Transports through the Straits of Florida

PETER HAMILTON

Science Applications International Corporation, Raleigh, North Carolina

JIMMY C. LARSEN

Department of Earth and Space Sciences, University of Washington, Seattle, Washington

KEVIN D. LEAMAN AND THOMAS N. LEE

Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida

EVANS WADDELL

Science Applications International Corporation, Raleigh, North Carolina

(Manuscript received 8 October 2003, in final form 4 August 2004)

ABSTRACT

Transports were calculated for four sections of the Florida Current from Key West to Jupiter, Florida, using a moored current-meter array and voltages from cross-channel telephone cables at the western and northern ends of the Straits of Florida. In addition, moored arrays were used to estimate transport through the Northwest Providence, Santaren, and Old Bahama Channels that connect the Florida Current to the southwestern part of the North Atlantic Ocean. Transport measurements were obtained for an 11-month period from December 1990 to November 1991. Mean transports of ~25 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}) for the flow across the western ends of the straits, which agree quite well with recent estimates of 23.8 ± 1 Sv entering the Gulf of Mexico through the Yucatan Channel, were obtained from both the Key West to Havana cable and the moored array. This estimate is about 5 Sv less than the generally accepted transport through the northern end of the straits at 27°N. This difference was partially accounted for by inflows through the side channels with more transport from the Old Bahama than the Northwest Providence Channel. The variability in the southern part of the straits was larger than at 27°N and included large diversions of the Florida Current south of the Cay Sal Bank and into the Santaren Channel that were caused by large meanders of the flow. The variability of transport in the side channels contributed to the variability of the Florida Current and reduces the correlations of the transports at the ends of the straits. Therefore, the well-measured transport at 27°N is not an accurate indicator of the transport of the Loop Current out of the Gulf of Mexico.

1. Introduction

Recent measurements of transport of the Gulf Stream system in the Yucatan Channel obtained a net value, over 10 months, of 23.8 ± 1 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}) from the Caribbean to the Gulf of Mexico (Sheinbaum et al. 2002). The only exit for this inflow is the Straits of Florida, and transport out of the Gulf, between Key West and Havana, is expected to closely match the net transport into the Gulf through the Yucatan, from continuity. Bunge et al. (2002) indicate that volume storage in the Gulf, at time scales of order a few days, is very small and the throughflow transports balance within about 1%. The Subtropical Atlantic Climate Studies (STACS) program, in the northern part of the straits, made measurements of the Florida Current transport at 27°N (Schott et al. 1988), and a net value of 30.5 ± 1 Sv (April 1982–June 1984) was found. Standard deviations of both the Yucatan and STACS measurements were a similar ~2 Sv. Thus, there is an apparent 4–5-Sv discrepancy between net transports out of the Gulf and out of the northern end of the Straits of Florida. Atkinson et al. (1995), using current data from the same measurement program reported below, found an estimated 3 Sv flowing into the Straits of Florida system through the narrow Old Bahama Channel (Fig. 1), which partially accounts for the increased transport at 27°N over the Yucatan Channel. Flows into and out of the Florida Current from the Northwest Providence

Corresponding author address: Peter Hamilton, Science Applications International Corporation, 615 Oberlin Road, Suite 100, Raleigh, NC 27605.
E-mail: phamilton@raleigh.saic.com

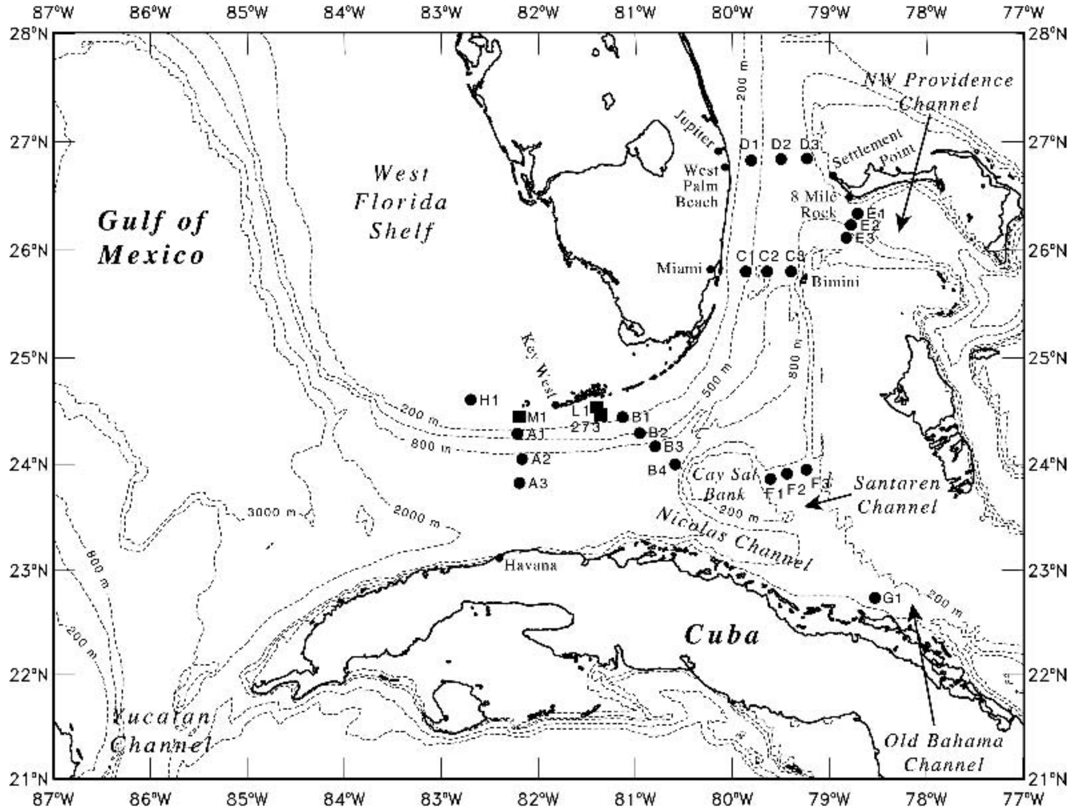

FIG. 1. Map of mooring positions for the Straits of Florida study (dots) and SEFCAR (squares).

and Old Bahama channels are possible pathways where a portion of the North Atlantic Subtropical Gyre western boundary circulation bypasses the Caribbean Sea. Schmitz and McCartney (1993) show this type of inflow in their cartoons of the general upper-layer circulation of the North Atlantic.

The Yucatan and 27°N transport measurements are separated by more than a decade. However, a large program of current measurements was carried out between November 1990 and November 1991 that deployed moorings, simultaneously, across a number of sections in the Straits of Florida and its subsidiary channels (SAIC 1992b). The number of moorings and instruments in each section was not as comprehensive as the Yucatan and STACS studies, but the experimental design was based on STACS results on the number of moorings required to make reasonable transport estimates. This data allows closer examination of how transports are distributed in the channels of the Straits of Florida as well as the effects of variability of the transport contributions to the outflow of the Florida Current into the South Atlantic Bight.

Between the Yucatan Channel and the western end of the Straits of Florida, the flow is known as the Loop Current (LC), which extends northward, at irregular intervals of between about 6 and 15 months, into the eastern Gulf of Mexico and sheds large anticyclonic eddies (Vukovich et al. 1979; Sturges and Leben 2000). The sill depths in the Yucatan Channel and Straits of Florida are 2040 and 800 m, respectively. The majority of the flow in the LC is above ~1000 m. Bunge et al. (2002) have shown that changes in the upper-layer inflow of the LC are correlated with the LC extensions and retractions (i.e., changes in the volume of the LC), and because the total transports into and out of the Gulf balance to within about 1%, the changes in the upper-layer inflows are compensated by changes in the lower-layer outflow in the Yucatan Channel. Bunge et al. (2002) used the 6°C isotherm, which is at about 730-m depth in the straits, to divide the upper- and lower-layer flows. Therefore, the time variability of the upper-layer inflow of the LC will not be the same as the inflow into the western end of the Straits of Florida, even though the total transports will be balanced.

The LC also has boundary features that propagate clockwise around an extended LC front (Vukovich 1986). These frontal cyclonic eddies often stall off the southwest corner of the west Florida shelf near the Dry Tortugas (Paluszkiewicz et al. 1983; Fratantoni et al. 1998). Periodically, these cyclonic frontal eddies move into the straits and translate eastward along the Keys (Lee et al. 1995). These eddies can produce large southward displacements or meanders of the eastward flowing Florida Current. There were a number of these episodes in the current observations in the western straits and in at least one case the flow of the Florida Current was partially diverted south of the Cay Sal Bank and into the Nicholas and Santaren Channels (Fig. 1). Thus, the variability of the flows and transports in the western straits can be quite complex in comparison with that in the northern straits (Schott et al. 1988; Lee et al. 1995).

2. Observations

a. Current meters

The Straits of Florida study deployed 21 moorings on six sections (A: Key West to Havana, B: Cay Sal Bank, C: Miami to Bimini, D: Jupiter to Settlement Point (27°N), E: Northwest Providence Channel, F: Santaren Channel, and G: Old Bahama Channel) between November 1990 and November 1991 (Fig. 1). Instruments are labeled by section, mooring number within the section, and depth level on the mooring, with numbers increasing down from the surface. Thus, instrument B32 refers to the second current meter from the surface (300-m depth level) on mooring B3 in the Cay Sal Bank section B. A 150-kHz acoustic Doppler current profiler (ADCP) was used for the first deployment of B31 (293 m). However, it failed on the second deployment and was replaced by a current meter (B30) at 145 m for the third and fourth deployments. The ADCP was subsequently redeployed, for the last 3 months, at the 288-m level on B4 and was known as B40. Moorings were rotated quarterly. Moorings A2 and A3 were not deployed until February 1991. A number of moorings were also deployed on the shelf, south of the Keys by the South and East Florida Caribbean Recruitment (SEFCAR) study (Lee et al. 1992). Moorings M, L, and 273 were in place for a portion of the deployments of sections A and B. Mooring 273 was an upward-looking ADCP mounted near the bottom. Apart from the two ADCPs, Aanderaa RCM current meters were used below 500 m in the channels and on the shelf, and General Oceanics, Niskin Winged Current Meters (NWCM) were used on the upper levels. The latter measurements are not affected by mooring tilt caused by the high-speed upper layers of the Florida Current. All instruments at the top of the channel moorings measured pressure so that mooring drawdown, and thus instrument depths, could be estimated. The distribution of the current meters across the sections is shown in Fig. 2. If section D is compared with the STACS array at 27°N (Schott et al. 1988), it can be seen that it corresponds to the reduced STACS-V, three-mooring configuration, which correlated with the transport from the full array at about 0.82 with an increase in the error to about ±2 Sv.

The time series (current velocity, temperature, and pressure) from the four deployments were concatenated where appropriate, and short gaps filled by linear interpolation. Data return from the current meters was about 90%. The clean records were filtered with a 3- and 40-h low-pass (HLP) Lanzcos kernel with the latter decimated to 6-h intervals. The component axes of the velocity records were rotated so that the V components were perpendicular to the section. Section B is not quite perpendicular to the trend of the deepest isobaths. Based on the direction of the isobaths and a principal axis analysis of the 40-HLP current records, a direction of 60°T (true) was used for the rotation of the V-component axis for this section. Transport calculations were projected on a section normal to this direction as in Leaman et al. (1995), with positive being in the direction of Florida Current flow (i.e., east at A and north at D), or directed into the Florida Current for the subsidiary channels (i.e., west at E and north at F). The rotation is denoted by the addition of "Rθ" to the instrument ID, where θ is the direction of the V-component axis clockwise from true north. Details of the instrumentation, data return, and data processing are given in SAIC (1992a).

b. Cable measurements

The STACS program devoted considerable resources to calibrating the inactive telephone cable, between Jupiter, Florida, and Settlement Point, Grand Bahama Island, for transport. The theory of using cross-stream potential differences to measure transport across a seafloor cable is given by Larsen (1992). Calibrated cable-derived transports for 27°N had a correlation of 0.97 with profiling data (Larsen and Sandford 1985) with a root-mean-square discrepancy of 0.7 Sv. Unfortunately, the Jupiter–Settlement Point cable ceased functioning on 30 November 1990, just after the moorings were deployed. Consequently, the voltage-derived transports for section D were based on the voltage from the in-service cable between West Palm Beach and Eight Mile Rock (WPB-8MR) on Grand Bahama Island (Fig. 1). These voltages were calibrated by comparison with the Jupiter–Settlement Point voltage when both systems were working. Larsen (1992) discusses in detail these comparisons as well as the problems in using active cables. He found that the correlation (R^2) between the two transport estimates was 0.6 and the rms misfit was 1.9 Sv. Since 1988, daily averaged transport values at the two cables differed by less than 5 Sv, which is comparable to transport errors from the three-mooring array across section D used in this study and in the STACS reduced array studies (Schott et al. 1988).

An inactive cable between Key West and Havana was available for transport estimates. This cable was terminated in shallow water, a few miles offshore of Havana, and therefore, was similarly configured to the Jupiter–Settlement Point cable. An initial calibration factor of 26 Sv V^{-1}, based on experience with the Jupiter–Settlement Point cable, was used to derive transports. Based on model studies, the calibration factor could lie between 22.9 and 34.5 Sv V^{-1}. Comparison of cable-based transport estimates with those calculated

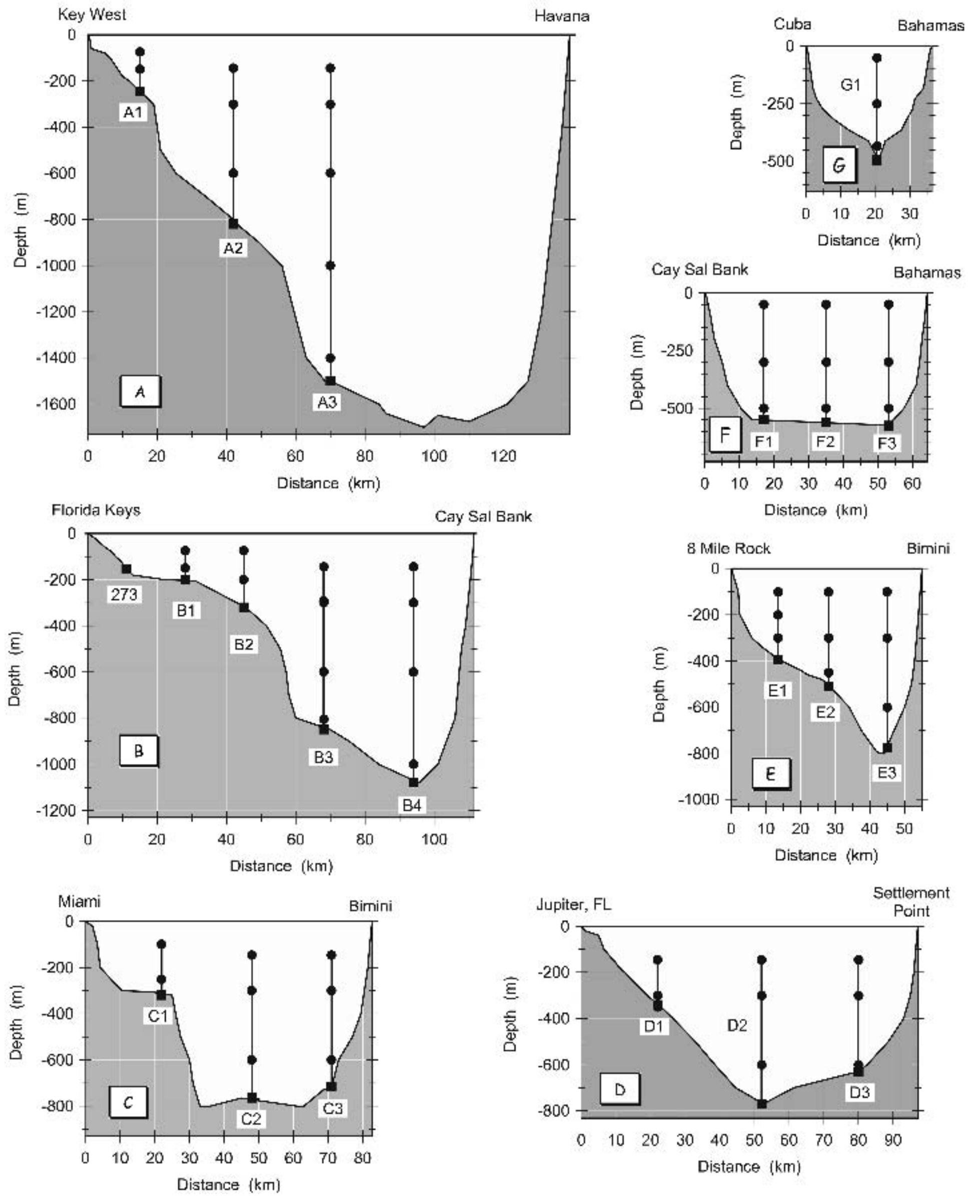

FIG. 2. Channel cross sections (see Fig. 1) showing the moorings and distribution of instruments.

from current meters, which includes setting a base level for the cable, are discussed below.

c. Profiling measurements

As part of the measurement program for this study, Pegasus profiling was performed on four, quarterly cruises for the Santaren Channel (section F), Northwest Providence Channel (section E), and the Cay Sal Bank Section (B). Leaman et al. (1995) discuss the results and gave the transports for each section. Each section was profiled over 2 days so as to minimize aliasing by the tides. In addition, nine dropsonde profiling cruises were conducted by the National Oceanic and Atmospheric Administration (NOAA)–Atlantic Oceanographic and Meteorological Laboratory (AOML; M. Bushnell 1991, personal communication) in October and November 1991 for section D (27°N). The dropsonde cruises took about 7 h to transit across the section, and thus there are biases in the transport estimates of 1–2 Sv caused by tidal flows (Mayer et al. 1984). These data will be used to estimate the accuracy of current-meter-derived transports.

3. Transport estimates

The subtidal volume transports for each section were calculated based on a general method developed for the

STACS program (Lee et al. 1985; Schott et al. 1988). Apart from using splines under tension for horizontal and vertical interpolations, the method used here is very similar to method C of Lee et al. (1985). The 40-HLP records of the along-channel velocity component and depth of the instrument were obtained for all the current meters in a section. On most moorings, the near-surface current meter on each string recorded pressure. However, on some deployments, the pressure sensor gauges may not have functioned properly or instruments without pressure sensors were used. The missing pressure records were synthesized for the near-surface instruments by using a linear regression of pressure against the square of the current speed. For the overlapping part of the records, the synthetic pressure correlated with measured record with $R^2 > 0.9$. Figure 3 shows the synthetic and measured pressure record for the 145-m instrument on D1. The depression of an in-

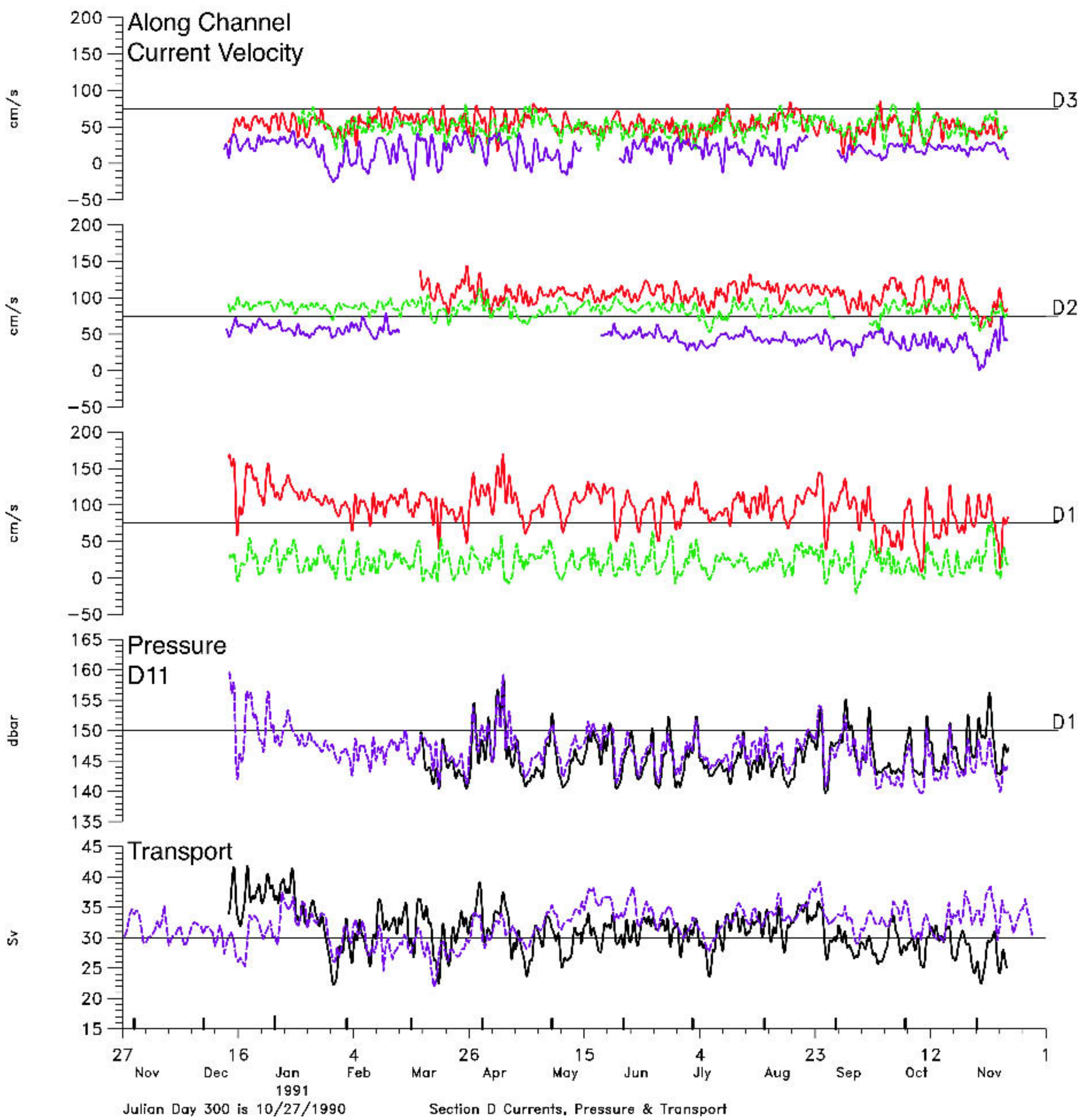

FIG. 3. Top three panels show along-channel 40-HLP velocities at the indicated moorings on section D. Nominal depths are 145 (red), 300 (green dashed), and 600 m (purple). Depth of the 145-m instrument on D1 as measured (solid black) and estimated (purple dashed), and the calculated (solid black) and cable-derived transports (purple dashed) are on the bottom two panels, respectively.

strument from its nominal depth was found by scaling the top meter's drawdown, derived from the instrument's pressure, by d_i/d_m, where d_i and d_m are the heights of a middepth and the near surface instrument above the bottom, respectively, with the mooring slack. Below 300 m, the depth variations of the instruments caused by mooring tilt were less than 5 m and were neglected. The design or nominal depth was used in these cases.

Once pressure records had been constructed for each instrument, the along-channel velocity (V) profiles were interpolated through the water column for each mooring using splines under tension with a moderately strong tension factor. The bottom boundary condition was assumed to be $V = 0$ and the surface velocity estimated by extrapolation to the surface using the subsurface values. Where the near-surface current meter was deeper than 145 m, an additional constraint, $\partial V/\partial z = 0$, was assumed at the surface in order to give more realistic surface current values. The interpolated profiles were resampled at 10-m intervals, and for each 10-m level the cross-sectional profile was horizontally interpolated using splines under tension at 5-km intervals (3 km for sections E and G) assuming that $V = 0$ at the sides of the channel. For consistency, the introduction of $V = 0$ points at the sides of the channel for the horizontal spline interpolation also applies to the Old Bahama Channel (G; see Fig. 2). The resulting two-dimensional grid of velocity values was summed to generate the transport. The 10 m $\times$ 5 km area of the grid cell was adjusted, if the cross section was not quite normal, to the along-channel flow direction (e.g., section B) by projecting onto the normal direction. Generally a minimum of two current-meter velocity values on each string were required for vertical interpolation, and except for G, three vertical profiles were required for horizontal interpolation, to produce a transport value at a given time. If these criteria were not met, then a flag value was written to the time series. Figure 3 shows the calculated transport and individual 40-HLP along-channel velocity component records for section D (27°N). The velocity records are fairly typical of the Florida Current sections in that the strongest current shears are found on the left-hand side (looking in the direction of the current). On the right-hand side, there is often a subsurface maximum where the 300 m exceed slightly the 145-m level flows.

4. Transport comparisons

Figure 3 shows that the transport estimated from current meters and the WPB-8MR cable differ at times. This active cable is known to be less accurate than the well-calibrated Jupiter–Settlement Point cable used in STACS (Larsen 1992). Therefore, the cable measurements are not necessarily a good measure of the accuracy of the current-meter-derived transports. Accurate transports were obtained by Pegasus profiling for sections B, F, and E during four cruises (Leaman et al. 1995). Each section was traversed several times over about 2 days and the sum of transports B + F + E are an estimate of the transport at D, even though there is an uncertainty in the timing because the individual transport estimates were separated by 0.5–1 days. Section E, during the 28 May–2 June 1991 cruise, was not measured, and the mean of the other three cruises was substituted for E in estimating transport for section D (Leaman et al. 1995). This is reasonable because transports through E were relatively small with low variability compared to those through B and F. The comparisons of the Pegasus estimates with the time series of transports for the four sections are given in Fig. 4.

Within the uncertainties of the timing, the time series estimates agree well with the Pegasus data, even for the Cay Sal Bank and Santaren Channel sections, which had large-amplitude fluctuations. At 27°N, the agreement is good for the current-meter derived transports, and good for the first two cruises with the cable transports. Estimates from the last two cruises differ from the cable by 5–7 Sv. The dropsonde sections in October and November 1991, at 27°N, were aliased by tidal transports of 1–2 Sv (Mayer et al. 1984). However, the nine measurements are in reasonable agreement with the current meter derived transports, particularly with the decrease at the beginning of November, which is not shown by the cable. This is reflected in the statistics of the comparisons (Table 1) with the cable showing higher mean transport and lower correlation than the dropsonde data. Therefore, the current-meter transports show reasonable agreement with independent estimates and the errors are estimated at about 10% of the maximum transports observed in each of the sections.

5. Results

The transports, over an 11-month interval, from current and cable measurements for all the sections, are given in Fig. 5. Immediately apparent is the difference in character between the fluctuations in the southern part of the study area and the northern part. Variability through sections C, D, and E was mostly at shorter periods (<10 days) whereas longer-period fluctuations occurred on A, B, F, and G. Section B had at least three abrupt decreases to less than 15 Sv, which had corresponding (or approximately compensating) increases at section F but little effect on section C, implying that part of the transport is periodically diverted south of Cay Sal Bank and into the Santaren Channel.

Lee et al. (1995) analyzed the first of these events at the end of March 1991. They showed, with aid of satellite imagery, that reduction of flow through B was related to the slow eastward propagation of a large meander trough from the region of the Dry Tortugas (i.e.,

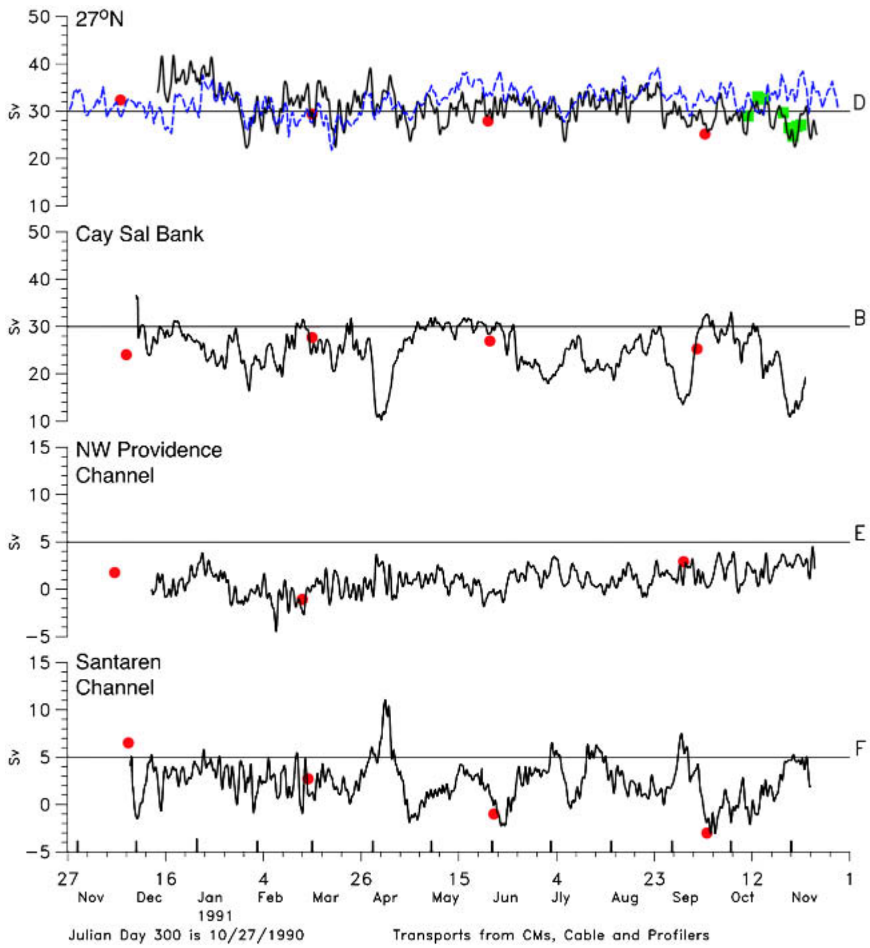

FIG. 4. Transports from current velocities (black) for the indicated sections. Red dots are transport estimates from Pegasus profiler sections. For section D, the red dots are the sums of the profiler measurements for channels B + F + E. Green squares are transports from NOAA–AOML dropsonde sections at 27°N, and the blue dashed line is the transport from the West Palm Beach to Eight Mile Rock cable.

the "Tortugas Gyre"). The southward movement of the Florida Current core at B, as the gyre moved into the northern part of the section, has now been shown to produce a clear reduction in transport, which was not, however, observed in the northern part of the straits. Therefore, the Florida Current transport must have been partially diverted south of the Cay Sal Bank and into the Santaren Channel to rejoin the main current at C. There is little evidence in the time series (Fig. 5) that these "diversion events" cause corresponding increases or decreases in flow through the Old Bahama Channel (G). Neither is there any evidence of a foreshadowing of the abrupt decreases at Section B by increases or decreases in transport south of Key West. This is not unexpected because meander motions of the Florida Current do not cause corresponding fluctuations in transport through the entire channel width (Johns and Schott 1987).

The differences between the transport fluctuations at A and D have already been noted. This implies that transport in the Straits of Florida cannot be considered to be uniform with flow out of the Gulf of Mexico corresponding to flows at 27°N. There were substantial contributions from the Old Bahama and Northwest Providence Channels. It also implies that cable measurements for the Jupiter–Settlement Point section are not a good substitute for the outflow of the Loop Current from the Gulf of Mexico. Thus, contributions from the subsidiary channels (G and E) were sufficient to

TABLE 1. Comparison of 1991 transport measurements for section D on 10, 15, 18, 28, and 31 Oct and 2, 4, and 6 Nov 1991.

	Transports (Sv)		
	Profile	Current meter	Cable
Mean	28.70	27.82	33.91
Std dev	2.97	3.06	2.58
R^2 with profile cruises	—	0.69	0.33

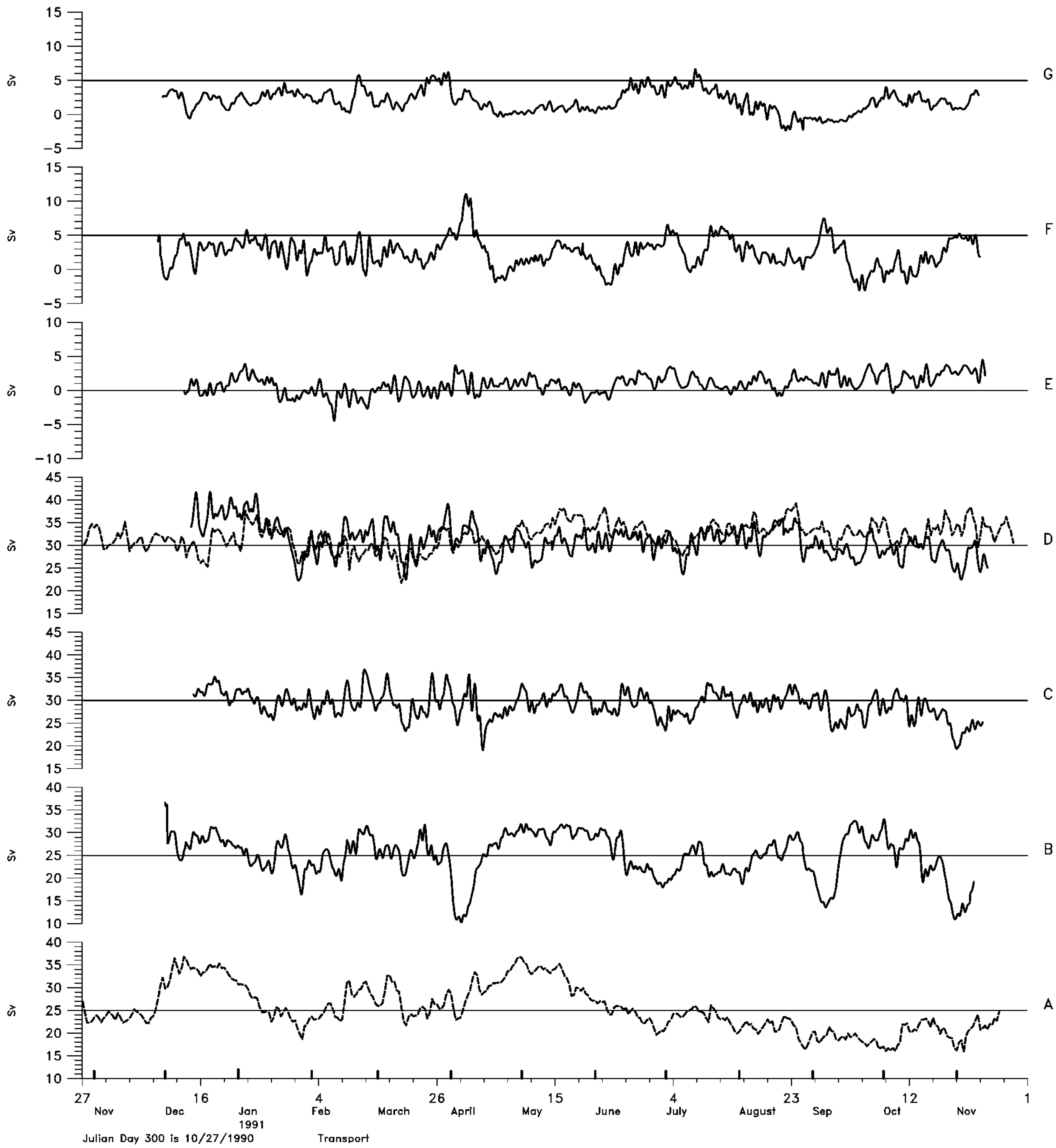

FIG. 5. Transports calculated from current-meter records (solid) and derived from cable measurements (dashed) for the indicated sections in the Straits of Florida.

cancel out much of the monthly variability of the transport through A that was not observed at C and D. This is illustrated in Fig. 6 where monthly mean transports are shown for the three sections (A, C, and D) that span the Florida Current. The means are calculated for 30 days centered on the first of the month because this allows 11 estimates over the period of the current-meter deployments. Monthly transports for C and D track each other fairly closely with C being less than D, which reflects average inflow from the Northwest Providence Channel. The monthly signal at A is quite different with decreasing transports in the summer. Transports at A were less than at D, except for May 1991. The discrepancies between A and C can only be made up by transports through G that had a different low-frequency variation.

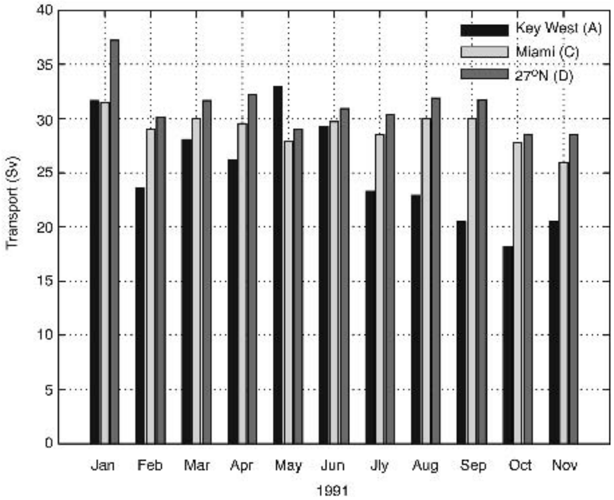

FIG. 6. Monthly mean transports (centered on the first of the month) for sections A (Key West–Havana cable), C (Miami–Bimini), and D (Jupiter–Settlement Point current meters) of the Florida Current.

Monthly variability (rms ≈ 3–4 Sv) of the transport at 27°N (D) has been attributed to a combination of along-channel (north–south) wind forcing (Lee and Williams 1988) and remote wind forcing in the Northwest Atlantic (Schott et al. 1988; Anderson and Corry 1985). The affect of along-channel wind forcing on transport in the southern Straits of Florida is not known, but if it were important, it would be different just because of the east–west direction of the channel. Remote forcing is also different because the transport through the Caribbean is supplied both from the western subtropical Atlantic and the South Atlantic via the North Brazil Current (Schott et al. 1993; Johns et al. 1998). Therefore, transports through A would not be expected to show the same monthly variability as at 27°N.

A measure of the realism of the current meter-derived transports can be assessed by continuity checks. There were not sufficient sea level measurements to determine accurately the rates of change of volume caused by the average rise and fall of sea level integrated over the surface area of the straits. In comparison with errors in estimation of Florida Current transports of ≈ 3 Sv, neglect of the sea level term in the continuity computation is justified if unavoidable. Larger errors are expected from the calculation of transport differences. The following sum and difference transports were calculated:

$$A = B + F - G, F = C - B, \quad \text{and} \quad E = D - C.$$

These sum and difference transports are compared with their corresponding section transports in Fig. 7. The correspondence of (B + F − G) to the cable-derived transport for section A is remarkably good except for deviations around the beginning of April and in September. (The base level of the cable was taken so that the means were in near agreement.) These events are attributed to large decreases of transport at B, which are not being entirely compensated by corresponding increases at F. Since currents at F often show a bimodal (Leaman et al. 1995), cross-channel structure, it is possible that the transport is less well resolved than for the unidirectional flows in the Florida Current. This is equivalent to resolving one against a half cycle of a sine wave with three points. The latter will integrate to a more accurate result. A comparison of (B + F) with A is very similar to the complete simulation showing that fluctuations in Old Bahama Channel transports (G) have only a minor influence on the continuity calculation of transport through A.

Accessing the accuracy of the cable transports for A is difficult because of the uncertainties in the component transports (B, F, and G) used for the comparison. If it is assumed that transports through the channel balance on a daily time scale, then examining the mismatches of inflows and outflows through interior sections would be a measure of the realism of cable derived transports. Two continuity checks were calculated:

$$B + F - G - A \quad \text{and} \quad C - G - A,$$

where A transports are from the cable. If B + F = C, then the two checks would be identical; however, even though B and F are anticorrelated, their fluctuations do not precisely cancel. Even small deviations of the checks from 0, imply large changes in sea level. For example, a 1-Sv difference between the inflows at A and G over the outflows at C is equivalent to a 1-m change in sea level over ~18 h.

The time series of the two continuity checks are given in Fig. 7. Both series are similar with rms deviations of 4.7 and 5 Sv, using B and C, respectively. Apart from the two large diversion events in April and September 1991, the two series have very similar long period variability. This could be the result of the cable voltages changing because of long-term shifts in the position and/or direction of flow across the wide Key West to Havana section of the straits. These results suggest that the errors associated with the inactive cable at A are closer to the ~5 Sv of the active cable at D rather than the ~3 Sv of the current meter derived Florida Current transports. Until transports can be directly measured across section A, cable derived transports there should be used with caution, and details of some of the transport fluctuations through A, B, and F may be suspect.

The difference of two large Florida Current transports, (C − B) and (D − C) with their respective subsidiary channel directly estimated transports on sections F and E, (Fig. 7) tends to overestimate the magnitude of the fluctuations but, in general, the direction is reproduced. The difference calculation at F is better than for E, because of the larger signal at F. The volume transports through E (≈3 Sv) were within the

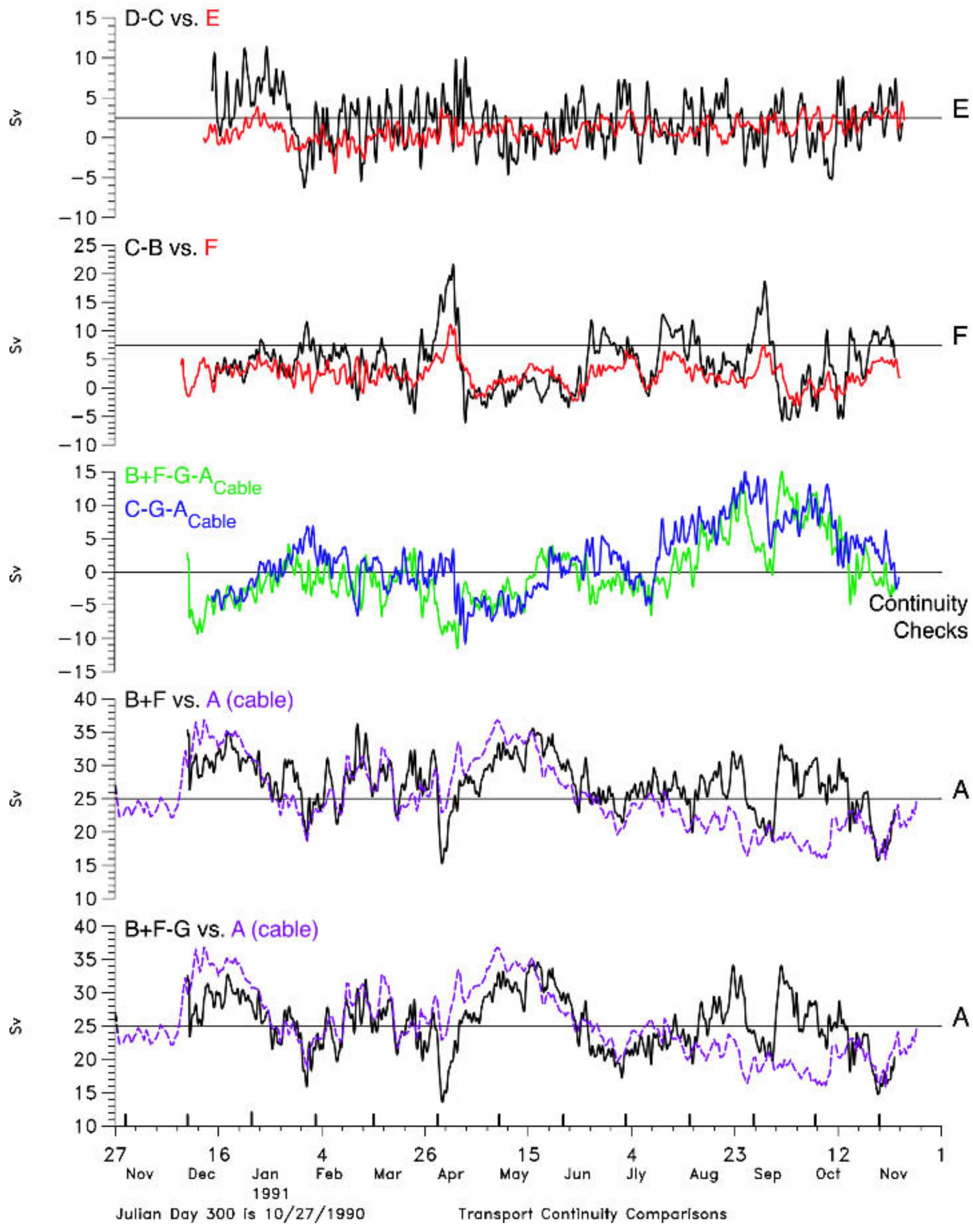

FIG. 7. Comparisons of transports for the indicated sections estimated by sum and difference (solid black), cable (dashed purple), and directly from current meters in the section (solid red). Here B + F − G is the estimate of transport across A using continuity. Continuity mismatches between the transports for the cable (A) and sections B + F (green) and C (blue) are given in the center panel.

noise levels of the calculated transports through C and D. Therefore, a good reproduction of E (from the difference calculation, D − C) is not to be expected.

The statistics of the current-meter-derived and cable-derived transports are given in Table 2. The 11-month means for the Florida Current show a general increase from 25 to 31 Sv from Key West to Jupiter. The standard deviations, however, show the opposite trend, decreasing from about 5–3 Sv. Subsidiary transports from Old Bahama and Northwest Providence Channels accounted for one-half of this increase in the means by contributing 2 and 1 Sv, respectively. Therefore, the mean transports balanced to within 3 Sv, which is the approximate margin of error in estimating the Florida Current transport through B, C, or D. The agreement of the statistics between the cable at 82°W (A) and the continuity-derived transport, (B + F − G), is remarkably close and thus is the basis of not adjusting the base calibration of 26 Sv V^{-1}, which was the initial (and independent) best guess. The statistics for the current-

TABLE 2. Transport statistics (13 Dec 1990–18 Nov 1991).

Section	Mean	Std dev	Min	Max
A (cable)	25.2	5.16	15.9	36.8
G	1.9	1.67	−2.4	6.6
B + F – G	25.3	4.27	13.6	34.5
B	24.8	4.87	10.3	33.0
F	2.4	2.14	−3.1	11.1
B + F	27.3	3.93	15.3	36.2
C	29.1	2.88	19.1	36.8
C – B	4.2	4.73	−6.1	21.6
E	0.9	1.33	−4.5	3.9
D – C	2.0	3.10	−6.3	11.4
D	31.1	3.49	22.3	41.8
D (cable)	32.2	2.90	21.8	39.2

meter and cable-derived transports for 27°N (D) agree similarly with means differing by ≈ 1 Sv.

Perhaps the most interesting aspect of these transport calculations is the importance of the Old Bahama Channel (G). Examination of the current-meter records shows that flows at the lower two instruments, nominally at 250- and 435-m depths, were always toward the straits. Flow at the 50-m instrument occasionally reversed toward the Caribbean. High currents were measured at all depths with an extreme speed of 200 cm s^{-1} occurring at the middepth instrument. The mooring was often drawn down by more than 150 m, which indicated that larger flows, in the upper layer, might have been missed by the current meters. Because of these "draw downs," estimating the velocity profile was error prone at times for the upper-water column and thus, despite the narrow channel, the transport estimates may not be capturing the larger volume flows. However, the transport estimates show that volume transport was toward the Florida Straits about 95% of the time with extremes greater than 6 Sv. The strongest inflow occurred at the depths of the salinity maximum (100–300 m), which indicates that the Old Bahama Channel may be an important source of highly saline Atlantic subtropical underwater for the east side of the Florida Current. Maximum salinities at 200-m depth from the hydrographic cruises often reached 37 (Atkinson et al. 1995).

The mean total transport across B + F, C, and D shows the largest discrepancy of ~2 Sv in continuity between B + F and C. Means for C + E and D agree, and D is consistent with annual means from the detailed measurements of STACS. This implies that B and/or F means are underestimated; B was the most extensively instrumented section and thus is less likely to be in error, though transport over the shelf, offshore of the Florida Keys, may have been missed or underestimated. Increasing the mean transport at F by 1–2 Sv has no effect on the derived transport through A as long as the increase results from a similar increase through G. This would be consistent with the estimated mean of 25.3 Sv through A being similar to the 10-month Yucatan Channel estimate of 23.8 Sv by Sheinbaum et al. (2002). Therefore, the mean transport through G and F appears to be underestimated by 1–2 Sv, which might be a result of under sampling of the surface layer in the former and cross-channel variability in the latter.

The correlation coefficients given in Table 3 confirm the comparisons discussed qualitatively above. Transport fluctuations between B and F, and C and E are inversely correlated. The correlations of transports for B + F − G, derived from continuity versus A, derived from the cable B + F versus C and C versus D, show that the fluctuations at F were dominated by the diversions around Cay Sal Bank, which swamp the contributions from Old Bahama Channel (G). The inverse correlation of C and E shows that pulses from C may force Northwest Providence Channel transports and the cyclonic gyre in the entrance that is often observed in SST imagery (SAIC 1992b; Lee et al. 1995, plate 1), and corresponds to westward and eastward flows on the north and south side of the channel, respectively, sometimes found in current measurements (Richardson and Finlen 1967). The correlation of the two measurements for section D is disappointing and results from the poor long-period correspondence of the fluctuations that is a combination of using the active cable and varying number of good current-meter records in each of the four deployments. The correlation between A and D is about 0.4 using the cable or current-meter-derived transports at A and the current meters at D. This indicates that the outflow of the Florida Current into the South Atlantic Bight is not an accurate measure of the outflow of the Loop Current into the southern straits.

6. Modes of transport fluctuations

The connections between the transport fluctuations in the straits and its subsidiary channels were examined by calculating the EOF modes. The input time series were the transports calculated from the current meters

TABLE 3. Correlations (R).

B vs C	0.34
B + F vs C	0.48
B vs F	−0.62
G vs F	0.21*
C vs F	0.10*
C – B vs F	0.70
C vs D	0.55
C vs E	−0.31
E vs D	0.00*
D – C vs E	0.28
B + F – G vs A (cable)	0.52
B + F vs A (cable)	0.58
D vs D (cable)	0.22
A (cable) vs D (cable)	−0.10*
A (cable) vs D	0.41
B + F vs D	0.38

* Not significant at 99% level.

for sections B–G. For section A, the cable-derived transport was used. The mean transports dominate in the main channel of the Florida Current (Fig. 8), but the fluctuations have similar variances in both the main and subsidiary channels (Table 2). The first three modes are significant by the criteria of Overland and Preisendorfer (1982) and represent 87.6% of the total variance. The spatial components of the modes are given in Fig. 9 where the units are in Sverdrups. The corresponding amplitude time series, which are normalized to unit variance and uncorrelated, are given in Fig. 10. The first mode shows coherent fluctuations of the Florida Current that decrease from south to north. It also shows small outflows into the Santaren and Northwest Providence Channels, as the Florida Current transport fluctuations are positive, and inflows from these channels when the Florida Current transport fluctuations are negative. This first mode is the predominant source of fluctuations in the Northwest Providence channel, suggesting that the variability is pumped by Florida Current fluctuations. The mode amplitudes have a general decreasing trend over the 11 months of the analysis.

The second mode can be characterized as a diversion or recirculation pattern because it is dominant in the Cay Sal Bank (B) and Santaren Channels. The amplitude time series, except for the last 2 months, has periods of relatively small positive values separated by shorter periods of large negative fluctuations of which most important is the April 1991 event discussed above (Fig. 10). A large negative fluctuation of this mode results in a decrease in the transport through B and a compensating positive transport through the Santaren Channel (F). This diversion around Cay Sal Bank also

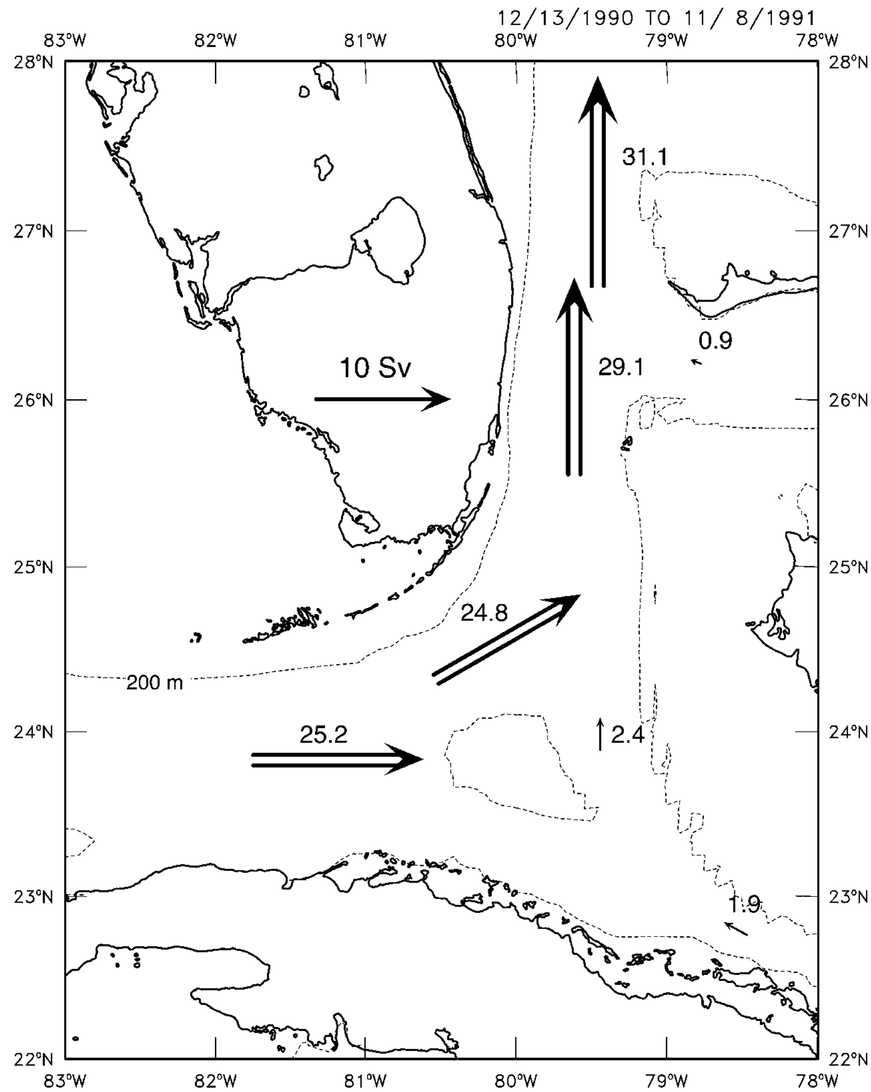

FIG. 8. Mean transports, with numerical values indicated, through the Straits of Florida sections. Arrows with two shafts have their magnitudes multiplied by 2.

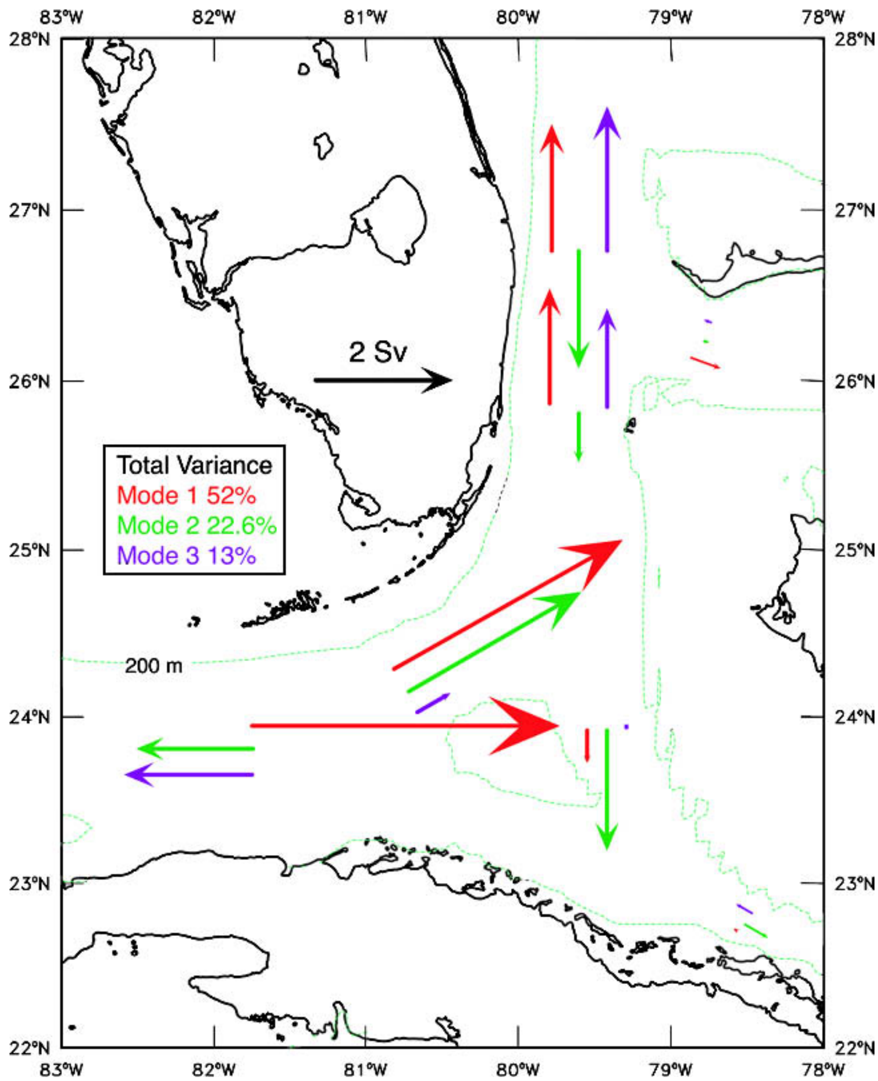

FIG. 9. Spatial components of the first three EOFs (color coded) from the transport time series derived from current meters except for section A, where cable measurements were used.

accompanied by increases in transport through the Florida Current sections both up- (A) and downstream (C and D) of B. There is also an increase in flow through the Old Bahama Channel (G). For a large positive fluctuation, local increases in transport through B are diverted south through the Santaren Channel with some flow escaping through G, but with the majority recirculated through A. This September–October 1991 fluctuation occurred when the mismatch between B + F − G and the cable measurement at A is large (Fig. 7) and this may influence the positive fluctuation of this mode. This mode seems to show that large amplitude meanders in the western straits can influence transport farther north even though these meanders are not directly observed in this region (Lee et al. 1995).

The third mode has a low-frequency signal (negative in spring, positive in late summer and autumn; see also Fig. 6) as well as short-term (~10–20 days) fluctuations. The mode amplitudes are negative and positive in the spring and summer, respectively (Fig. 10). Along with the positive mode components at C and D, this produces fluctuations in these sections that have some similarities with the average annual cycle of the Florida Current at 27°N, which shows a maximum in the summer (Schott and Zantopp 1985). The sense of the mode fluctuations is reversed for section A, with the maximum positive transport occurring in spring. However, evaluation of annual cycles from just 1 yr of data has little significance.

If the transport fluctuations are normalized to unit variance so that the time series are weighted equally, the first two EOFs, which account for 58% of the total

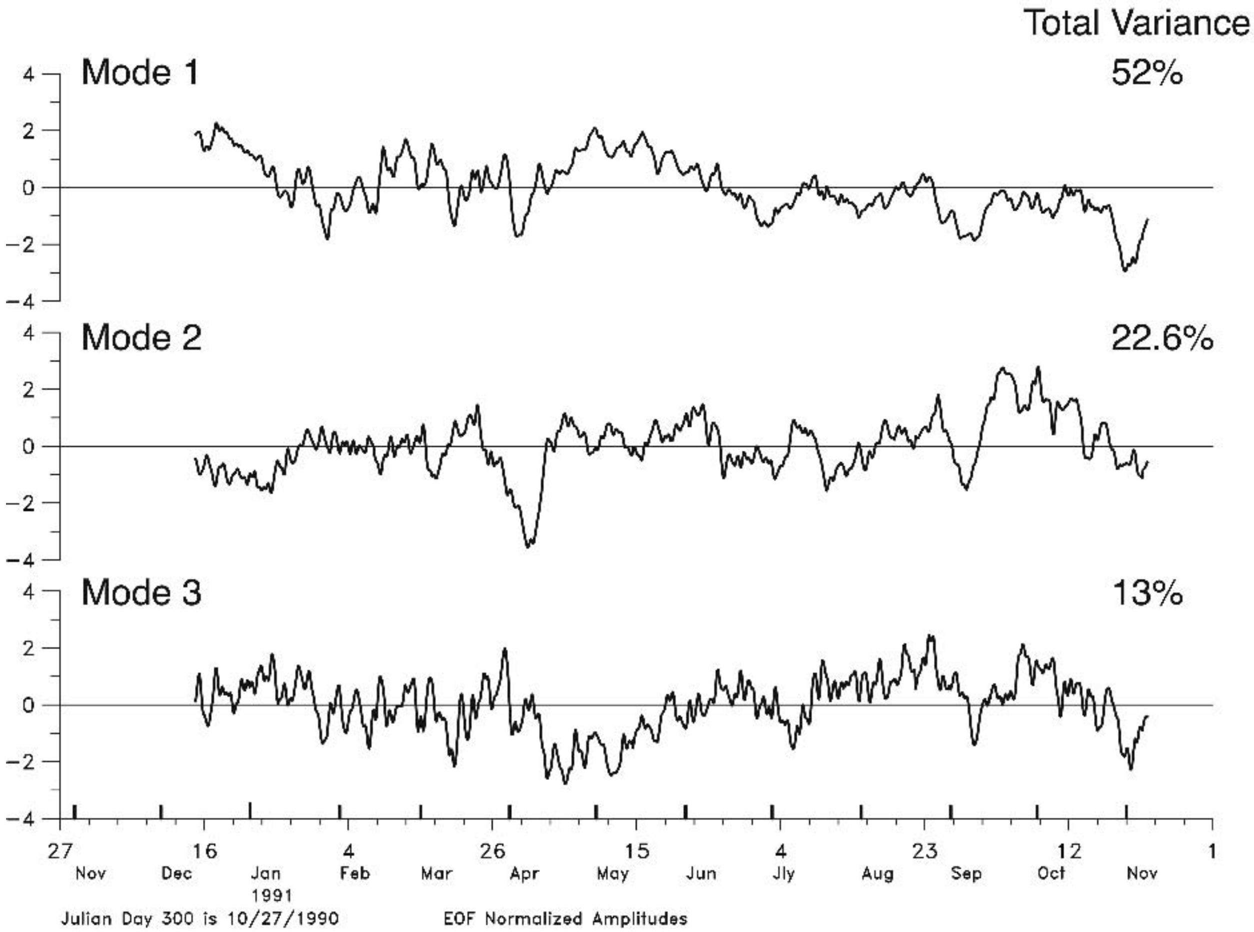

FIG. 10. Normalized amplitudes of the EOF transport modes.

normalized variance, have essentially the same structures as given in Fig. 9. Therefore, the first two modes appear to be robust. The higher modes in the normalized case do not appear to be significant, as they tend to emphasize single channels, particularly E and G. Thus, mode 3, discussed above, even though it satisfies the significance criteria, may not represent a physical signal. In interpreting EOFs, the orthogonality constraints between modes can produce component amplitudes, usually small, that imply stronger spatial correlations than are physically meaningful. For the diversion mode (2), the anticorrelation between B and E is the main feature, but its influence on the other parts of the system may be less physical.

7. Summary

Transports through four sections of the Straits of Florida from Key West to Jupiter, along with transports through the subsidiary Northwest Providence, Santaren, and Old Bahama Channels, were measured over an 11-month period (December 1990–November 1991) using moored current-meter arrays and telephone cable potential differences. The transport through the Key West–Havana section (A) was evaluated using the cable and through continuity using the moored arrays. Agreement was reasonable, though some individual events may be suspect, and a mean of 25.2 Sv was obtained, which is about 5 Sv less than the average transport at the northern end of the straits (section D or 27°N) that has been extensively documented by STACS. The ~25 Sv leaving the Gulf of Mexico across section A agrees well with an estimated 23.8 ± 1 Sv total transport entering the Gulf through the Yucatan Channel that was measured with a dense array, as described by Sheinbaum et al. (2002), between September 1999 and June 2000. The ~5 Sv difference in the mean transports between the western and northern end of the Florida Current was partially accounted for by the ~2 and 1 Sv flowing into the Florida Current from the Old Bahama and Northwest Providence Channels, respectively. Continuity arguments using the fairly densely instrumented Cay Sal Bank (B) section and the resolution of the current measurements in the Santaren (F) and Old Bahama Channels (G) indicate that the inflow to the Florida Current through the Santaren Channel might have been underestimated by the ~2 Sv that would be required to balance the transports through the straits.

The inflow from the side channels also influences the variability of the transport such that monthly to annual transport fluctuations at 27°N are smaller than at the Key West to Havana section. A maximum of 6.6 Sv was estimated for the Old Bahama Channel, which supplies subtropical underwater of southwest tropical North Atlantic origin to the east side of the Florida Current (Atkinson et al. 1995) as suggested by the circulation cartoons of Schmitz and McCartney (1993). These inflows also make the 27°N transports unreliable as estimates of the outflow of the Gulf of Mexico. An EOF mode analysis of the transport fluctuations shows quite complex patterns, particularly around the Cay Sal Bank. Transports through this section (B) are perturbed by large amplitude meanders on the Florida Current coupled to cyclonic eddies inshore of the displaced front, which were shown to divert part of the flows into the Santaren Channel. These diverted Santaren Channel transports rejoin the Florida Current in the northern part of the straits. The mode analysis indicates that these large diversions influence the transport fluctuations up and downstream in the Florida Current as well as flows in the Old Bahama Channel.

This experiment indicates that the Straits of Florida and its side channels should be considered as a complex system of flows rather than just a straight conduit from out of the Loop Current into the Gulf Stream.

Acknowledgments. The Straits of Florida study was funded by the Minerals Management Service under Contract 14-35-0001-30493 to Science Applications International Corporation, Raleigh, North Carolina. The authors acknowledge the support and encouragement from the project officers Murray Brown and Alexis Lugo-Fernandez during the execution of this program and the preparation of this paper. Doctor Julio Sheinbaum is also thanked for his review, which improved many aspects of this paper.

REFERENCES

Anderson, D. L. T., and R. A. Corry, 1985: Seasonal transport variations in the Florida Straits. *J. Phys. Oceanogr.,* **15,** 773–786.

Atkinson, L. P., T. Berger, P. Hamilton, E. Waddell, K. Leaman, and T. N. Lee, 1995: Current meter observations in the Old Bahama Channel. *J. Geophys. Res.,* **100,** 8555–8560.

Bunge, L., J. Ochoa, A. Badan, J. Candela, and J. Sheinbaum, 2002: Deep flows in the Yucatan Channel and their relation to changes in the Loop Current extension. *J. Geophys. Res.,* **107,** 3233, doi:10.1029/2001JC001256.

Fratantoni, P. S., T. N. Lee, G. P. Podesta, and F. Muller-Karger, 1998: The influence of Loop Current perturbations on the formation and evolution of Tortugas eddies in the southern Straits of Florida. *J. Geophys. Res.,* **103** (C11), 24 759–24 799.

Johns, W. E., and F. A. Schott, 1987: Meandering and transport variations of the Florida Current. *J. Phys. Oceanogr.,* **17,** 1128–1147.

——, T. N. Lee, R. C. Beardsley, J. Candela, R. Limeburner, and B. Castro, 1998: Annual cycle and variability of the North Brazil Current. *J. Phys. Oceanogr.,* **28,** 103–128.

Larsen, J. C., 1992: Transport and heat flux of the Florida Current at 27°N derived from cross-stream voltages and profiling data: Theory and observations. *Philos. Trans. Roy. Soc. London,* **338,** 169–236.

——, and T. B. Sandford, 1985: Florida Current volume transports from voltage measurements. *Science,* **227,** 302–304.

Leaman, K. D., P. S. Vertes, L. P. Atkinson, T. N. Lee, P. Hamilton, and E. Waddell, 1995: Transport, potential vorticity, and current/temperature structure across the Northwest Providence and Santaren Channels and the Florida Current off Cay Sal Bank. *J. Geophys. Res.,* **100,** 8561–8570.

Lee, T. N., and E. Williams, 1988: Wind-forced transport fluctuations of the Florida Current. *J. Phys. Oceanogr.,* **18,** 937–946.

——, F. A. Schott, and R. J. Zantopp, 1985: Florida Current: Low-frequency variability as observed with moored current meters during April 1982 to June 1983. *Science,* **227,** 298–302.

——, C. Rooth, E. Williams, M. McGowan, A. F. Szmant, and M. E. Clarke, 1992: Influence of Florida Current gyres and wind driven circulation on transport of larvae and recruitment in the Florida Keys coral reefs. *Cont. Shelf Res.,* **12,** 971–1002.

——, K. Leaman, E. Williams, T. Berger, and L. P. Atkinson, 1995: Florida Current meanders and gyre formation in the southern Straits of Florida. *J. Geophys. Res.,* **100** (C5), 8607–8620.

Mayer, D. A., K. D. Leaman, and T. N. Lee, 1984: Tidal motions in the Florida Current. *J. Phys. Oceanogr.,* **14,** 1551–1559.

Overland, J. E., and R. W. Preisendorfer, 1982: A significance test for principal components applied to cyclone climatology. *Mon. Wea. Rev.,* **110,** 1–4.

Paluszkiewicz, T., L. P. Atkinson, E. S. Posmentier, and C. R. McClain, 1983: Observations of a Loop Current frontal eddy intrusion onto the West Florida shelf. *J. Geophys. Res.,* **88,** 9639–9652.

Richardson, W. S., and J. R. Finlen, 1967: The transport of Northwest Providence Channel. *Deep-Sea Res.,* **14,** 361–367.

SAIC, 1992a: Straits of Florida physical oceanographic field study, data report. OCS Rep. MMS 92-0024, U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans, LA, 85 pp.

——, 1992b: Straits of Florida physical oceanographic field study, final interpretative report. Volume II: Technical report. OCS Rep. MMS 92-0024, U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans, LA, 179 pp.

Schmitz, W. J., Jr., and M. S. McCartney, 1993: On the North Atlantic circulation. *Rev. Geophys.,* **31,** 29–49.

Schott, F. A., and R. Zantopp, 1985: Florida Current: Seasonal and interannual variability. *Science,* **227,** 308–311.

——, T. N. Lee, and R. Zantopp, 1988: Variability of structure and transport of the Florida Current in the period range of days to seasonal. *J. Phys. Oceanogr.,* **18,** 1209–1230.

——, J. Fischer, J. Reppin, and U. Send, 1993: On mean and seasonal currents and transport at the western boundary of the equatorial Atlantic. *J. Geophys. Res.,* **98** (C8), 14 353–14 368.

Sheinbaum, J., J. Candela, A. Badan, and J. Ochoa, 2002: Flow structure and transport in the Yucatan Channel. *Geophys. Res. Lett.,* **29,** 1040, doi:10.1029/2001GL013990.

Sturges, W., and R. Leben, 2000: Frequency of ring separation from the Loop Current in the Gulf of Mexico: A revised estimate. *J. Phys. Oceanogr.,* **30,** 1814–1819.

Vukovich, F. M., 1986: Aspects of the behavior of cold perturbations in the eastern Gulf of Mexico: A case study. *J. Phys. Oceanogr.,* **16,** 175–188.

——, B. W. Crissman, M. Bushnell, and W. J. King, 1979: Some aspects of the oceanography of the Gulf of Mexico using satellite and in-situ data. *J. Geophys. Res.,* **84** (C12), 7749–7768.