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A comparison of direct observations of velocity and transport in the Windward Passage

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RESUMEN

Se considera la velocidad y el transporte de agua a través del Paso de los Vientos a través de una revisión de las investigaciones anteriores y el reanálisis de observaciones de anclajes que la Ex-Unión Soviética condujo el 18 de febrero 1965 y el 19-23 de noviembre 1970, que probablemente son las únicas mediciones directas de velocidad llevadas a cabo allí hasta el presente. El conjunto de las mediciones directas de las corrientes indican un transporte de 8 Sv ± 4 Sv en el Mar Caribe, que es consistente con estimaciones de valores del transporte propuestas por otros autores. El transporte basado en los datos del 19-23 de noviembre 1970 se compone como una salida superficial de 0.8 Sv en la capa superior de 100 m, afluencia de 10.7 Sv en la capa interior de 100-700 m, y salida profunda de 2.0 Sv por debajo de 700 m. El sistema general de corriente-anticorriente en la capa superior de 200 m en el Paso de los Vientos coincide satisfactoriamente con las observaciones recientes de ADCP en el Paso de Gran Inagua.

PALABRAS CLAVE: Paso de los Vientos, mediciones de corrientes, comparación de datos.

ABSTRACT

Velocity and water transport through the Windward Passage is estimated from a review of prior investigations and a new analysis of mooring observations conducted on February, 18, 1965 and November, 19-23, 1970 in the former USSR. These may be the only available direct velocity measurements in this area. Direct current measurements indicate a transport of about 8 Sv ± 4 Sv into the Caribbean sea, which is consistent with values estimated by other authors. The transport figure based on November, 19-23, 1970 data is interpreted as a surface outflow of 0.8 Sv in the upper 100 m, a mid-depth inflow of 10.7 Sv in the 100-700 m layer, and an outflow of 2.0 Sv below 700 m. The general current-countercurrent flow system of the upper 200 m in Windward Passage compares satisfactorily with recent ADCP observations in the Great Inagua Passage.

KEY WORDS: Windward Passage, current measurements, data comparison.

INTRODUCTION

The Caribbean sea is a semi-enclosed basin bounded by a chain of closely spaced islands to the east and to the north. The islands from Guadalupe to Grenada are the Lesser Antilles, while the larger islands to the north (Cuba, Haiti and Puerto Rico) are called the Greater Antilles (Figure 1).

Water exchange through the passages of the Caribbean sea has been the subject of oceanographic studies aimed at understanding the components of the measured transport of approximately 30 Sv in the Florida Current (Larsen and Sanford, 1985). A great deal of uncertainty remains, however, about the distribution of the inflow through each of the Caribbean passages. Some passages have been studied in more detail than others. Observation programs have been undertaken over the past several decades by investigators from the former Soviet Union (FSU) and the USA, to estimate water exchange through the passages of the Caribbean sea.

The FSU program was conducted from 1964 through 1983. Moored current meter data was obtained in practically all passages of the Caribbean sea. The current meters were short-term (a few days), but they were well resolved spatially (see collective monographs Studies of the Caribbean sea, 1974; Oceanographic studies of the Caribbean sea and adjacent regions, 1980; Sukhovey *et al.*, 1980; Complex studies of Atlantic tropical zone and Caribbean sea, 1983; Experimental studies of the hydrophysical fields, 1983; Oceanographic studies in the Central-American seas, 1984; Bulgakov *et al.*, 1991). The FSU studies were conducted as a part of CICAR (Complex Investigation of the Caribbean) and IOCARIBE (International Organization CARIBE) International programs. This data is available at World Data Center A, Oceanography (Silver Spring, USA) and at World Data Center B (Obninsk, Russia). See Guide to CICAR data (1977) and Catalogue of data and report of data exchange (1999).

The USA program was initiated in the 1970's with long-term (a few months) moored observations of deep-water cur-

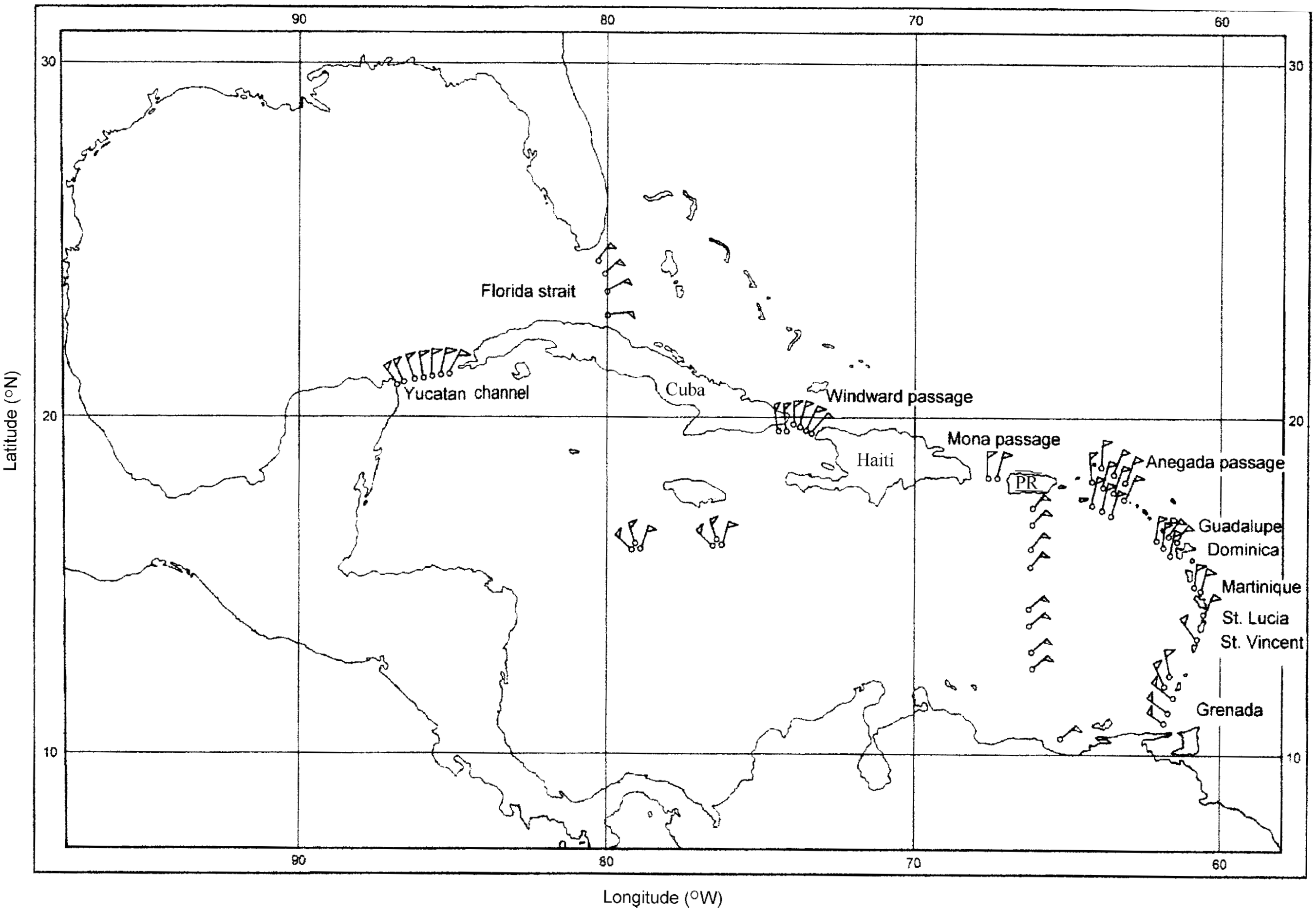

Fig. 1. Gulf of Mexico and Caribbean sea, showing the major passages and the FSU mooring stations denoted by flags.

rents in the Caribbean passages (Stalcup and Metcalf, 1972; Stalcup *et al.*, 1975; Hansen and Molinari, 1979; Mazeika *et al.*, 1983; Maul *et al.*, 1985; Atkinson *et al.*, 1995; MacCready *et al.*, 1999). It was followed by satellite-tracked Lagrangian observations in the 1980's (Molinari *et al.*, 1981; Duncan *et al.*, 1982; Kinder, 1983) and acoustic Doppler current profiler (ADCP) measurements (Smith and Morrison, 1989; Wilson and Johns, 1997; Johns *et al.*, 1999).

The issue of the mean volume transport and the variability of the flow patterns through the various passages of the Caribbean sea is still debatable (e. g., Schmitz and Richardson, 1991; Wilson and Johns, 1997; Johns *et al.*, 1999). However, no formal comparison between FSU and USA data has been done. Furthermore, it is apparent from the literature in English and from our personal communications that the FSU investigations in the Caribbean remain much less familiar to Western readers than the USA studies, except for the early paper by Sukhovey and Metal'nikov (1968). Thus, a brief review of the FSU observation programs may be useful.

Complex oceanographic studies of the Mexican-Caribbean basin were carried out by the FSU through the Marine Hydrophysical Institute (Sevastopol, Ukraine), under CICAR (1968-1975) and IOCARIBE (1976-1983) International Programs. An investigation of the water exchange between the Caribbean sea and the Atlantic ocean through the straits was one of the main objectives of these field observations. Thirteen cruises on board R/V *Mikhail Lomonosov* and R/V *Academician Vernadsky* were undertaken by the Marine Hydrophysical Institute (MHI). More than 50 current meter mooring stations were installed for a period of a few (1 to 9) days in the passages of the Greater and the Lesser Antilles, in the Yucatán Channel, and in the Caribbean interior. The location of the mooring stations is shown in Figure 1.

Rotating current meters of the BPV type were used by MHI before 1978, and DISK (MHI-1301) current meters were utilized after 1979. Both types were designed at MHI. According to laboratory tests the standard deviations of the velocity errors were about (1.85 + 4.50_*V*)/100 for the BPV current meter and (0.65 + 2.85·*V*)/100 m/s for the DISK (MHI-

1301), where *V* is maximum velocity measured in m/s. Measurement precision of the current directions was 7.5 and 3.0 degrees respectively (see Bulgakov *et al*., 1991).

In this paper we review the water exchange in the Windward Passage, one of the less studied passages of the Caribbean sea. Progress in the state of the art may be attainable based on a synthesis of the independent investigations contained in the literature in English and in Russian.

The following two sections describe US studies of the Windward Passages dynamics, and FSU current meter observations in this strait. Summary and discussion are presented in the last section.

USA STUDIES OF THE WINDWARD PASSAGE

The history of the studies of Windward Passage (WP) began with Wust (1964) and continues up to the present.

The Windward Passage probably represents a primary inflow passage from the Atlantic through the Greater Antilles into the Caribbean sea. It runs in a NW-SE direction between Cuba and Haiti (Figure 1). This V-structure gap is roughly 45 miles wide. The WP sill depth was reported to be 1625 m by Wust (1964) and 1560 m by Metcalf (1976) and Maul *et al*. (1985).

Gordon (1967) inferred from his geostrophic calculations that flow through the WP was less than 5 Sv. Worthington (1976) attempted a property balance for the whole North Atlantic which required roughly 10 Sv to enter the Caribbean through the Windward Passage, and about 20 Sv to enter the eastern Caribbean. Roemmich (1981) estimated 7 Sv using an inverse technique with hydrographic data collected in 1954-1974. He was the first to constrain the speed contours in WP (see Roemmich, 1981; Figures 5f and 8f), and to find a surface intensified inflow (negative values up to 60 cm/s) at the NW channel end.

Gunn and Watts (1982) analyzed the hydrographic data from two surveys in 1972 and 1973 in addition to historical data in the region leading towards the WP. Their transport estimates, based on dynamic calculations, showed a significant seasonal flow variability. The summer surveys revealed a maximum flow into the WP, with a transport estimated at 15±5 Sv. During the fall and winter seasons, the flow from the Atlantic into the WP was also found to be strong (about 9 Sv). In contrast, a lack of exchange was noted in spring. Nof and Olson (1983) modeled the inflow and reviewed prior measurements, suggesting a Windward Passage inflow of 12 Sv, which is more than one-third of the total transport into the Caribbean. Kinder *et al*. (1985) suggested 10 Sv for the mean flow through the Windward Passage in a review article based on hydrographic observations and computation results. They assumed that a maximum mass transport occurs in the Caribbean during mid-summer, and a minimum transport of half the summer value in wintertime, because of the larger zonal gradients of wind stress in summer. Schmitz and Richardson (1991) supposed, from water mass analysis, that the contribution through the WP is 6.8 Sv, exceeded only by the Grenada Passage transport (7.7 Sv). Wilson and Johns (1997) conducted full-depth ADCP measurements in the four southern passages (Grenada, St. Vincent, St. Lucia, and Dominica). Their total transport was estimated to be 9.5 Sv. Therefore roughly 20 Sv must enter the Caribbean north from Dominica, approximately 8 Sv of which could come through the WP. Johns *et al*. (1999) first examined shipboard ADCP observations of the velocity in the northern Caribbean passages (Anegada, Mona, and Great Inagua). This data was collected during 1984-1996 in the upper 200 m of the water column.

Great Inagua (GI) Passage is located between the Bahamian island of Great Inagua and the northwestern coast of Haiti northeast of the WP (see Figure 2, adapted from Johns *et al*., 1999). It was considered as a proxy for the flow through the WP. The Great Inagua Passage transect was occupied nine times through August, 1984 and February, 1991. An average velocity to the southwest was observed, with a subsurface westward maximum of greater than 20 cm/s near the lower limit of the observations (150-200 m) at the northern end of the strait. On the southern side of the channel, along the coast of Haiti, the flow was reversed and surface flow intensified, with an average counterflow from the Caribbean of 10-15 cm/s in the upper 50 m. Data comparison with the other northern passages (Mona and Anegada) showed that they shared a similar mean velocity structure, with a persistent subsurface velocity maxima directed into the Caribbean, and with surface-intensified counterflows along one side of each channel. In contrast, it was found that the passages of the Lesser Antilles featured surface-intensified flows into the Caribbean with strong vertical and horizontal shears.

Johns *et al*. (1999) noted that long-term cruise-to-cruise variability of flow in the GI passage was not very high. However, during four of the nine crossings, the countercurrent was not observed along the Haitian coast, though it was present during the other five cruises. Maximum counterflow velocities were higher than 60 cm/s during July and August of 1986. The standard deviation of the eastward velocity component was less than ±10-15 cm/s over the northern half of the transect, but higher (±20-25 cm/s) over its southern half. The northward velocity component was weak (<5 cm/s). It was directed mainly to the south (Figure 2).

The average transport through the GI passage toward the Caribbean in the upper 200 m was estimated at 2.2 Sv

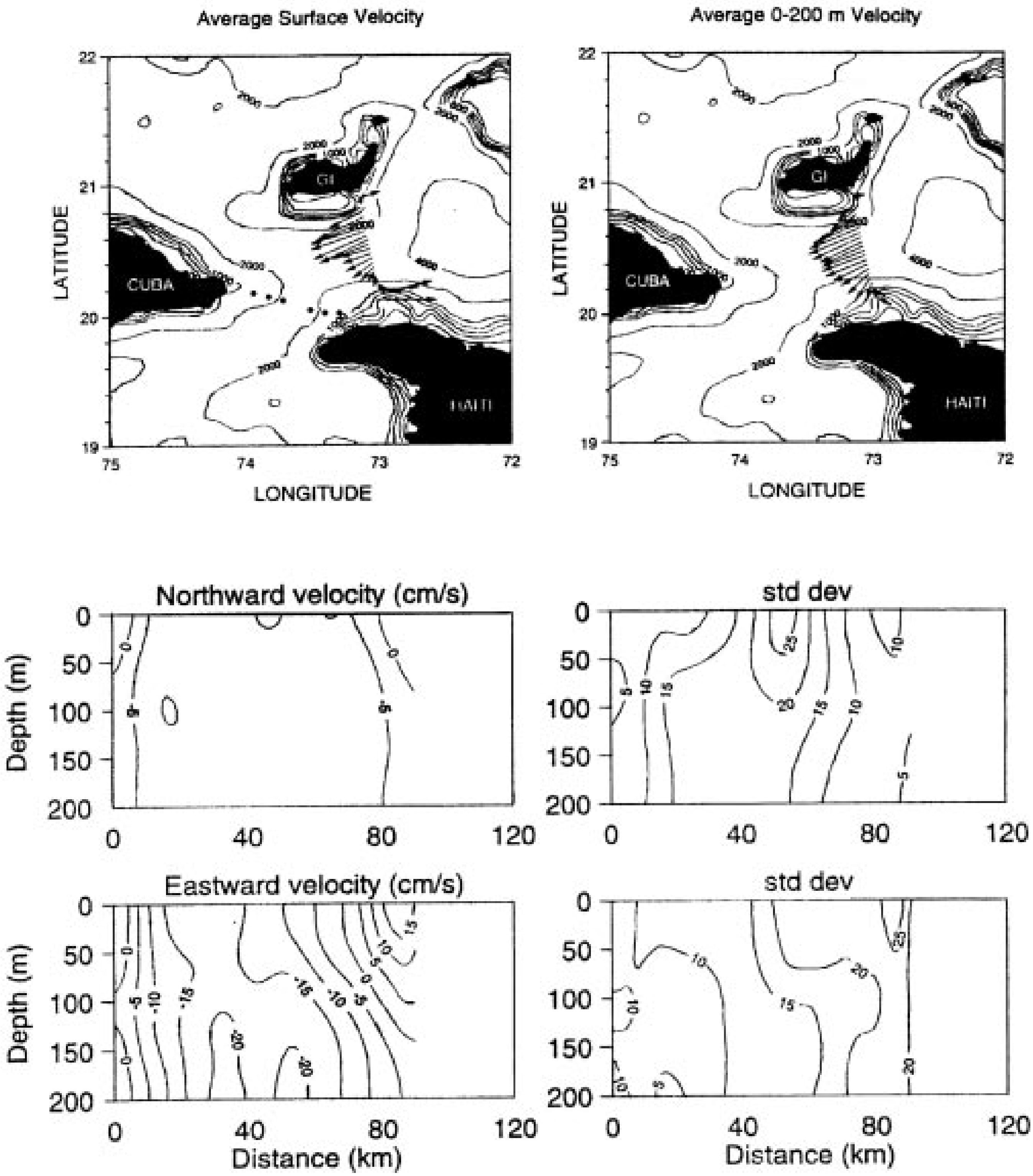

Fig. 2. ADCP vector maps of the average surface velocity (left, top) and the average 0-200 m velocity (right, top) for the Great Inagua Passage. The velocity vectors are scaled so that 50 cm/s equals 1° of latitude. Also shown are vertical sections of ADCP velocity in cm/s for the northward and eastward velocity components (left, bottom) and their standard deviations in cm/s (right, bottom). The orientation of the vertical sections is from northwest to southeast along the transect. The positions of the FSU mooring stations in Windward Passage anchored in November, 19-23, 1970 are shown by dots (left, top).

with ±1.5 Sv of standard deviation. A low value of 0.5 Sv was observed during July and August of 1986 and a high value of 5.2 Sv during August and September of 1989.

Finally, it was suggested that a rough estimate of the total transport here could be made by multiplying the upper 200 m transport by a factor of two. This was assumed from a comparison with Florida Current transport data, from the submarine cable (which gives a total water column transport) to the shipboard ADCP data of the upper 200 m which contained about 50% of the total 800-m transport, assuming a common velocity vertical shear structure in WP. This extrapolation yielded a mean total transport through the GI Passage of about 4-5 Sv.

FSU OBSERVATIONS IN THE WINDWARD PASSAGE

FSU current meter observations in the WP were conducted on February, 18, 1965 (R/V Mikhail Lomonosov, Cruise 17) and on November, 19-23, 1970 (R/V Academician Vernadsky, Cruise 3). In total, 7 mooring stations with 75 current meters spaced non-uniformly in the vertical were installed for a 1 or 2-day period directly in WP between Cuba and Haiti (dots in Figure 2, top left). General information about these mooring stations is presented in Table 1.

During these cruises the sill depth was observed at 1688 m by Sukhovey and Metal'nikov (1968). The deepest point (1712 m) in the strait entrance was reported by Avdeev (1984). It was also found that the WP is 42 miles wide as measured at the 200 m isobath from Cuba to Haiti.

Each BPV current meter recorded speed and direction during a 5-minute interval and provided 24 or 48-hour data. The maximum velocities measured during the observations were 50-60 cm/s. Thus, the expected errors for the current meters did not exceed 4-5 cm/s and 7-8 degrees in the flow direction.

The flow patterns in February, 1965 were reported by Sukhovey and Metal'nikov (1968), in Studies of the Caribbean Sea (1974), and by Sukhovey *et al*. (1980). These current meter observations were conducted utilizing a single mooring station anchored near the deepest point. The records (Figure 3) showed a net inflow into the Caribbean between 300 and 600 m with the highest speeds near 400 m. In the upper 50 m layer the flow was directed into the Atlantic. Below 700 m the flow was out of the Caribbean with maximum speeds near 1200 m.

Current meter observations obtained in November, 1970 were discussed in the collective monographs Studies of the Caribbean Sea (1974) and Sukhovey *et al*. (1980). Unfortu-

Table 1

Mooring stations, summary

Station	Latitude (N)	Longitude (W)	Date	Duration (h)	Depths (m)
1389	20°13.8'	73°36.0'	18.02.65	24	25, 50, 300, 400, 500, 600, 700, 1000, 1200, 1400, 1600
183	20°11.3'	73°36.3'	19.11.70	48	25, 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1200, 1500
184	20°15.1'	73°47.2'	19.11.70	24	50, 100, 200, 300, 400, 500, 600, 800, 1000
185	20°12.0'	73°40.9'	19.11.70	24	25, 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1500
186	20°09.4'	73°22.7'	21.11.70	48	25, 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1100
187	20°07.3'	73°12.6'	22.11.70	48	25, 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1200
188	20°09.4'	73°17.1'	23.11.70	24	25, 50, 100, 200, 300, 400, 500, 600, 800, 1200

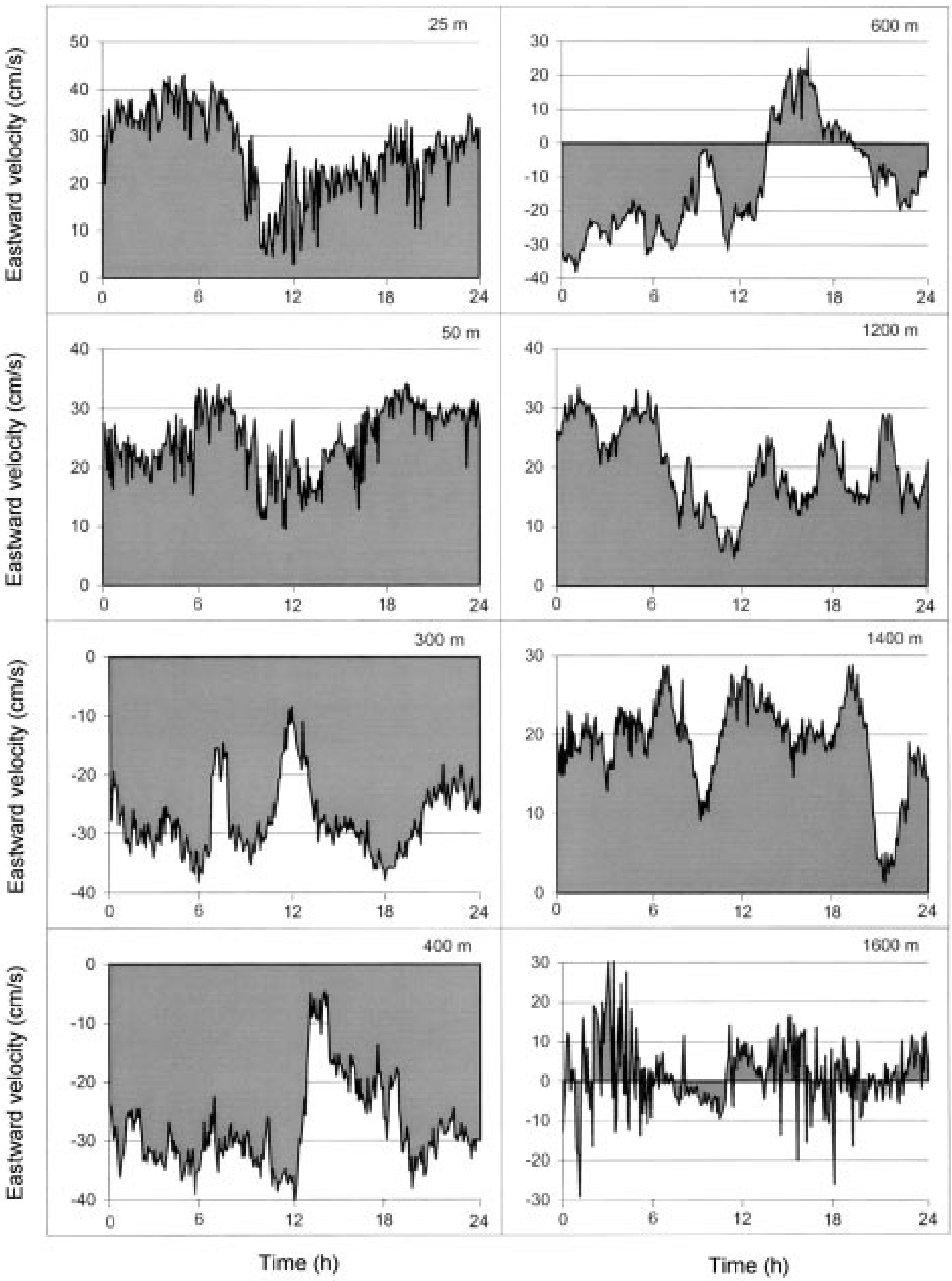

Fig. 3. A 24-hour time series of the eastward component of the velocity vector (cm/s) at different levels of the deep-water station 1389 on February 18, 1965.

nately, their analysis was confined to a single component of the velocity vector. In the present paper we have expanded the analysis of this observation data. The moored data have not been filtered. No tidal corrections have been made in the velocities for a better comparison with the Great Inagua observations by Johns *et al.* (1999).

All current meter measurements from a set of 6 stations spanning the WP were vector averaged. The linearly interpolated mean eastward and northward components of velocity vectors are shown in Figure 4. Most of the inflow of Atlantic waters into the Caribbean was directed to the west-

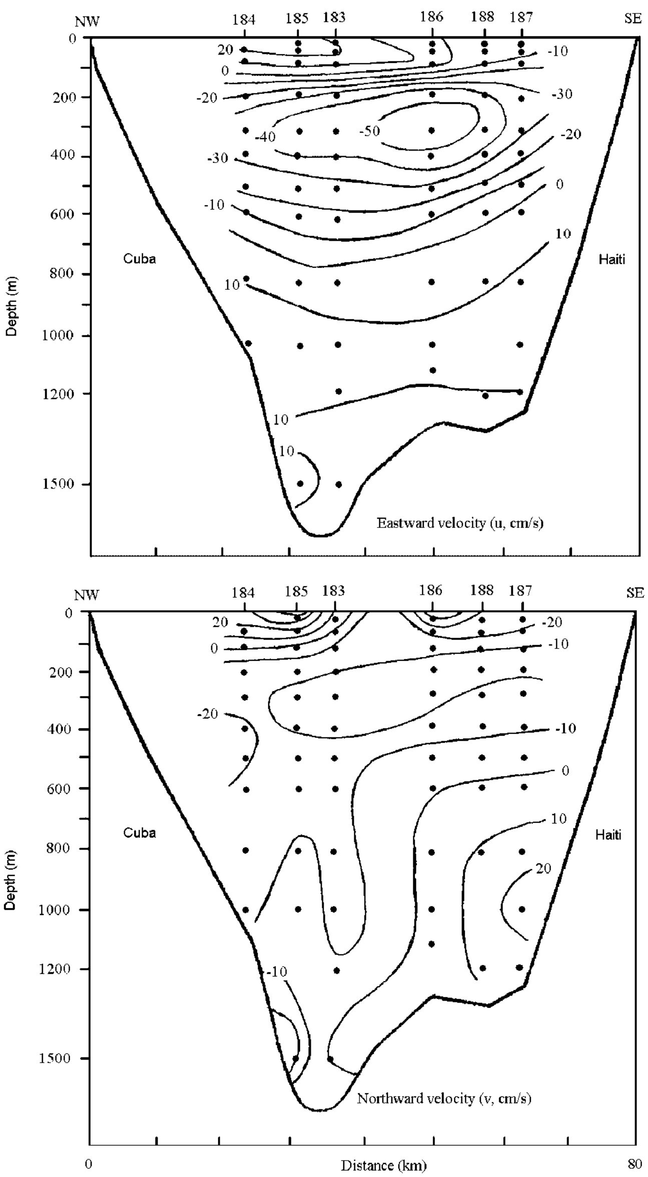

Fig. 4. Mean eastward (top) and northward (bottom) components of velocity vector (cm/s) on the northwest-southeast transect based on FSU mooring data collected in Windward Passage during November 19-23, 1970. The instrument positions are shown by dots.

southwest, as observed between 100 and 700 m depths. The core of this subsurface inflow was located at 200-400 m depth. The maximum measured inflow velocities were as large as 50-60 cm/s.

Surface counterflow to the NE was observed in the western half of the strait along the eastern coast of Cuba, with velocities of 20-40 cm/s found within the upper 100-m layer. In contrast, a surface counterflow in GI passage was observed by Johns *et al.* (1999) along the Haitian coast in five out of nine crossings. The variability of the surface counterflow could be related to wind conditions at the passages. Below 700 m there was a secondary outflow, with maximum speeds up to 20 cm/s, observed at 1000 m depth close to the Haitian coast. Thus, general flow patterns (mid-depth inflow between surface and deep outflows) were similar to those observed on February, 18, 1965.

The mean profile of the component of the velocity vector perpendicular to the NW-SE cross-section is presented in Figure 5. Negative values are directed towards the Caribbean. The layered structure of the circulation is characteristic of the WP. There is a subsurface velocity maximum directed into the Caribbean and a surface-intensified counterflow, also reported by Johns *et al.* (1999) for the GI Passage. The mean velocity structure based on the 1965 and 1970 data shows a secondary deep-water counterflow into the Atlantic below 700 m.

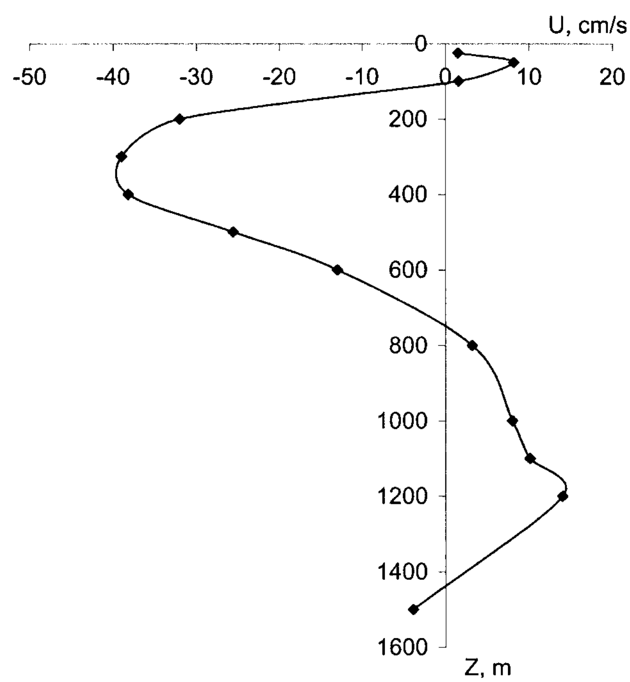

Fig. 5. The resulting mean profile of the velocity vector perpendicular to the northwest-southeast transect in Windward Passage from the FSU mooring data collected during November 19-23, 1970. Negative values are directed towards the Caribbean sea.

Transport estimates for the WP passage were obtained from this mean velocity profile and bottom topography information. An integration of mean velocities for each 100 m depth yields the following values of water transport: surface outflow (0-100 m) 0.8 Sv; mid-water inflow (100-700 m) 10.7 Sv; deep outflow (below 700 m) 2.0 Sv. Thus the net inflow into the Caribbean sea was approximately 8 Sv. The transport errors may be estimated as ± 4 Sv taking into account the maximum errors for the current meters (5 cm/s) and for an approximate WP area of 80 km^2.

It is interesting to evaluate the persistence and variability of water exchange in WP based on observation data recorded during November, 1970. The short-term variability can be evaluated based on the standard deviations and time series of the observation data. Standard deviations of the (u,v)-components of velocity are shown in Figure 6. Minimum values (less than 5-10 cm/s) correspond to the cores of subsurface inflow into the Caribbean at 200-400 m depth, and to the deep-water outflow into the Atlantic at 800-1000 m close to Haiti. The maximum standard deviation values (>15 cm/s) are visible above the thermocline and in the zones separating the inflowing and outflowing waters. Thus, the flow structure in the WP is characterized by a relatively persistent subsurface maximum inflow as well as by a deep outflow, and by a more highly variable flow regime in the rest of the passage entrance.

Persistence of measured currents can be quantified using the diagrams, which represent the probable occurrence of the speed and flow direction for each velocity record defined in percent. The band of flow intensity was divided into 6 intervals of 10 cm/s each, based on maximum velocity values. The directionality of the flow was subdivided into 4 quadrants of 90° each, where 0° corresponds to the northward direction. These diagrams of observations at 25, 200, 1000 and 1500 m depths at the deepest strait point (station 183) are shown in Figure 7. Columns on the left represent the persistence of flow speed, and columns on the right demonstrate the directionality of flow. These show, in particular, that during the 48-hour period of observations the appearance of southwestward flow (180°-270°) at 200-m depth was very high (83%), with the most frequent intensity of 40-50 cm/s at 64%. The southeast flow (90° -180°) at 1000 m had also a very high persistence of directionality (90%), whereas its intensity was highly variable. More variable flow patterns were observed above and below the subsurface maximum inflow and the deep-water outflow.

This kind of variability can be understood from an analysis of the time series of scaled kinetic energy $(E = \frac{u^2 + v^2}{2})$ and from the prevailing eastward component of the velocity vector, shown in Figures 8 and 9 respectively for deep-water station 183. Both graphs show prominent

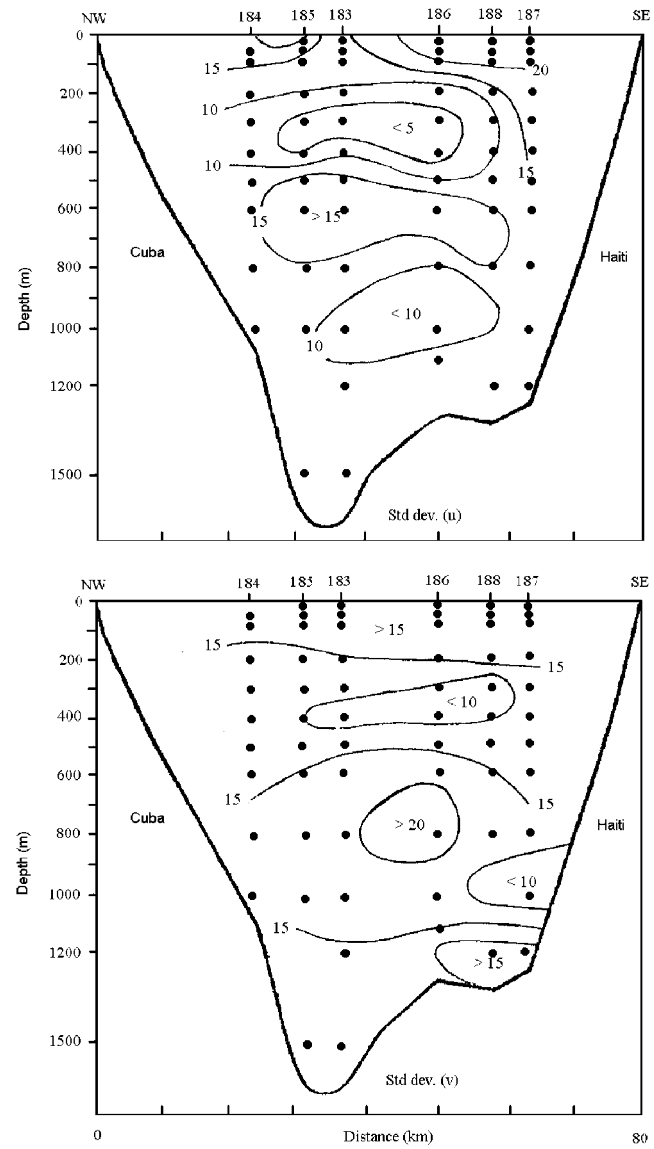

Fig. 6. Standard deviations of eastward (top) and northward (bottom) components of velocity (cm/s) on the northwest-southeast transect based on mooring data collected in Windward Passage during November 19-23, 1970.

peaks at about 12 hours related to the semidiurnal tidal component. These tidal currents are dominant at 600-800 m depth, separating the subsurface maximum inflowing and the deep-water outflowing waters. As seen in Figure 9, the tidal currents have maximum amplitude of about 40 cm/s, exceeding the residual currents' values there. Currents at the depth of the subsurface maximum inflow are less subject to periodic tidal oscillations.

For comparison, previous results by Stalcup and Metcalf (1972) for the Grenada Passage have shown that tidal currents can be as large as the mean deep flow. Mazeika *et al.*

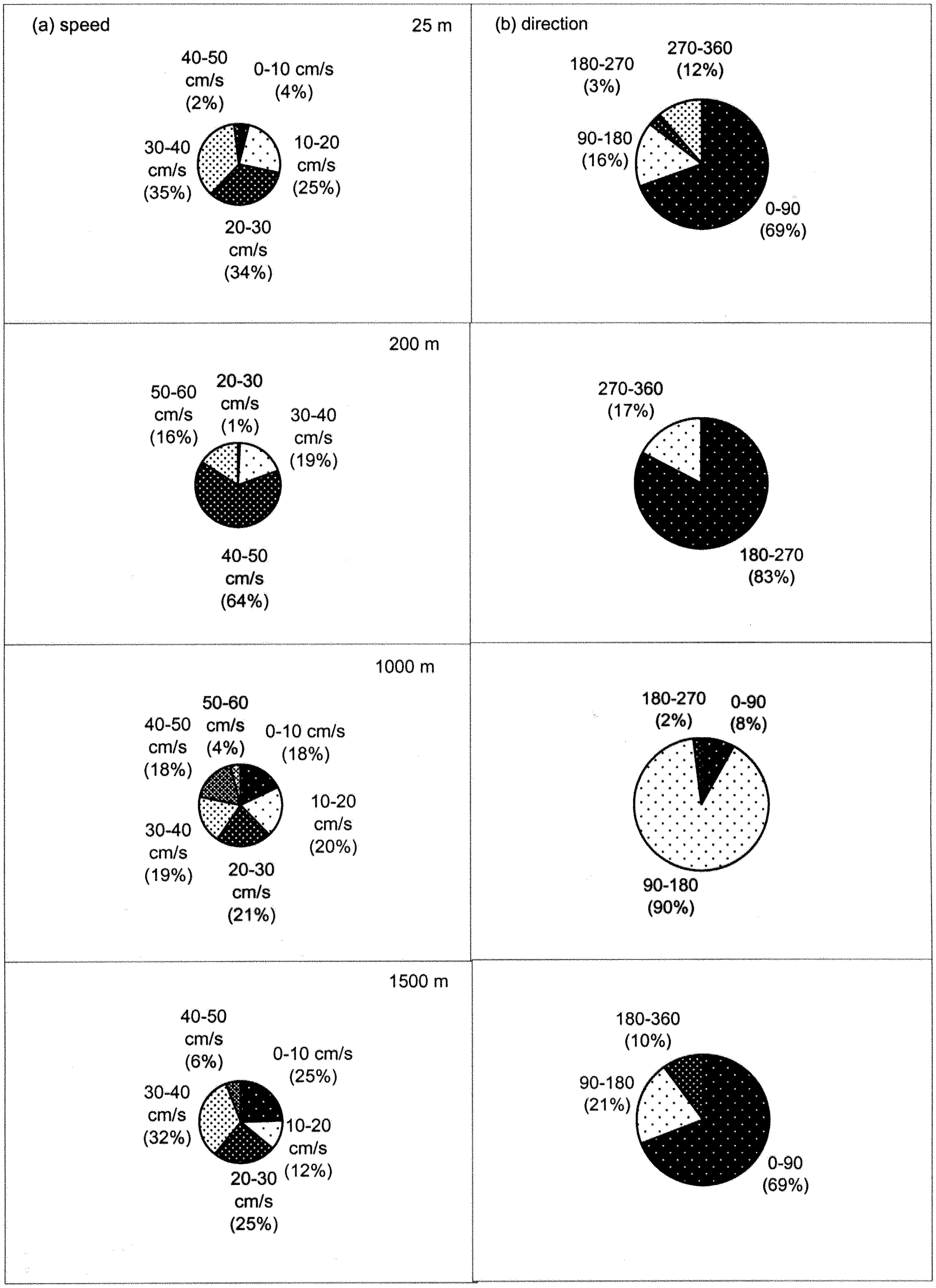

Fig. 7. Diagrams showing (a) the persistence of the speed (left column) and (b) flow direction (right column) given as percentages for velocity records at 25, 200, 1000 and 1500 m of deep-water station 183 during November 19-20, 1970.

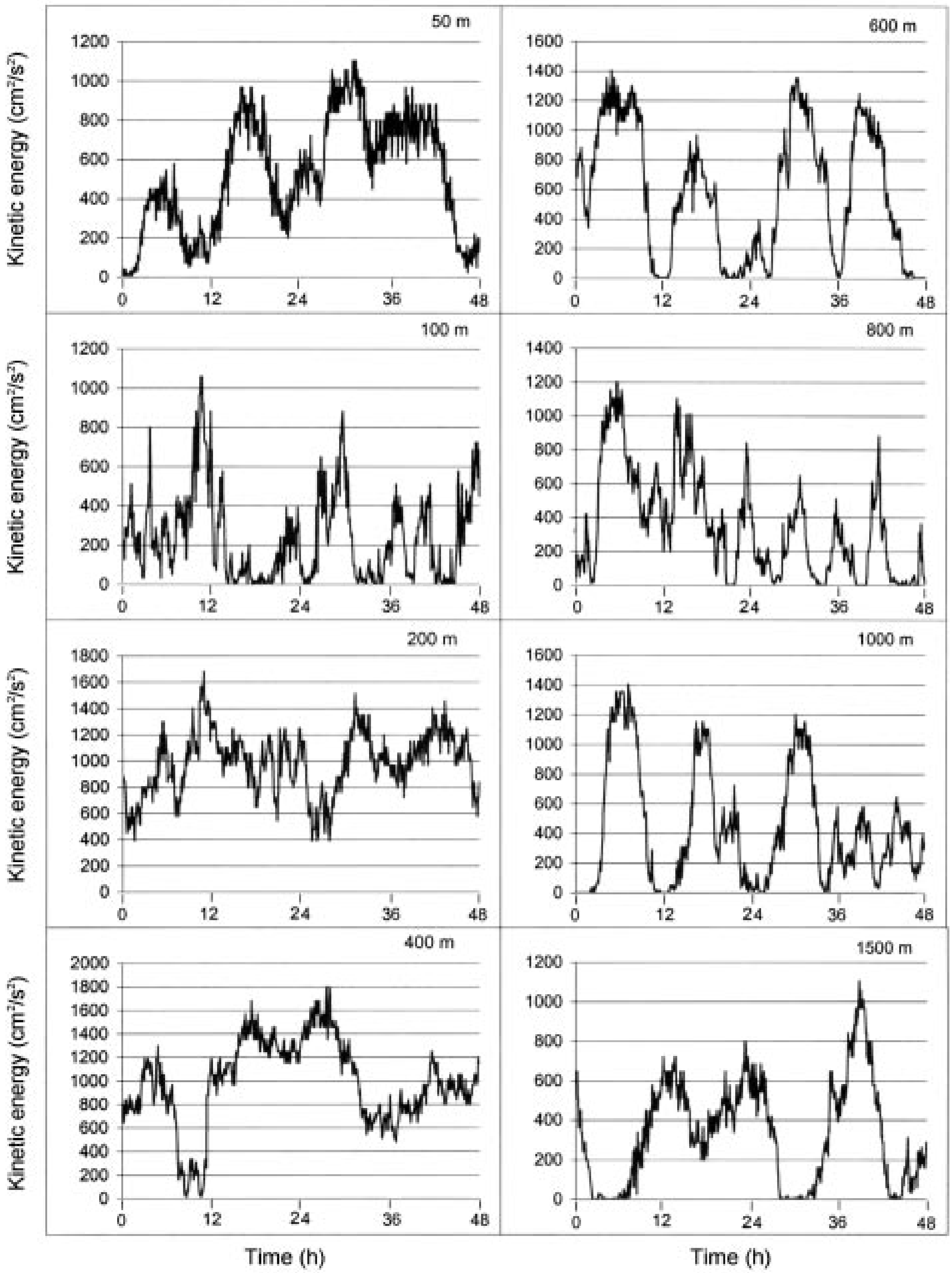

Fig. 8. The 48-hour time series of the kinetic energy (cm^2/s^2) at different levels of deep-water station 183 during November 19-20, 1970.

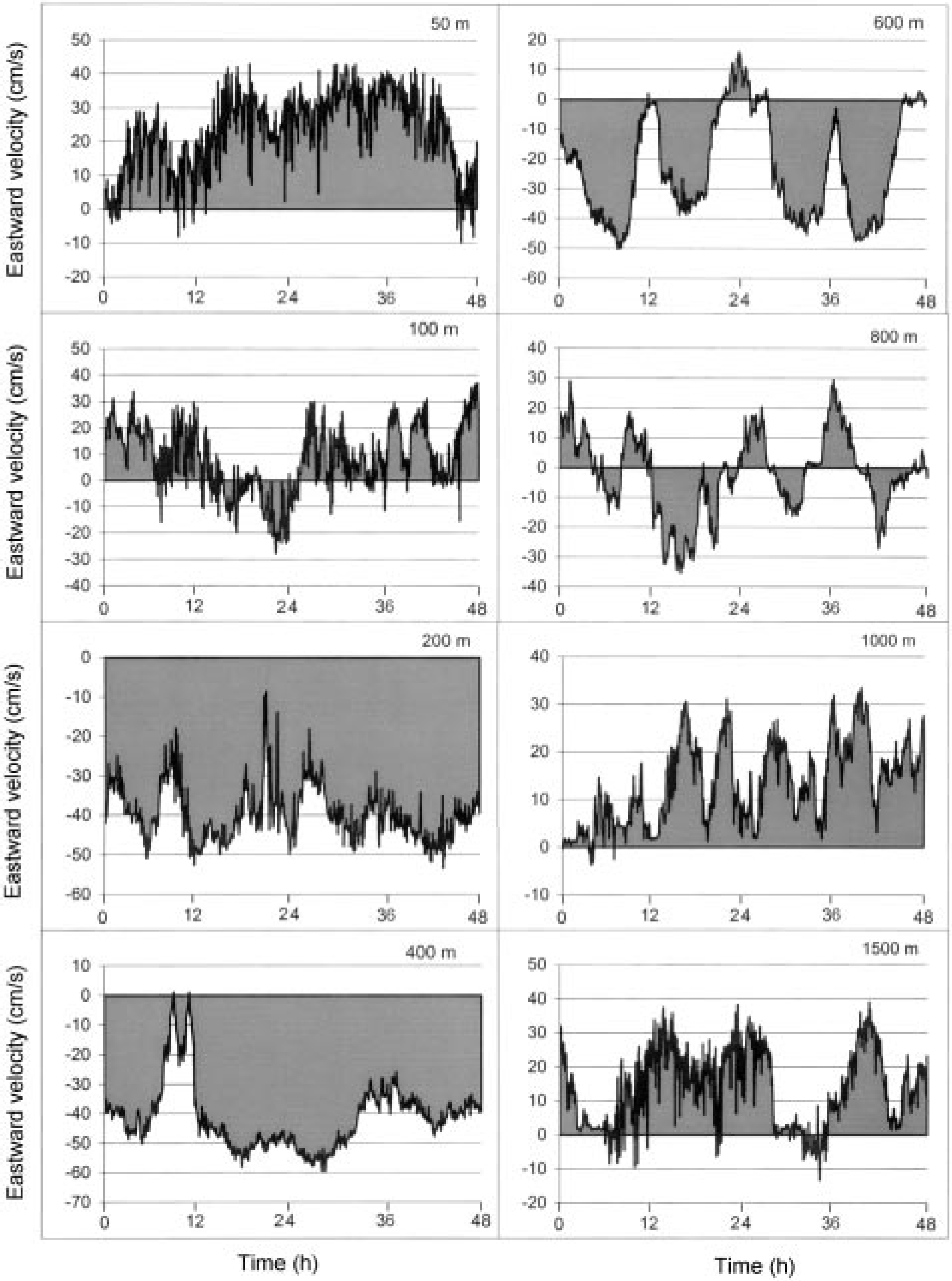

Fig. 9. The 48-hour time series of the eastward component of the velocity vector (cm/s) at different levels of deep-water station 183 during November 19-20, 1970.

Table 2

Hydrological stations, summary

Station	Latitude (N)	Longitude (W)	Date	Depths (m)
1389a	20°24.7’	73°31.0’	19.02.65	0, 10, 25, 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1200, 1500, 2000
1389b	20°10.3’	73°46.6’	19.02.65	0, 10, 25, 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1200
1389c	20°09.9’	73°27.0’	19.02.65	0, 10, 25, 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1200
183	20°11.0’	73°36.0’	19.11.70	0, 25, 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1200
184	20°11.0’	73°46.0’	19.11.70	0, 25, 50, 100, 200, 300, 400, 500, 600, 800
185	20°11.0’	73°40.0’	20.11.70	0, 25, 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1200
186	20°10.0’	73°22.0’	23.11.70	0, 25, 50, 100, 200, 300, 400, 500, 600, 800, 1000
187	20°09.5’	73°11.0’	22.11.70	0, 25, 50, 100, 200, 300, 400, 500, 600, 800
188	20°10.0’	73°16.0’	22.11.70	0, 25, 50, 100, 200, 300, 400, 500, 600, 800

(1983) estimated that semidiurnal tidal currents in the St. Vincent and Grenada Passages are dominant (10-30 cm/s).

The long-term variability of water exchange in the WP is poorly understood, because of the scarcity of direct current meter observations. However, transport estimates based on hydrological data suggest the possibility of the seasonal flow pattern found previously by Gunn and Watts (1982) and by Kinder *et al.* (1985).

A few hydrological stations were observed in 1965 and 1970 in the vicinity of the mooring stations. The temperature and salinity probes were taken utilizing the standard bathometers. The hydrological stations summary is shown in Table 2. From Table 2, three hydrological stations 1389a-1389c were observed around mooring station 1389 in 1965. In 1970 hydrographic observations were done at six hydrological stations (183-188) spanning the WP in quasi-zonal direction. The geostrophic velocities were calculated. Comparison to direct current meter measurements was poor due to the small number of stations and their locations.

Mean T-S curves were plotted for 1965 and 1970 using spline interpolation in the vertical direction (Figure 10a,b). The hydrological structure was similar for both cruises. Three characteristic water masses were observed in February, 1965 and November, 1970. These are: (1) surface warm (>24°C) Caribbean, (2) subsurface salty (>36.5‰) Northern Atlantic, (3) relatively fresh (<35.5‰) and cold (<12°C) deep Caribbean water masses. From the T-S curves and T-S analysis, the vertical levels separating these water masses could be defined at approximately 100 m and 500 m depth. Thus, there is no close correspondence at 100 and 700 m depths separating mid-depth inflow into the Caribbean from surface and deep-water outflow measured at the mooring stations (Figure 4a and 5). A probable reason is that we don’t know the real mean distribution of T-S curves below 1200 m.

SUMMARY AND DISCUSSION

Over the past several decades independent observation programs were conducted by investigators from the USA and the FSU to describe water exchange in the Windward Passage, a major route of Atlantic waters into the Caribbean. The USA studies consisted of evaluations of water transport based on diagnostic computations, water mass analysis, and ADCP current observations in the Great Inagua Passage. The FSU focused on short-term mooring observations with a good spatial coverage in February, 1965 and November, 1970. No comparison of these data sets had previously been performed. Such a comparison is relevant to the characteristic flow patterns and variability of current

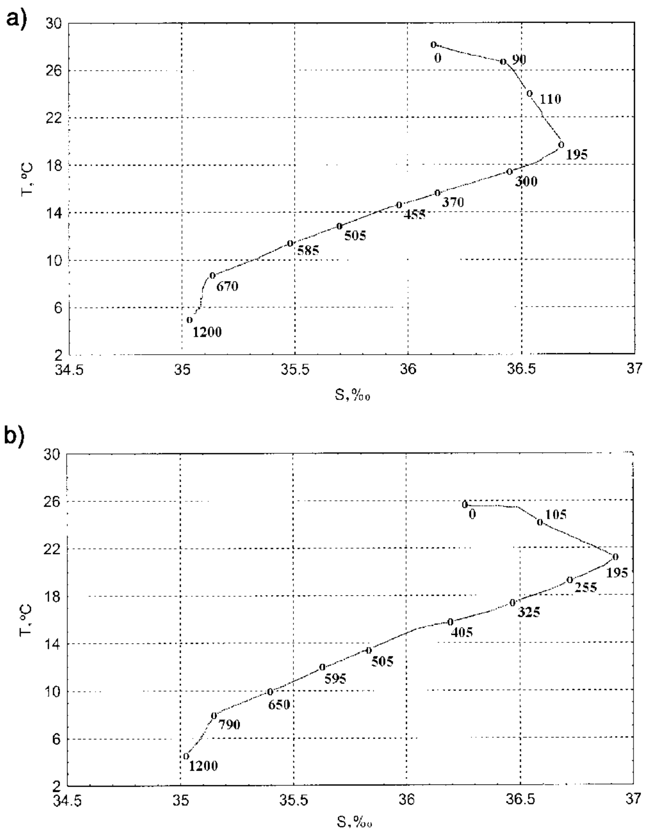

Fig. 10. Mean T-S curves for Windward Passage based on February 19, 1965 (a) and November 19-23, 1970 (b) hydrographic observations.

structure in WP. The main objective of the present study is to review the state of knowledge of the currents in the WP, to reexamine the FSU data, and to compare existing transport estimates. Values of transport through the WP reported by Gordon (1967), Worthington (1976), Sukhovey *et al.* (1980), Roemmich (1981), Gunn and Watts (1982), Nof and Olson (1983), Kinder *et al.* (1985), Schmitz and Richardson (1991), Wilson and Johns (1997), and Johns *et al.* (1999) were found to yield a fairly wide range of 4 to 15 Sv.

We have reexamined the FSU data obtained in November, 1970 and we found 8 ± 4 Sv of inflow into the Caribbean sea. This transport value agrees with Sukhovey *et al.* (1980), Roemmich (1981), Gunn and Watts (1982), and Wilson and Johns (1997). Gunn and Watts (1982) have analyzed hydrographic data obtained in 1972 and 1973. From their geostrophic velocity calculations, transport from the Atlantic into the Caribbean during the fall-winter period was found to be 9 Sv, in good agreement with the 8 Sv transport estimate found by us from the November, 1970 mooring data.

Mooring observations were compared to velocity measurements reported in the other studies. Thus, ADCP current meter observations by Johns *et al.* (1999) in the Great Inagua, Mona, and Anegada passages suggested that the northern straits have a common velocity structure, with subsurface velocity maxima and persistent surface-intensified counterflows along one side of each passage. This was also observed in WP using the FSU mooring observations carried out in 1970.

The shipboard ADCP observations of Johns *et al.* (1999) were limited to 200 m depth, whereas the FSU mooring observations were conducted from the surface to the bottom. The deeper moored data show that the core of the subsurface maximum was located at a depth of 200-400 m. The mooring observations have also shown the presence of a deep outflow (>700 m) in the WP. A similar 3-layer velocity structure was observed during both February, 1965 and November, 1970. In terms of volume transport, 0.8 Sv and 2.0 Sv were found to leave the Caribbean in the upper 100 m and below 700 m, respectively. The water inflow at mid-depths had a magnitude of 10.7 Sv, based on November, 19-23, 1970 mooring data, against a net transport into the Caribbean of approximately 8 Sv.

During a 48-hour period of mooring measurements obtained in November, 1970, the persistence of the subsurface maximum inflow and deep-water outflow was relatively high in spite of strong semi-diurnal tidal oscillations. However, there could be greater variability and stability of currents over longer periods.

One should be skeptical of short-term transport measurements, and the question is whether one can conclude anything meaningful from 1-2 days data records. We consider these short-term mooring observations as a snapshot of the current structure in the WP during November, 1970, as any single shipboard occupation of a passage is unlikely to reproduce the mean. However, each ADCP cross-section in GI passage (Johns *et al.*, 1999) took only a day or two; thus these two types of current meter data are comparable for analysis. Thirdly, the discrepant transport estimates obtained by other investigators using geostrophic calculations should be confirmed from direct velocity observations. As we know, the FSU mooring observations conducted in 1965 and 1970 are merely direct-velocity measurements carried out in WP. Finally, the observations described may be useful as a guide for planning future work.

From these direct observations, it is found that the flow through the WP is significant, and currents in the WP deserve further observations. New direct current meter observations are badly needed as the WP probably has a greater inflow into the Caribbean from the Atlantic than other passages. The use of full-depth ADCP instruments and long-term continuous measurements of currents in WP could be a promising approach.

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