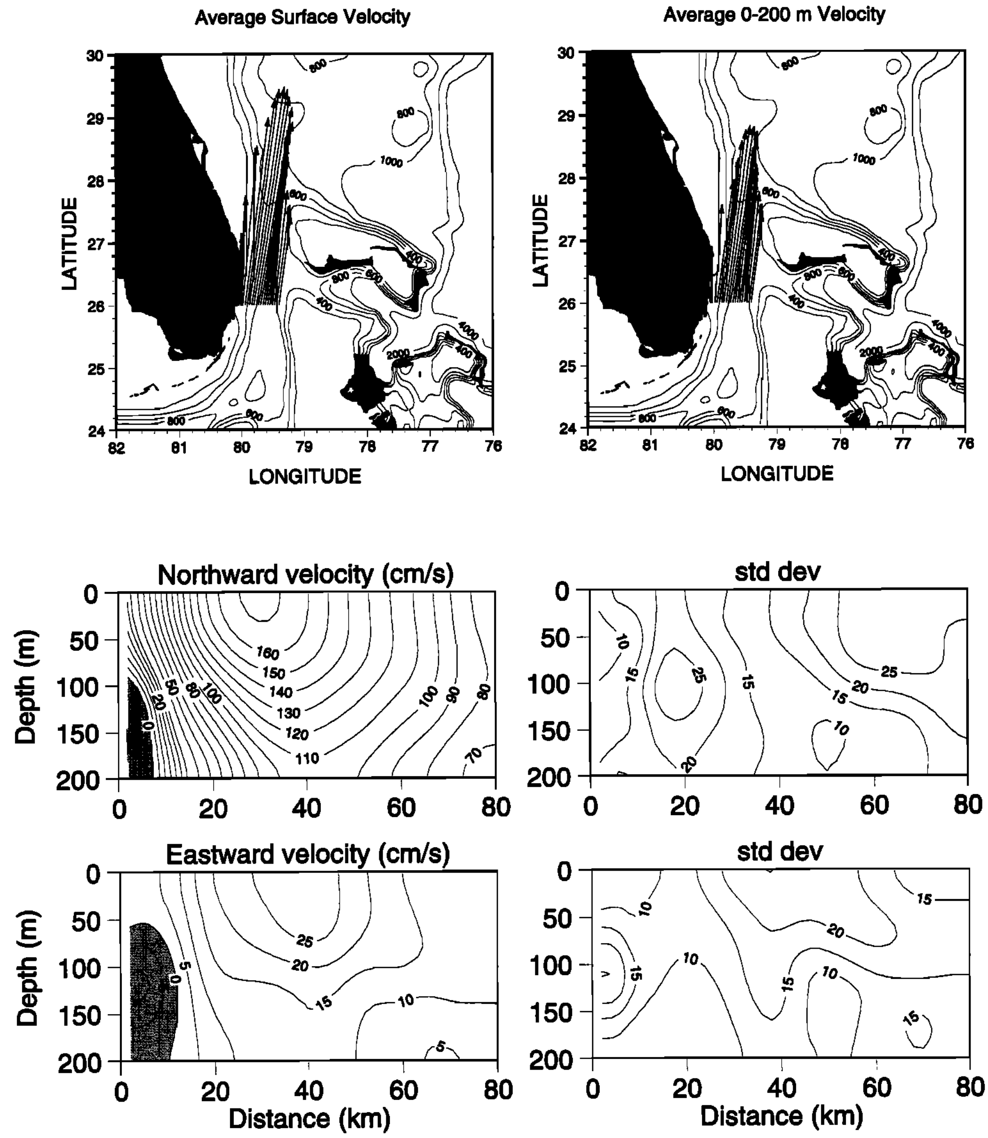

Figure 3. Same as Figure 2, but for the Florida Current at 26°N.

depth; i.e., the flow is divergent on average at 26°N as opposed to the convergent flow at 27°N, with higher standard deviations at 26°N, particularly within the westward velocity area. The average transport of the seven 26°N transect occupations is 15.5 ± 1.4 Sv, with a low of 13.7 Sv observed during January 1992 and a high of 17.6 Sv during March 1994 (Table 1).

3.3. Northwest Providence Channel

The Northwest Providence Channel (NWPC) is located to the east of the Florida Current between Grand Bahama Island and the Great Bahama Bank (Figure 4). This transect was occupied 10 times between August 1989 and July 1996 (Table 1). The surface and 0–200 m average vector maps show that the flow is generally to the west on average, with the strongest westward flow found at the northern side of the channel, and with a surface-intensified current reversal to the east located at the southern edge of the channel along the Bahama Bank (Figure 4). The vertical section of average velocity (Figure 4) shows that there is a subsurface maximum in the westward velocity, with speeds greater than 30 cm/s located below 150 m. The velocity structure is highly variable from cruise to cruise, as evidenced by the standard deviations which are generally ±10 to 20 cm/s, i.e., higher than the mean currents. The average transport through the NWPC from the 10 transect occupations is −0.4 ± 0.8 Sv (negative transport is directed to the west), ranging from a maximum inflow toward the Florida Current of −1.7 Sv during September 1990 to a minimum of +0.5 Sv (eastward flow, i.e. directed away from the Florida Current) during August 1992 (Table 1).

3.4. Great Inagua Passage

The Great Inagua Passage is located between the Bahamian island of Great Inagua and the northwestern coast of Haiti (Figure 5). Here the prevailing currents are generally to the southwest, toward the Caribbean, with the majority of transport most likely flowing directly into the Caribbean through the Windward Passage between Cuba and Haiti. Thus we assume that this passage can be considered as a proxy for the flow through the Windward Passage. Any westward flow that does not enter the Windward Passage would instead eventually

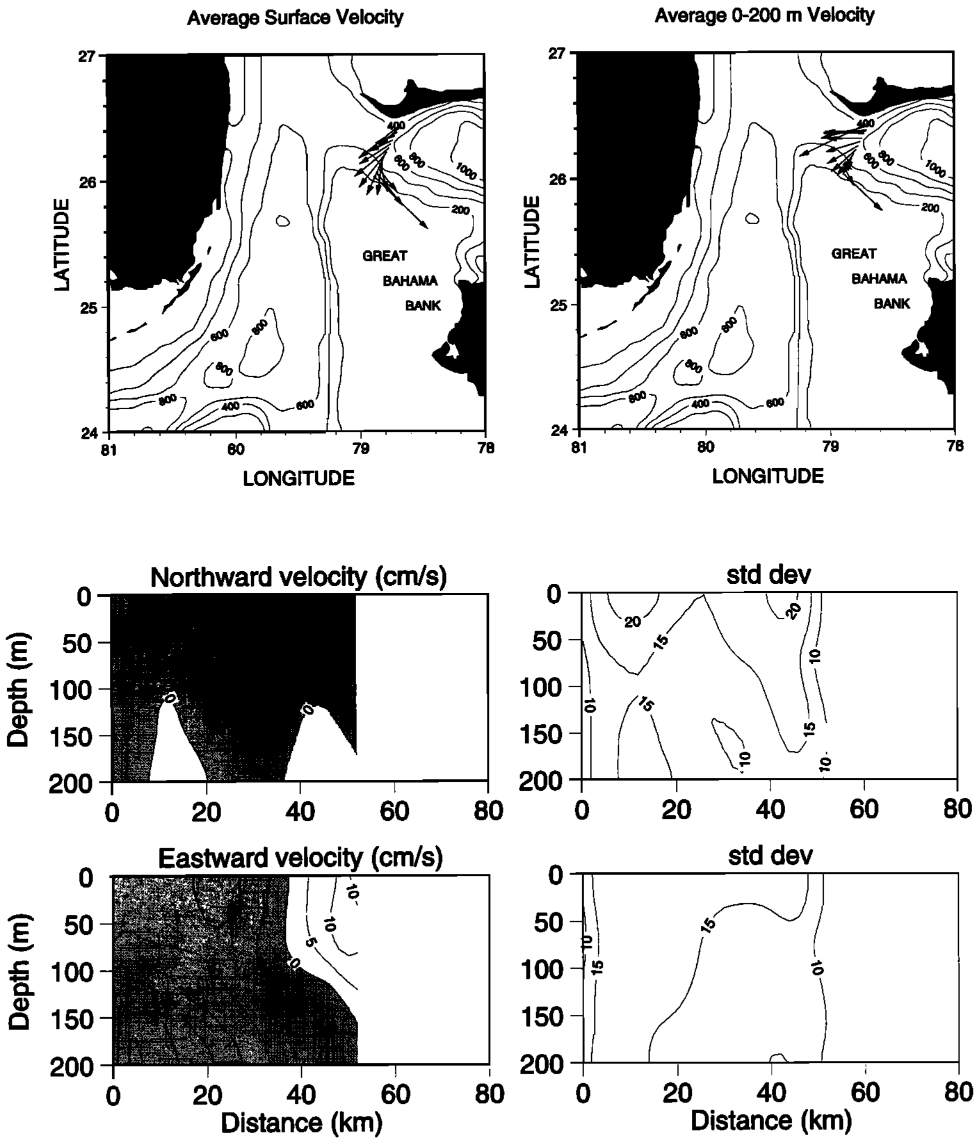

Figure 4. Same as Figure 2, but for the Northwest Providence Channel. The orientation of the vertical sections is from northeast to southwest along the transect.

join the Florida Current via the Old Bahama Channel (Figure 1). Transport along this route has been estimated at 1–2 Sv [*Atkinson et al.*, 1995] and is highly variable.

The Great Inagua Passage transect was occupied a total of nine times between August 1984 and January 1991 (Table 1). The average velocity was to the southwest (Figure 5), with a subsurface westward maximum of greater than 20 cm/s located midtransect below 100 m depth. On the south side of the channel (along the coast of Haiti) the flow is reversed and surface intensified, with an average counterflow out of the Caribbean of 10–15 cm/s in the upper 100 m (Figure 5). During four of the nine crossings the countercurrent was not present along the Haitian coast. During the other five cruises where it was present, maximum velocities were 30–40 cm/s, and greater than 60 cm/s during July 1986 (not shown). The standard deviation of the eastward velocity component is less than ±10–15 cm/s over the northern half of the transect, and higher (±20–25 cm/s) over the southern half. The northward velocity component is weak (<5 cm/s) and directed primarily to the south. The average transport through the Great Inagua Passage in the upper 200 m is −2.2 ± 1.5 Sv (negative transport is directed to the southwest, i.e., toward the Caribbean), with a low of −0.5 observed during July 1986 and a high of −5.2 Sv during August 1989 (Table 1).

3.5. Mona Passage

The Mona Passage is located just west of Puerto Rico, between Puerto Rico and the east coast of the Dominican Republic, and was occupied five times between August 1989 and July 1996. The average 0–200 m flow is predominantly southward, i.e., into the Caribbean, through this passage (Figure 6). A shallow shoal that extends eastward from the northeast corner of the Dominican Republic seems to partially block the flow, causing the current to split into two bands (Figure 6). Similarly to the Great Inagua Passage and the NWPC, the southward inflow shows a subsurface maximum, greater than 20 cm/s at 200-m depth in midchannel. In addition, there is a persistent countercurrent (i.e., out of the Caribbean) located

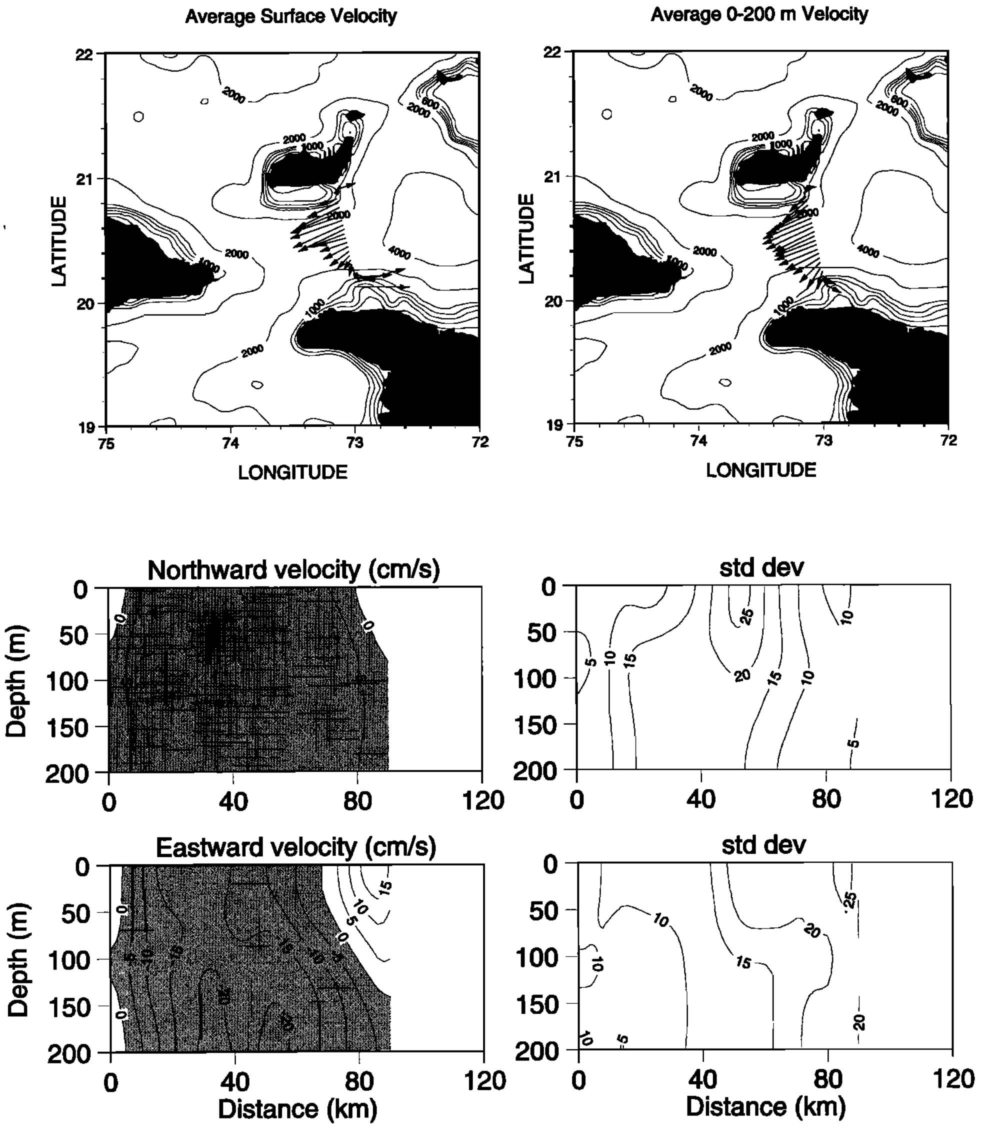

Figure 5. Same as Figure 2, but for the Great Inagua Passage. The orientation of the vertical sections is from northwest to southeast along the transect.

along the coast of Puerto Rico with average speeds over 10 cm/s, maximum at the surface (Figure 6). Cruise-to-cruise variability is very high in this passage, with the standard deviation of the southward flow generally in the ±15–25 cm/s range, as high or higher than the average velocity. The average transport through the Mona Passage in the upper 200 m is −2.8 ± 2.1 Sv directed into the Caribbean, with a high of −5.0 Sv observed during January 1991 and a low of +0.1 Sv directed out of the Caribbean observed during September 1990 (Table 1).

3.6. Anegada Passage

The Anegada Passage is located at the northeast corner of the Caribbean, between the Virgin Islands and Saba Bank (Figure 7). Two standard transects were occupied across this passage, with somewhat different transect lengths and angles, but both generally crossing the entire passage.

The first Anegada Passage transect was occupied five times between July 1986 and June 1993 (Table 1). The flow is predominantly southward into the Caribbean, with the most intense flow found at the west side of the transect near the Virgin Islands, where there is an average maximum southeastward speed of over 60 cm/s (Figure 7). This high average speed is largely caused by extremely high velocities observed during two transect occupations, July 1986 and October 1986, when speeds were observed in excess of 110 cm/s. The vertical section shows a subsurface southward velocity maximum of 10–15 cm/s in the center of the channel and a very weak flow reversal at the surface. Standard deviations are generally in the ±10–20 cm/s range, with higher values in the high-velocity region near the Virgin Islands. The flow is strongly convergent over this transect, with an eastward component over the western half of the transect and a westward component over the eastern side and with a tendency along the eastern side to be aligned along the bottom topography (Figure 7). The average transport in the upper 200 m is −3.4 ± 3.5 Sv directed into the Caribbean, with a low of +0.9 Sv (outflow from the Caribbean) observed during September 1991 and a high of −8.4 Sv during October 1986, indicating a very large transport range (Table 1).

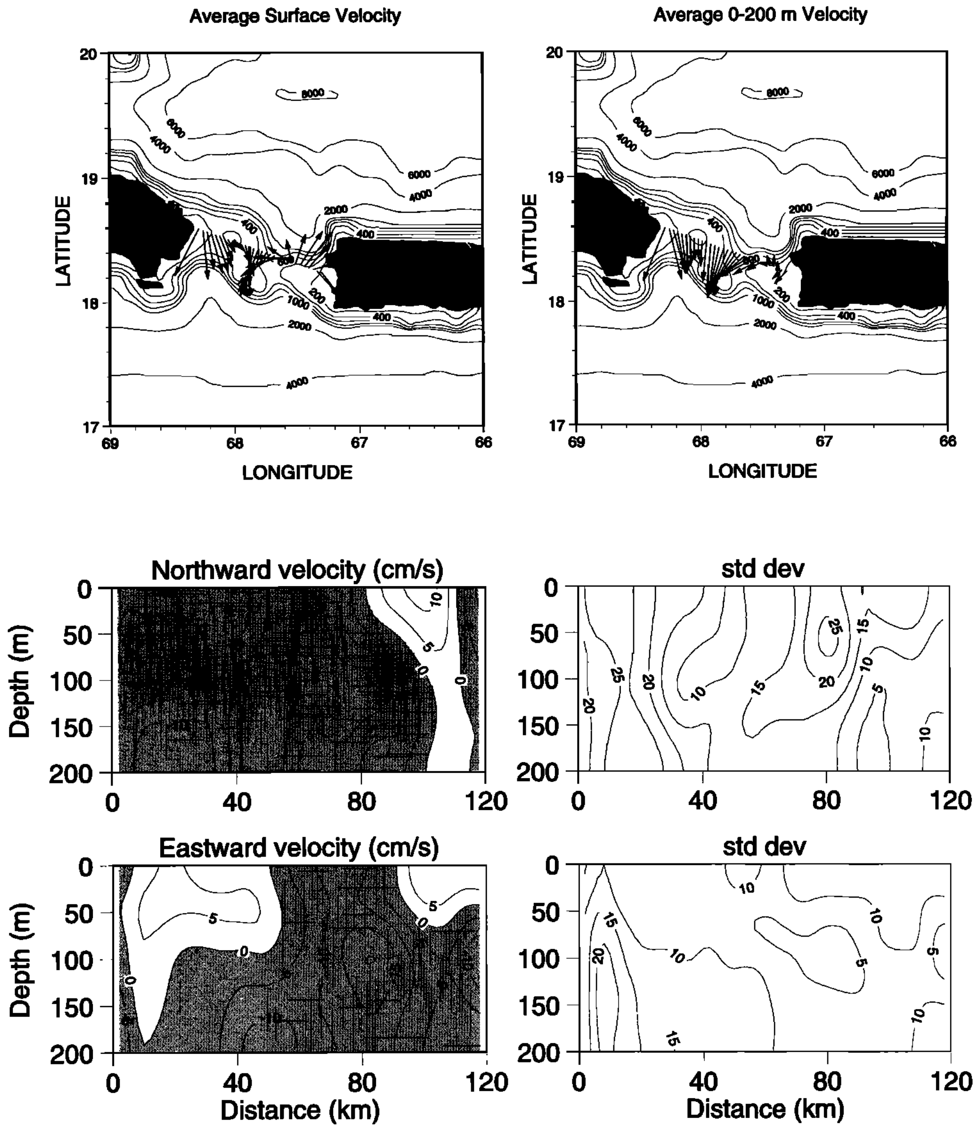

Figure 6. Same as Figure 2, but for the Mona Passage.

The second of the two Anegada Passage transects was occupied four times between March 1994 and July 1996 (Table 1). The flow was again southward, into the Caribbean, and weaker than the first Anegada transect, with counterflows out of the Caribbean on the east side along Saba Bank and on the west side near the Virgin Islands (Figure 8). The vertical section again shows a subsurface maximum midchannel. Standard deviations are equivalent to the average speed, ±5–15 cm/s. The average transport in the upper 200 m is −1.2 ± 0.8 Sv into the Caribbean through this transect (Table 1), and it was always directed into the Caribbean with a range of −0.3 Sv during July 1994 to −2.2 Sv during March 1994. If the values for the two Anegada Passage transects are merged for transport computations, the average upper 200 m transport for the nine occupations is −2.4 ± 2.8 Sv into the Caribbean (Table 1).

3.7. Eastern Caribbean

The eastern Caribbean section is oriented along the Aves Ridge at 63.5°W, from Saba Bank on the northern end to the Venezuelan shelf on the southern end. Five occupations of this transect were made between August 1985 and October 1986 (Table 1). These data have been discussed by *Smith and Morrison* [1989] and *Morrison and Smith* [1990]. The average flow is predominantly to the west (Figure 9). Maximum average surface speeds of up to 80 cm/s directed to the northwest are found at the southern end of the transect, where most of the flow originates from the Grenada Passage. The average flow has three major westward branches, at 11.5°–13°N, 13.5°–15°N, and 16.5°–17°N, with counterflows between the branches (Figure 9). Counterflows were present on each individual cruise transect (not shown) but varied in latitude and number. The vertical section of eastward velocity (Figure 9) shows that these branches of flow are all surface-intensified. The average transport above 200 m for these five sections is −9.5 ± 4.7 Sv to the west, with a minimum value of −1.7 Sv observed in October 1986 and a maximum of −14.2 Sv in August 1985 (Table 1).

3.8. Grenada Passage

Two different transect locations were used for the Grenada Passage. The first runs from Grenada southeast to near the

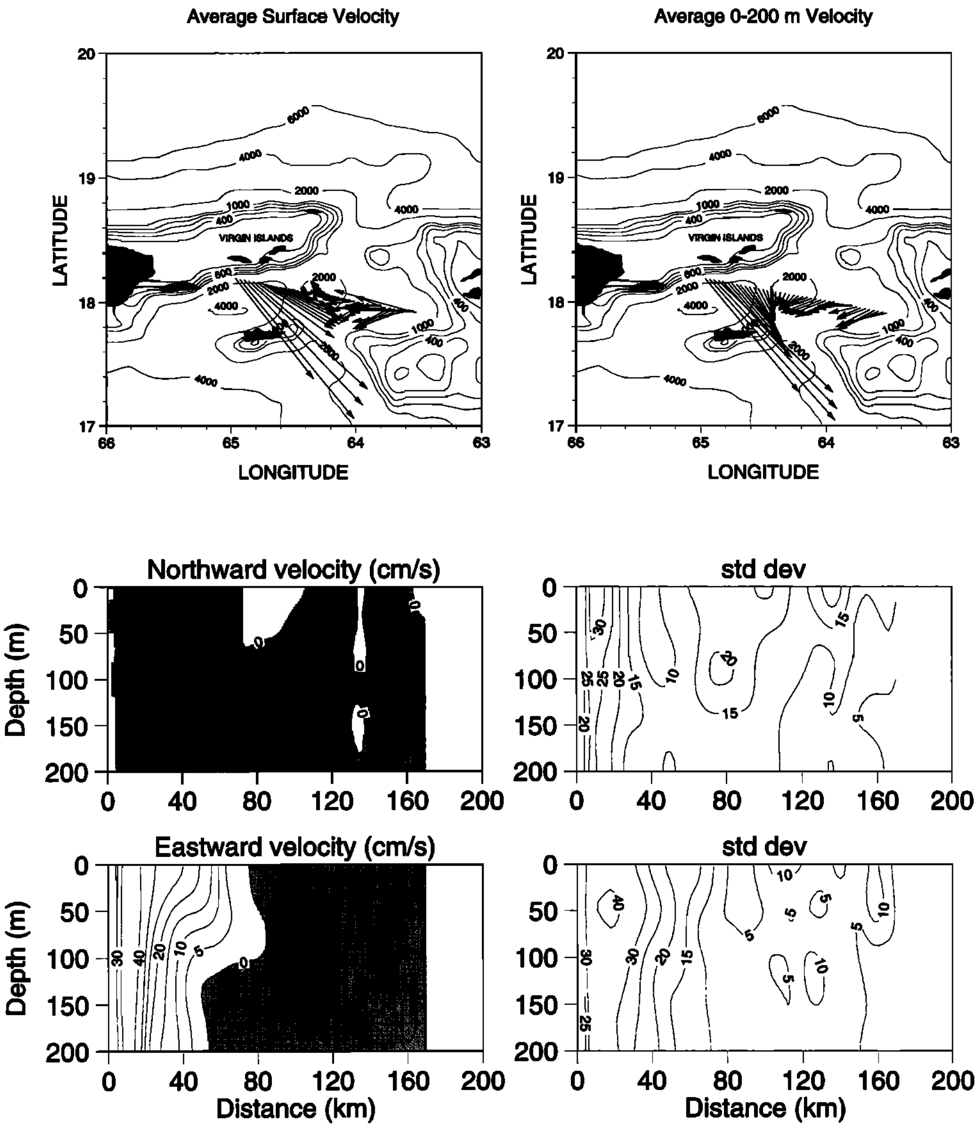

Figure 7. Same as Figure 2, but for the first Anegada Passage transect.

coast of Tobago (Figure 10). It was occupied three times between January and September 1991 (Table 1). The average 0–200 m velocity vectors show strongest inflow to the Caribbean on the Grenada side, with northwestward flow near Tobago (Figure 10). The average velocity sections show that the strong inflow to the Caribbean through this section is surface-intensified and shows that the northwestward flow along the coast of Tobago is also highest at the surface (Figure 10). The maximum average surface speed is over 90 cm/s directed to the southeast, and the standard deviations are also high, ±15–30 cm/s over nearly the entire transect, highest at the northern side near Grenada, and also in the center of the passage. The average upper 200-m transport is −6.9 ± 3.2 Sv directed into the Caribbean (Table 1), with a low of −4.0 Sv in June 1991 and a high of −10.3 Sv in January 1991. This average value is likely to be an overestimate, as the very high transport observed during January 1991 appears to be anomalous.

The second Grenada Passage transect runs southwest from Grenada to the shallow shelf waters off Venezuela at ~62°W (Figure 11) and was occupied five times between June 1993 and July 1996 (Table 1). The average velocity is slightly south of due west, reaching a maximum in the center of the passage of over 90 cm/s (Figure 11). The vertical section of eastward velocity shows that the highest velocity is located in the center of the passage, directed into the Caribbean, and a weak average subsurface counterflow is located at the southern end of the transect below 120 m. Stronger countercurrents are evident in each of the individual cruise transects (not shown), but they vary in horizontal location and thus do not create a strong mean countercurrent flow. The standard deviation of the current reaches a maximum of over ±40 cm/s in the center of the passage near the surface, owing to both variability in maximum surface current speed (which ranged from 60 cm/s in March 1994 to over 130 cm/s in March 1996) and lateral meandering of the surface current core. The average transport in the upper 200 m is −3.7 ± 1.3 Sv, directed into the Caribbean, with a low of −1.6 Sv in March 1994 and a high of −5.2 Sv in March 1996. If the eight values for the two transects are combined to yield an average transport through the Grenada Passage, the observations give an average transport of −4.9 ± 2.6 Sv into the Caribbean (Table 1).

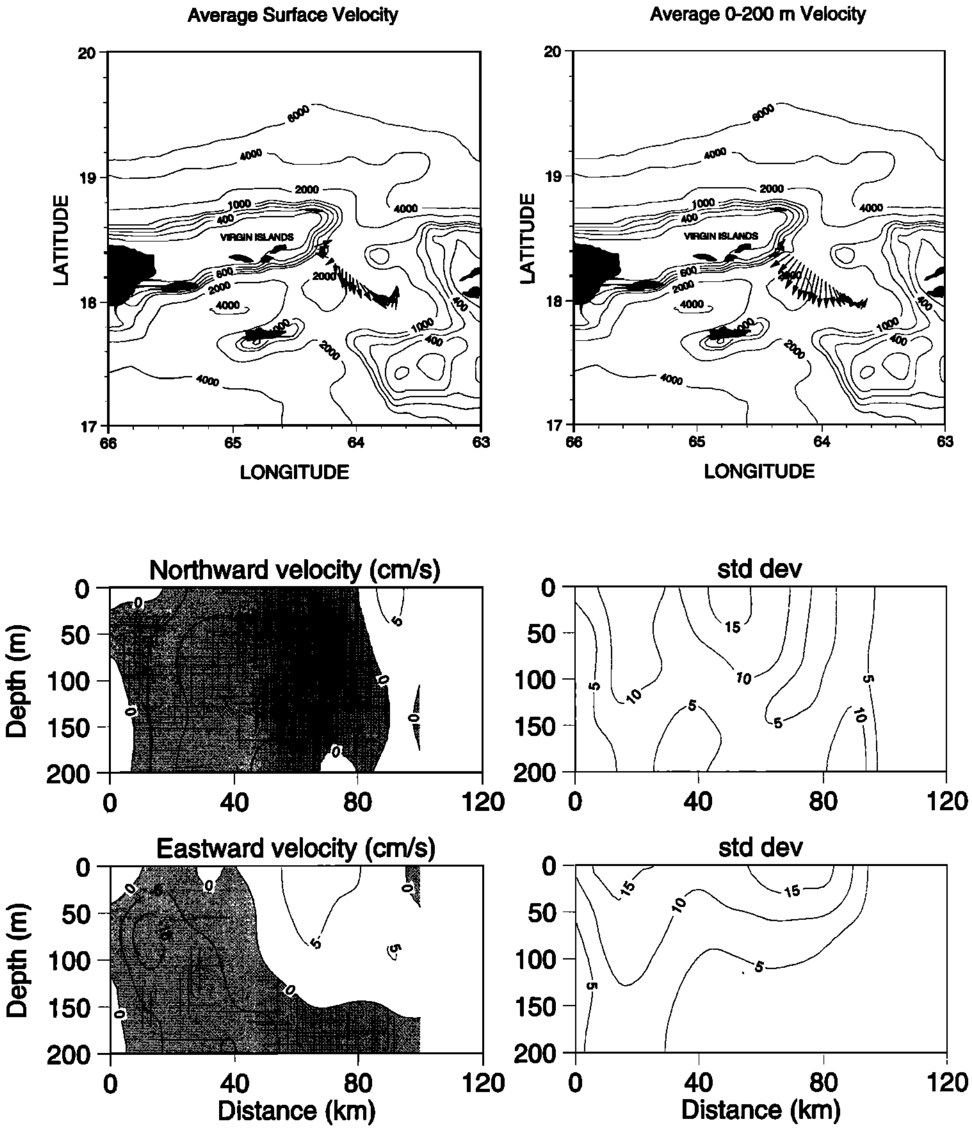

Figure 8. Same as Figure 2, but for the second Anegada Passage transect.

4. Discussion

The observations of velocity structure in and transport through the passages described above confirm many features reported by previous investigators but also bring to light new elements of the flow in the passages, particularly in the northern passages (e.g., NWPC, Great Inagua, Mona, and Anegada) where few previous observations have been made. Interesting features that these passages have in common include the presence of a subsurface velocity maximum and persistent surface-intensified counterflows that tend to be found along one side of each passage. The Florida Current, the eastern Caribbean, and the Grenada Passage also share a common velocity structure, having high velocity, narrow surface-intensified flows with strong vertical and horizontal shears.

4.1. Comparison With Previous Studies

The observations in the Florida Current at both 26°N and 27°N (Figures 2 and 3) are very consistent with previous studies, in terms of velocity structure and transport, as determined by dropsondes [*Schmitz and Richardson*, 1968], submarine cable measurements [*Larsen*, 1992], acoustic velocity profiling [*Leaman et al.*, 1987], and moored current meters [*Lee et al.*, 1985]. The shipboard ADCP observations reported herein add little new information about such an intensely studied ocean current but do demonstrate the reliability of the technique and lend confidence to the observations in the other passages that do not have extensive previous and ongoing studies with which to compare.

Several studies have been done previously in the Northwest Providence Channel (NWPC). The first, by *Richardson and Finlen* [1967], used dropsondes to directly measure transport. They obtained four sections across the NWPC during March 20–22, 1966. They found westward (toward the Florida Current) flow in the northern half of the channel and eastward flow in the southern half, just as we observed in the present study (Figure 4). They found maximum surface velocities in both directions of 60–80 cm/s, which are somewhat higher than our observations, but it must be kept in mind that theirs were taken during one limited time period and ours are an average. *Richardson and Finlen* [1967] observed a transport

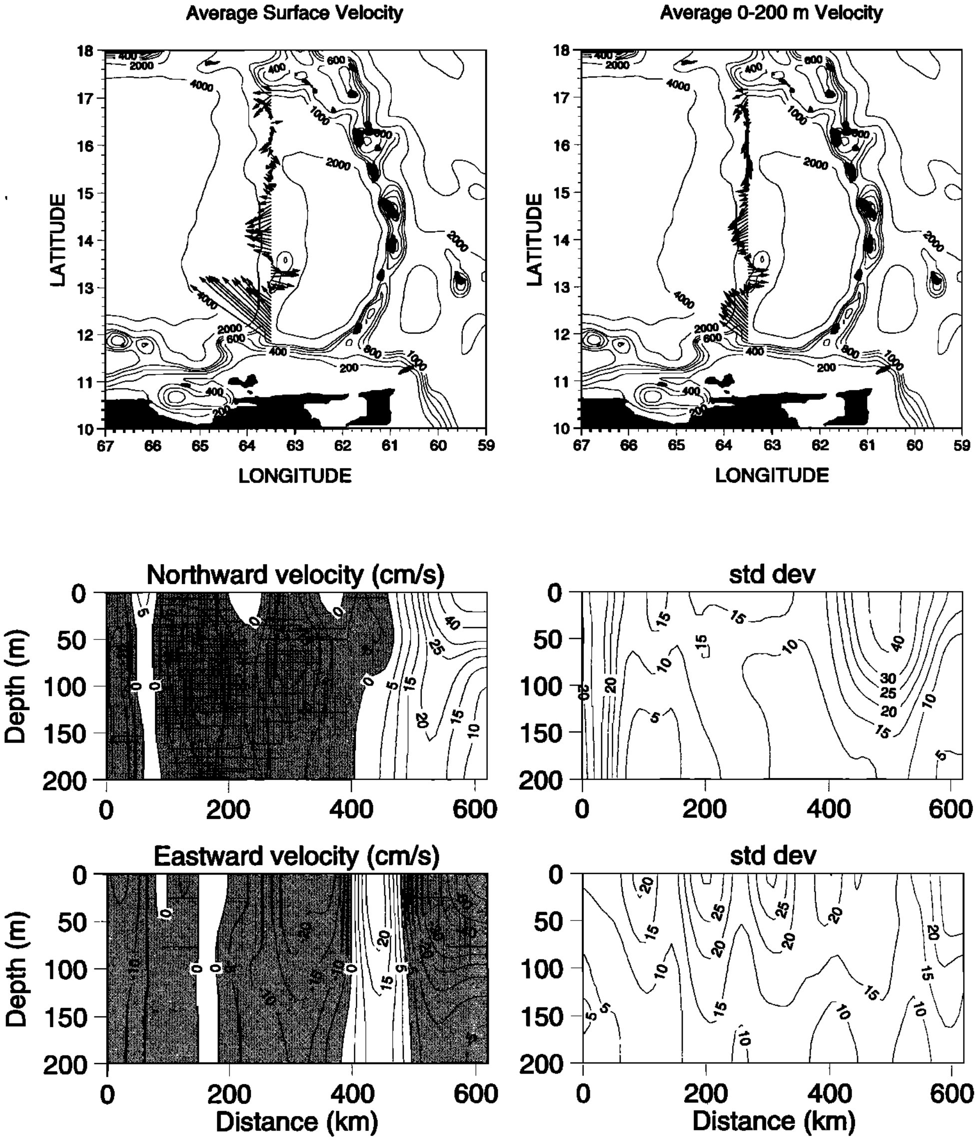

Figure 9. Same as Figure 2, but for the Caribbean transect along 63.5°W. The orientation of the vertical sections is from north to south along the transect.

range over the full water column of −1.5 to −2.5 Sv toward the Florida Current, consistent with our transports considering that our observations are for the upper 200 m only and theirs are for the whole channel depth. An interesting result discovered during the present study by comparing Florida Current transport data from the submarine cable, which gives total water column transport, to the shipboard ADCP data is that due to the vertical shear structure the upper 200 m contains ~50% of the total 800-m transport. Examination of full water column transports in the eastern Caribbean passages [*Wilson and Johns*, 1997] yielded the same percentage, implying that there is a common baroclinic structure to these currents, and thus a rough estimate can be made of total transport by multiplying the upper 200-m transports by a factor of 2. (Of course, this is not always valid and may vary for individual passages as well as temporally. The presence of counterflows below 200 m is also a possibility that would cause such extrapolation of the transport to be invalid.)

More recently, *Leaman et al.* [1995] reported observations made in the NWPC using the Pegasus acoustic velocity profiler during three cruises between November 1990 and September 1991. They found an average transport addition to the Florida Current of −1.2 Sv over the full water column, consistent with our observations. They also present velocity sections perpendicular to and along the transect orientation, which can also be compared with our observations (at least in the upper 200 m). Their results differ from ours, in that they observed inflow to the Florida Current only below 80–100 m depth, and outflow above that depth and on the northern half of the channel. We, on the other hand, observed inflow in the center of the channel all the way to the surface, although as described above and shown in Figure 4, we note that the inflow velocity does increase with depth, so at least the shear structures of the two studies agree. *Leaman et al.* [1995] also show the cross-transect component of velocity, which is small (<15 cm/s), southward, and confined to the upper 50 to 100 m within the southern half of the channel, in good agreement with our observations.

We are not aware of any previous observations in the Great

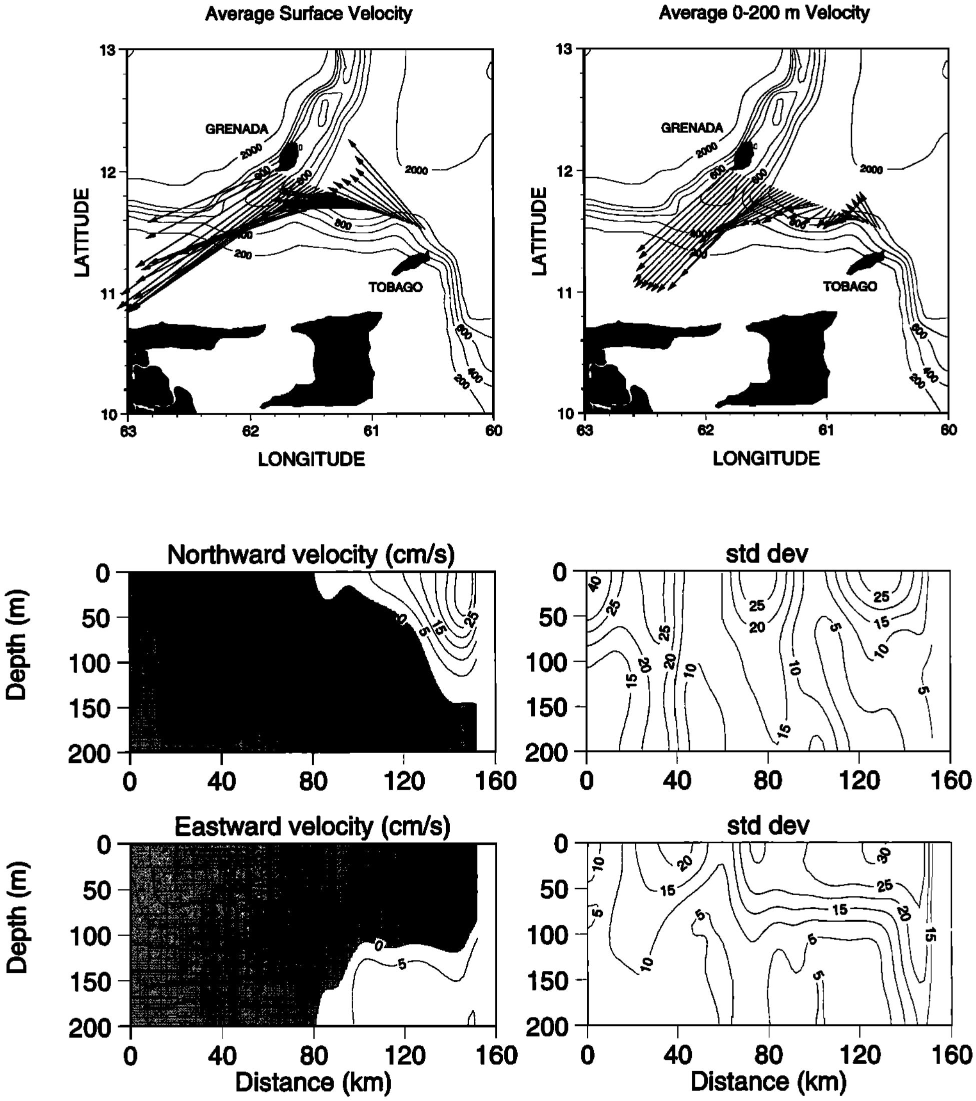

Figure 10. Same as Figure 2, but for the first Grenada Passage transect. The orientation of the vertical sections is from northwest to southeast along the transect.

Inagua–Haiti Passage, and few studies have been done in the Windward Passage, even fewer with direct velocity observations. *Roemmich* [1981], in his inverse calculation of the circulation of the Caribbean Sea using hydrographic data collected between 1954 and 1974, concluded that the flow through the Windward Passage above the 27.4 sigma theta surface (the approximate sill density of the Florida Current) was −7 Sv, with −22 Sv coming from the eastern Caribbean and the other few Sv necessary to balance the Florida Current coming from the Old Bahama Channel and the NWPC. However, there is a great deal of variability in Great Inagua Passage (and presumably also the Windward Passage), with our nine transects showing a low of −0.5 Sv and a high of −5.2 Sv, so *Roemmich*'s, [1981] −7 Sv certainly falls within our observed transport range if we take into account the transport extrapolation which could double our 200-m transports. *Kinder et al.* [1985], in a review article on the circulation of the Caribbean, attributes −10 Sv to the Windward Passage, based on a compilation of results by *Worthington* [1976], *Roemmich* [1981], and several others. In these studies, which were based on hydrographic rather than velocity observations, the role of the other northern passages was not considered to be significant. On the contrary, our observations show that the Mona and Anegada Passages may contribute nearly the same amount of transport as the Windward Passage (Table 1).

Very few direct velocity observations have been made in Mona Passage. An earlier study [*Metcalf et al.*, 1977] conducted using 423 drift bottles released in the passage (of which only 29 were returned) concluded that flow there was highly variable, with some bottles traveling out of the Caribbean into the Atlantic, and others going in the opposite direction into the Caribbean, more in agreement with our observation of an average inflow. In a later study, a satellite-tracked surface drifter was released near Mona Passage in October 1980 and tracked for 6 months [*Williams*, 1986]. Again, a complex flow pattern was observed, as the drifter remained north of the Caribbean for the first 4 months, and then subsequently turned and traveled through Mona Passage into the Caribbean at an average speed of 38 cm/s. *Williams* [1986] estimated the transport associated with the drifter motion to be −1 to −4 Sv.

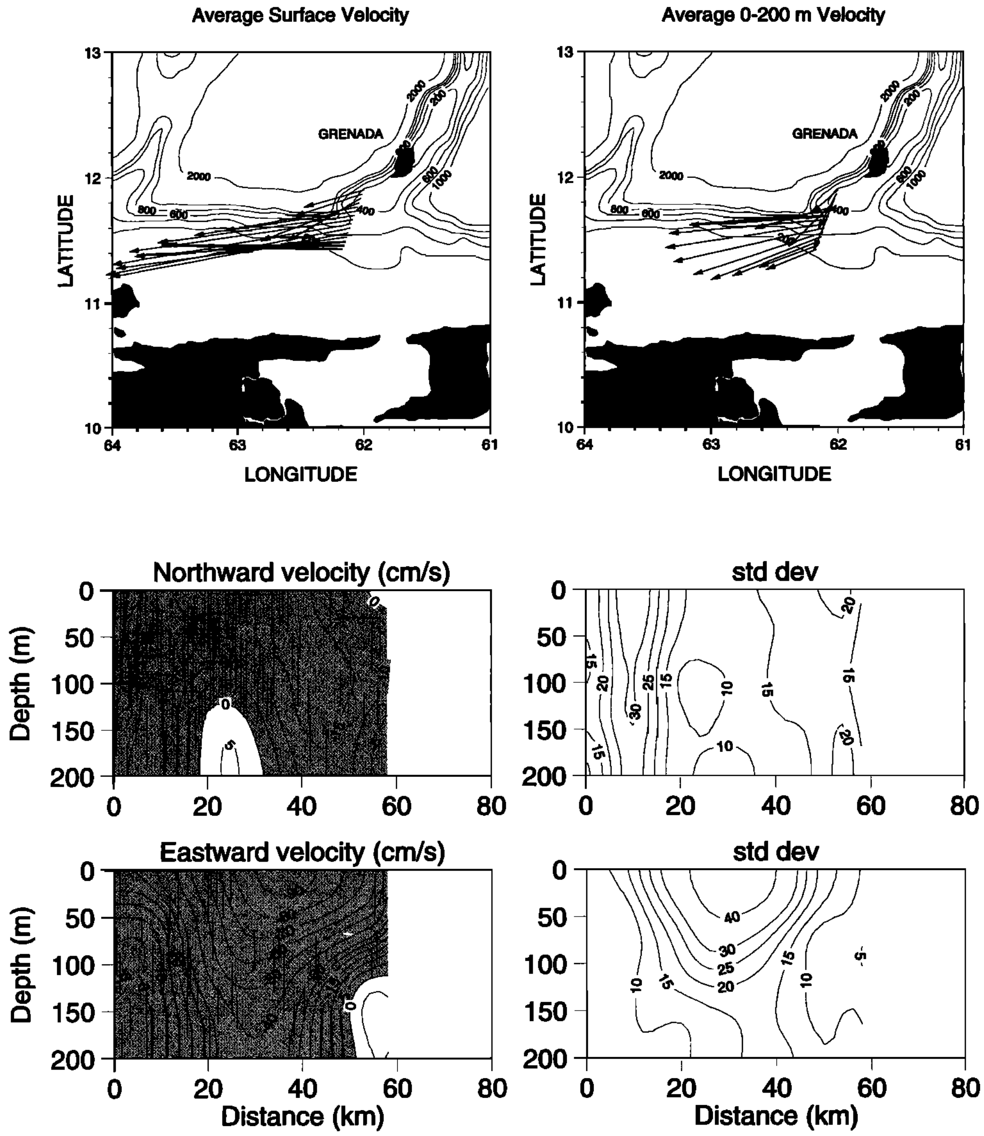

Figure 11. Same as Figure 2, but for the second Grenada Passage transect. The orientation of the vertical sections is from north to south along the transect.

These observations are consistent with our ADCP measurements, which also show highly variable transport (Table 1).

Similarly, few previous studies of the upper layer flow through Anegada Passage have been conducted. *Metcalf* [1976], using a combination of water mass analysis and geostrophic velocity computations as well as a few direct current measurements, computed a transport into the Caribbean of −1.4 Sv for the upper 200 m, well within our −2.4 ± 2.8 Sv average transport (Table 1). His conclusion was that the Anegada Passage is probably more significant in terms of deep inflows to the Caribbean, which ultimately fill the deep interior basins, rather than in upper layer transport when compared to the higher transport of the southern passages. However, *Schmitz and Richardson* [1991] concluded, based primarily on water mass analysis, that the Anegada Passage may play a more important role and should be examined more closely. Our observations agree with this, showing that the transport through Anegada Passage is similar in magnitude to Windward and Mona passages, and furthermore that the three northern passages together account for close to half of the total transport of the Florida Current as will be discussed below.

The data collected in the eastern Caribbean along 63.5°W in 1985–1986 have been described in detail by *Smith and Morrison* [1989] and *Morrison and Smith* [1990]. The former describes ADCP data methods and comparisons with acoustic velocity profiler observations and with geostrophic observations, and the latter discusses the observations with particular regard to seasonal variability of the geostrophic transport. The small differences between our reported transports for this section (Table 1) and those tabulated by *Smith and Morrison* [1989] are due to methodology differences such as smoothing, interpolation, gridding, etc. *Morrison and Smith* [1990] discuss the banded nature of the flow across 63.5°W, with three primary bands of westward flow separated by eastward bands or regions of little flow. They hypothesize that the eastward currents may either be a result of the spacing of the passages of the Lesser Antilles or a geostrophic response to the westward input of high-salinity subtropical underwater through the passages.

They report a mean geostrophic transport for the five sections of −18 Sv above a zero reference surface at 1000 m, consistent with the −9.5 Sv directly measured transport for the upper 200 m reported herein. They note that the seasonal variability observed is in agreement with the regional climatic wind stress curl distribution of *Hastenrath and Lamb* [1977] and is also consistent with Florida Current transport variability as measured by cable [*Larsen*, 1992] for the same 1985–1986 time period with a phase lag of 90–100 days. Other estimates of transport through the eastern Caribbean include *Roemmich*'s [1981] value of −22 Sv, *Schmitz and Richardson*'s (1991) recalculation from *Stalcup and Metcalf*'s (1972) data of −28.8 Sv, and *Schmitz and McCartney*'s [1993] estimates of −23 Sv through the eastern Caribbean. *Gordon* [1967] computed a geostrophic transport of −26 Sv along 64°30′W (which includes Anegada Passage), and *Kinder et al.* [1985] estimated the transport at −20 Sv. As listed in Table 1 for the upper 200 m, our observations along 63.5°W range from a high of −14.2 Sv in August 1985 to a low of only −1.7 Sv in October 1986 when there was a strong, wide eastward current present over much of the northern half of the section. Velocity structure for the individual cruises are shown by *Smith and Morrison* [1989].

The Grenada Passage has been the subject of several previous studies [cf. *Stalcup and Metcalf*, 1972], most yielding results from single shipboard occupations and therefore probably not representative of mean flow conditions. More recently, *Wilson and Johns* [1997] have conducted a comprehensive program to monitor the velocity structure in the passages of the eastern Caribbean using a cable-lowered ADCP in conjunction with hydrographic observations. The strongest flow of all the passages was found to be in Grenada Passage. The average velocity structure there, obtained from seven transects collected between December 1991 and July 1994 and shown in their Figure 4, showed surface-intensified westward flow with inflow speeds up to 60 cm/s in the center of the channel, and a counterflow located along the southern edge of the passage at 100–250 m depth with a speed less than 10 cm/s. Their mean transport for the six transects which had full-depth coverage (some of which were included in the present study) was −4.7 ± 1.6 Sv to the bottom of the passage, which is located at ~900-m depth. The observed velocity structure described by *Wilson and Johns* [1997] is in good agreement with that from the present study (Figures 10 and 11), but the transport is lower, as our average transport through Grenada Passage was −4.9 ± 1.9 Sv for the upper 200 m alone. Our value is −4.1 Sv if the anomalously high transport observed during one particular cruise is discarded. There are several reasons that could explain this apparent disagreement in transport. Variability due to tides and interaction with eddies impinging upon the islands from the east, coupled with an insufficient number of observations to obtain a stable mean, is possible. Also, only the last five of the passage occupations listed in Table 1 were colocated with the *Wilson and Johns* [1997] transect, and the mean of these five is only −3.7 Sv. Finally, the transport structure of the Grenada Passage reported by *Wilson and Johns* [1997] includes a mean outflow over much of the passage, mostly below 200 m, which would tend to reduce the total transport. More recent calculations of the average Grenada Passage transport from the ongoing *Wilson and Johns* [1997] program, which include 10 cruises through 1996, show the same features in the velocity structure and have a slightly higher mean transport of −5.6 Sv.

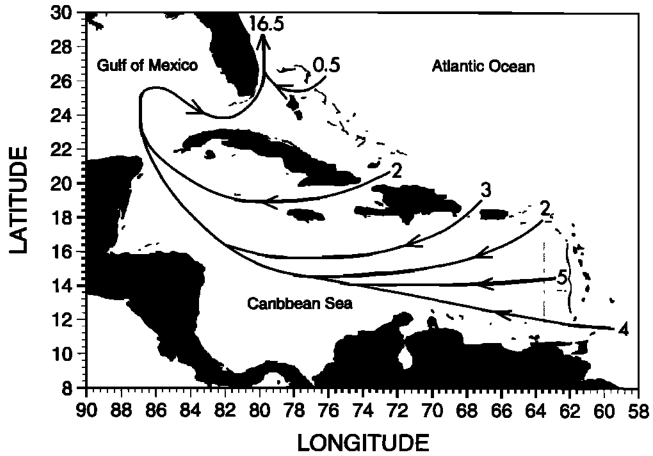

Figure 12. Schematic representation of the circulation of the Intra-Americas Sea in the upper 200 m based on the observed ADCP transports (Table 1). Approximate average transport is indicated in Sverdrups.

4.2. Transport Balance

The transport values for the upper 200 m of the transects represent a balance on average between inflow through all of the passages from the Northwest Providence Channel to Grenada Passage and outflow through the Florida Current at 27°N (Table 1). This result is shown schematically in Figure 12. The inflow sum is

$$0.4\ (\mathrm{NW}) + 2.2\ (\mathrm{GI}) + 2.8\ (\mathrm{MP}) + 2.4\ (\mathrm{AP}) + 9.5\ (\mathrm{CA}) = 17.3\ \mathrm{Sv}.$$

Note that Grenada Passage is not added to the sum, as any flow through the Grenada Passage would be included in the eastern Caribbean transect (Figure 1). This inflow sum balances the 16.5 Sv observed upper 200-m outflow of the Florida Current at 27°N to within less than 1 Sv. This balance is shown schematically in Figure 12. It must be noted that although the average transport is in balance, within any individual cruise the passage transports do not balance as closely. This is due primarily to lack of synopticity of the measurements, which were typically collected over a period of two to three weeks. Transport variability is undoubtedly high over that time frame. In the Florida Current, for example, *Larsen* [1992] has observed very large changes in transport (as high as 50% of the total transport) over month-to-month timescales. The synoptic transports do not necessarily have to be in balance anyway, as sea level changes can occur. However, over time, given enough individual realizations of each passage transport, a meaningful average transport for each passage can be obtained and an average transport balance achieved. Of course, Figure 12 is only a schematic of the average circulation. Drifter studies, for example, those presented by *Molinari et al.* [1981], always show that there is a great deal of eddy variability, particularly in the region of the eastern Caribbean, and so at any given time the flow field will be much more complicated than the schematic portrayal. Nevertheless, certain features of the Caribbean circulation do on average resemble the schematic of Figure 12, such as the convergence of the flow from the passages to form the Caribbean Current/Loop Current system.

The difference between the average upper 200-m transport at 27°N (16.5 Sv) and the transport at 26°N (15.4 Sv) is due to the addition of transport through the Northwest Providence Channel. The upper 200-m transports through the Great Inagua, Mona, and Anegada passages are all roughly equal at about −2.5 Sv each (Table 2) and summed together are 7.4 Sv, nearly half of the 26°N Florida Current transport. Of the −9.5 Sv total for the eastern Caribbean south of the Anegada Passage, Grenada Passage accounts for −4.9 Sv, or approximately half of that total. This is a significant finding, as the Grenada Passage is where the greatest input of water originating in the southern hemisphere is likely to be found. A new program to continuously monitor the transport through Grenada Passage using a submarine cable similar to the one that has been successfully monitoring the Florida Current transport is in the early stages (W. Johns, personal communication, 1998) and should produce enlightening results about the long-term mean and variability of the transport there.

4.3. Interannual Variaiblity

The earlier studies of transport in the eastern Caribbean discussed above [*Gordon*, 1967; *Stalcup and Metcalf*, 1972; *Roemmich*, 1981; *Schmitz and Richardson*, 1991; *Schmitz and McCartney*, 1993] all showed higher transport than the observations reported herein. It is tempting to speculate that these transports indicate a trend toward lower transport through the southern Caribbean passages over the past several decades. As the Florida Current transport is known not to have varied significantly over the same time period [*Larsen*, 1992], such a trend would imply that there may have been a shift in the prevailing large-scale circulation pattern, with a larger proportion of the flow now entering the Caribbean through the northern passages than in the 1970s.

The available observations are too limited to allow more than speculation on interannual variability, however. This is also why we do not address the subject of seasonal variability of the flow through the passages. The large range in transport through the various Caribbean transects (Table 1) shows the hazards in basing long-term mean estimates of transport on only a few realizations. However, indications from long time series climate data are that there have been some very noticeable changes in the tropical and subtropical North Atlantic on the same decadal timescale, including changes in large-scale wind patterns, sea surface temperature, hurricane frequency, drought conditions in Africa, and changes in ENSO strength and frequency [*Hastenrath*, 1990; *Landsea et al.*, 1992].

Schmitz and Richardson [1991] argue that the transport into the southern Caribbean includes a large southern hemisphere component required to maintain a thermohaline overturning circulation of ~15 Sv in the Atlantic. If the lower transports we observe in the eastern Caribbean also include correspondingly less southern hemisphere water, alternative pathways outside the Caribbean would be required for the cross-equatorial flows. Most likely possibilities include North Brazil Current Rings [*Johns et al.*, 1990; *Fratantoni et al.*, 1995], which may at times drift northwestward instead of impinging upon the island chain as they often do, and interaction between the North Equatorial Countercurrent and the North Equatorial Current [*Mayer and Weisberg*, 1993; *Bourles et al.*, 1999]. Additional analyses, particularly involving water mass tracer analysis, and numerical models forced by realistic winds for the decades in question will likely shed more light on these issues.

Finally, many of the observations presented above were obtained along ship tracks while the research vessel was "deadheading" to or from various research study areas in the IAS and off the coast of northeastern Brazil. Similar observations could in the future be easily made from Volunteer Observing Ships outfitted with ADCP units such as described herein, providing a cost-effective current monitoring tool. Monitoring the circulation of the IAS over a long time period should prove enlightening in terms of seasonal, interannual, and longer-term variability. Further understanding of the circulation of the IAS and its interconnectedness in terms of fisheries, pollution, larval transports, etc., will also depend on focused observational programs that incorporate satellite fields of sea surface temperature, ocean color and altimetry with Lagrangian drifters, and shipboard-based interdisciplinary process studies.

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