Florida Current: Low-Frequency Variability as Observed with Moored Current Meters During April 1982 to June 1983

Abstract. *A 1-year time series of volume transport through the Florida Straits near 27°N was derived from an array of five subsurface current meter moorings. The transport estimates, determined on the basis of constant shear extrapolation of the subsurface velocities to the surface, are in good agreement with transports derived from submarine cable and Pegasus measurements. The annual transport cycle in 1982–1983 is complicated by large-amplitude fluctuations on time scales of 1 to 3 weeks, but it does exhibit a transport maximum in summer and a minimum in fall-winter, consistent with historical results and of similar magnitude. The energy density spectrum of transports is continuous with a slope of about −1.5 and does not show a gap between the periods of weeks and seasonal. Evidence was found for atmospheric forcing of transport fluctuations, with highest coherence between transport and the local meridional wind stress at periods of 10 and 15 days during the summer and 5 and 40 days during the winter.*

The Florida Current is known to exhibit energetic transport fluctuations in the period band of several days to several weeks (*1*) and at the annual period (2), but very little is known about the current and transport variability in the period range from several weeks to seasonal. The Florida Current program carried out within the Subtropical Atlantic Climate Studies (STACS) provides considerable new information on Florida Current variability on time scales from tidal to seasonal.

Few time series of direct current measurements in the high-speed portion of the Florida Current have been obtained in the past because of technical difficulties associated with making measurements over long periods of time in swift currents. However, by using faired cable and improving the reliability of mooring components, we found that it was possible to maintain a moored current meter array covering much of the water column during STACS.

The purpose of this report is to present time series of transports calculated from the moored current meter data and to compare these with other transport measurements obtained by Pegasus (*3*) and submarine cable (*4*) (Fig. 1). Subsequently we will also discuss the main properties of the low-frequency fluctuations and present some preliminary evidence linking the fluctuations, in part of the frequency range covered, to wind forcing. Finally, we will discuss minimum requirements to monitor the Florida Current transport with moored current measurements.

The current meter array consisted of five moorings deployed in a saw-toothed pattern [figure 1 of (*5*)] between West Palm Beach, Florida, and the Bahamas, bracketing the submarine cable used by Larsen and Sanford (*4*). The saw-toothed pattern provides upstream information for measurements of phase propagation along the channel axis as well as cross-stream data for transport calculations. The first array (STACS-I) was deployed in April 1982 and was maintained for 2 months. In this array, the top instruments were at 50 m for the western station, mooring 146; at 150 m for moorings 147 and 148; and at 100 m for the two eastern stations, moorings 149 and 150. In subsequent arrays (STACS-II from June through December 1982 with moorings 151 to 155 and STACS-III from February to June 1983 with moorings 156 to 160) the depth of the top instrument at the western station was increased to 100 m because of extreme wear on this mooring during STACS-I (speeds of more than 250 cm/sec were observed at the top instrument).

A total of 25 current meters was deployed in each of the moored arrays. The instrument configuration for STACS-II is shown in Fig. 2a, superimposed on the mean downstream flow derived from the current meter data. In the high-speed core region we used mostly Niskin wing current meters (NWCM's), otherwise Aanderaa (ACM) instruments. Five out of the 25 current meters deployed in STACS-II had electrical or mechanical problems, and their data were not used. A number of intercomparisons between both instrument types showed only small deviations. The NWCM's were then corrected by a best-fit polynomial through the offset to make the two kinds of measurements compatible (*6*). Recording intervals for the 6-month deployments were 30 minutes for the ACM's and 1 hour for the NWCM's, where on the latter a burst sample of four readings separated by 1.3 seconds was taken every hour.

For the transport calculations, the northward current components were first filtered with a 40-hour Lanczos low-pass filter, which effectively removed the tides and other high-frequency fluctuations. There are three problems in determining transports from the five moored stations. (i) The current meter moorings covered only part of the water column (Fig. 2a), and current profiles had to be extrapolated to the surface and bottom. (ii) Mooring tilt due to current drag resulted in varying instrument depths. (iii) With only five stations, the resolution across the Florida Current was quite coarse; two of the stations were displaced upstream by about 20 km [figure 1 of (*5*)].

The mooring motion problem turned out to be not as severe as expected because of the use of plastic fairings, which were inserted over the cable in the high-speed parts of the flow (*7*). Standard deviations of the instrument depths were less than 5 m. We accounted for these depth changes by using the pressures recorded by the ACM's to deter-

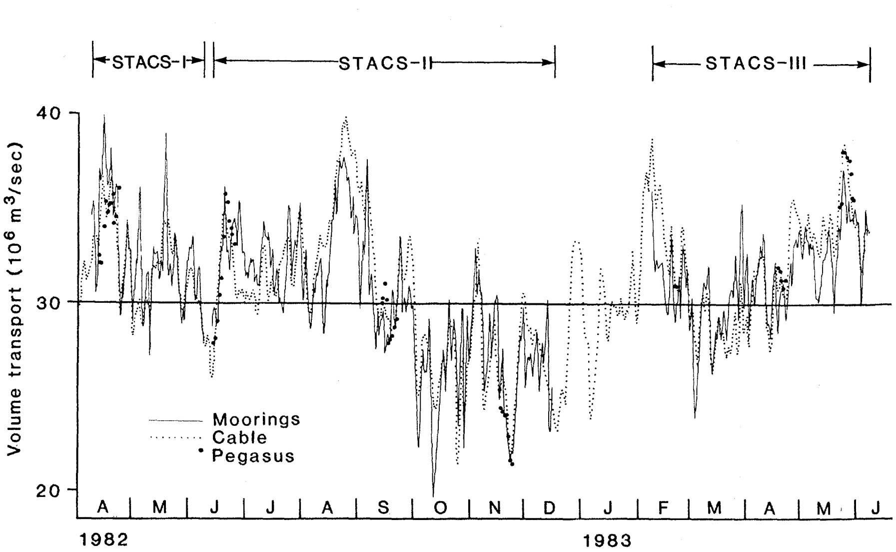

Fig. 1. Time series of transports determined from the five moorings (solid line), from cable voltages calibrated by Pegasus (dashed line), and from Pegasus sections (dots).

mine the actual depth of the individual current measurements.

Pegasus and current meter profiles of downstream velocities show near linear distributions over most of the Florida Current, except for the eastern site where a subsurface maximum and reversal of the velocity gradient in the vertical is often observed at about 250 m (Fig. 2a). Therefore, we tried several simple schemes to extrapolate the current to the surface and bottom. The method that gave the best results in comparison with Pegasus transports was to linearly interpolate between the measured downstream velocities at the different depths and zero at the bottom and extrapolate a linear fit to the surface. This technique was used for the four western moorings (8). For the eastern mooring, the linear gradient was extrapolated to the surface

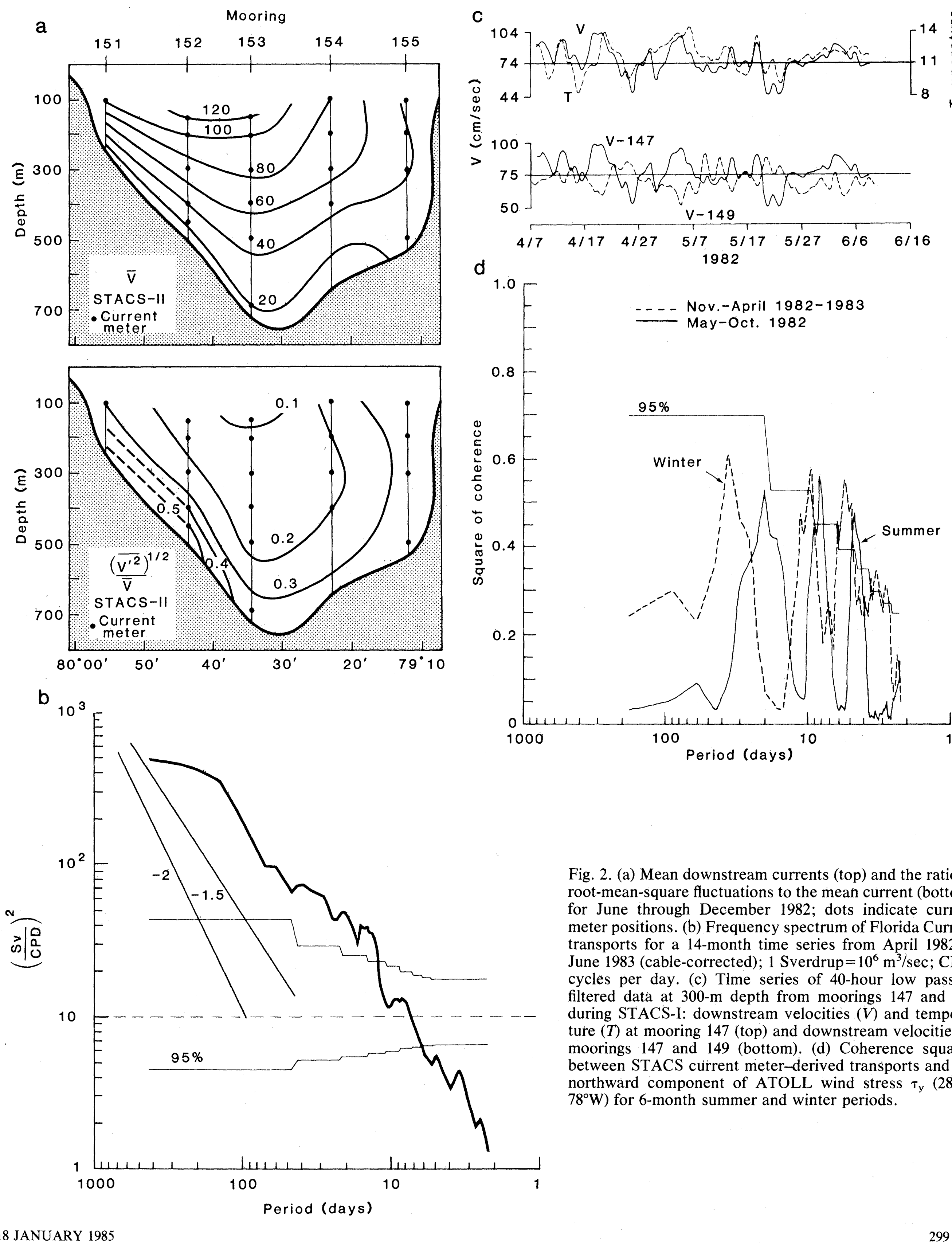

Fig. 2. (a) Mean downstream currents (top) and the ratio of root-mean-square fluctuations to the mean current (bottom) for June through December 1982; dots indicate current meter positions. (b) Frequency spectrum of Florida Current transports for a 14-month time series from April 1982 to June 1983 (cable-corrected); 1 Sverdrup=10^6 m^3/sec; CPD, cycles per day. (c) Time series of 40-hour low passed, filtered data at 300-m depth from moorings 147 and 149 during STACS-I: downstream velocities (V) and temperature (T) at mooring 147 (top) and downstream velocities at moorings 147 and 149 (bottom). (d) Coherence squared between STACS current meter–derived transports and the northward component of ATOLL wind stress τ_y (28°N, 78°W) for 6-month summer and winter periods.

Table 1. Statistical comparison of current meter–derived (CM) transports with Pegasus- or cable-derived transports.

Transport time series	Time period	Number of points	Mean* difference ($\times 10^6$ m^3/sec)	Standard deviation of difference ($\times 10^6$ m^3/sec)	Correlation coefficient
Pegasus versus CM	STACS-I	12	−1.82	1.97	0.58
Pegasus versus CM	STACS-II	29	−0.02	1.37	0.95
Pegasus versus CM	STACS-III	16	1.44	0.99	0.94
Pegasus versus CM	STACS-I to -III	57	−0.01	1.80	0.91
Cable versus CM	STACS-I	61	−0.57	1.75	0.78
Cable versus CM	STACS-II	186	0.38	1.95	0.87
Cable versus CM	STACS-III	120	0.60	1.79	0.80
Cable versus CM	STACS-I to -III	367	0.30	1.90	0.85

*Negative values if current meter–derived transport values are larger.

if no gradient reversal occurred; otherwise, the gradient reversal determined from Pegasus data was used for the upper level. The surface velocities determined by vertical extrapolation at each mooring site were used to estimate the surface velocities at the western and eastern boundaries by horizontal linear extrapolation. The boundary surface velocities were linearly decreased to zero at the bottom. Total volume transport was then determined by integration in the x and z directions of the extrapolated vertical velocity profiles at each mooring plus the boundaries. This method produced slightly better results than the simplest case—namely, just continuing the best-fit profile to the surface and bottom and multiplying by station separations.

The transport time series derived from moored current meters is shown in Fig. 1 for April 1982 to June 1983, together with the Pegasus transports and those derived from the cable voltages. No current meter data were obtained from the beginning of December 1982 to mid-February 1983 because of equipment overhaul between the deployment of STACS-II and -III arrays.

A statistical comparison of current meter–derived transports with Pegasus and cable-derived transport is given in Table 1. The mean difference between the moored current meter transports and the Pegasus transports for the entire 14-month period is only -0.01×10^6 m^3/sec, the standard deviation of the difference is 1.80×10^6 m^3/sec, and the correlation coefficient is 0.91. The best agreement between the transport fluctuations from moored data and Pegasus data occurred for the STACS-III array, which had the fewest current meter failures and for which mooring motion was further reduced as a result of an improved attachment of the cable fairings. The standard deviation of the difference between Pegasus and moored current meter transports for STACS-III was only 0.99×10^6 m^3/sec with a correlation coefficient of 0.94. Comparison of moored current meter transports with daily mean values of cable transport (*4*) also show good agreement (Fig. 1 and Table 1), with a correlation coefficient of 0.85 and a standard deviation of the differences of 1.90×10^6 m^3/sec for the entire data set.

The agreement for the three methods of measuring transport is remarkably good, if one considers the coarseness of the horizontal integration and the simplicity of vertical extrapolations of the moored currents and if one takes into account that two of the moorings were displaced upstream. The upstream mooring separation does not appear to have had a significant effect on the moored transport estimates, for the standard deviation of the difference between Pegasus-derived transports and cable-derived transports of 1.3×10^6 m^3/sec is only slightly less than the standard deviation of the difference between moored transport estimates and Pegasus of 1.80×10^6 m^3/sec for the total time series. We tried to determine a phase correction for northward-propagating meanders, using time-lagged correlations between the moored transport at the upstream positions against Pegasus transports measured downstream, that is, mooring 147 against Pegasus 2–Pegasus 3 and mooring 149 against Pegasus 6 [figure 1 of (*5*)]. However, the correlation function was found to be broad-banded, that is, no single dominant wave occurred, and no significant improvement in total transports could be obtained by this method. Attempts to use empirical orthogonal functions determined from the Pegasus sections (*9*) and then fitted to the current meter data to determine transports also showed no improvement over our simple linear extrapolation method.

Neither the moored current meter transports nor the cable transports show a simple sinusoidal annual cycle (Fig. 1). Rather, the continuous measurements show an event-dominated record with large transport bursts in August 1982 and May 1983 lasting less than 1 month and several minima occurring in the fall and winter. Monthly averages of the current meter–derived transports for the 14-month transport time series are shown in Figure 1c of Schott and Zantopp (*10*). These data reveal the significant asymmetry of the annual cycle as found in historical cable voltages and sea level differences across the Straits of Florida, which show a maximum in July–August and a minimum in October–November (*11*). The annual mean transport for May 1982 to April 1983 is 30.1×10^6 m^3/sec with a standard deviation of 3.3×10^6 m^3/sec in good agreement with historical estimates for the Florida Straits (*2*).

One interesting result of these transport time series is that there is no energy minimum over the period range of several weeks to seasonal [earlier studies from individual current records (*12*) and from shorter duration transport studies (*1*) had found such a minimum]. The spectrum in Fig. 2b (*13*) shows a continuous increase in energy density toward longer periods. For comparison, spectral slopes of −2 and −1.5 are also shown. The spectral slope for periods longer than 5 days in the Florida Current transport is actually larger than −1.5, whereas typical mid-ocean current spectra from the subtropical North Atlantic show slopes of −2 and less (*14*).

The distribution of perturbation kinetic energy across the Straits was found to be quite inhomogeneous. The mean and root-mean-square versus mean velocities for the downstream current component are shown in Fig. 2a, where the contours are based on 20 current records obtained during STACS-II. The highest fluctuation intensities relative to the mean are located in the vicinity of the western slope, where unfortunately only the top instrument at mooring 151 gave a full record, and along the bottom, which indicates that the fluctuation amplitudes decrease more slowly with depth than the mean, that is, the perturbations tend to be more barotropic than the mean. Similar distributions were found for the STACS-I and -III data sets.

In the center of the Straits the most prominent feature in the fluctuations is an east-west meandering motion of the axis. Data from STACS-I are used to describe the effect of meanders on moored current meter observations (Fig. 2c), but similar events can be found in all the data sets. An eastward meander is indicated by increasing velocity at mooring 149 (to the right of the axis) and by decreasing velocity at mooring 147 (to the left of the axis) and at the same time decreasing temperature at both mooring 147 and mooring 149 because of the positive eastward temperature gradient across the Florida Current. Correspondingly, a westward meander is indicated by increasing (decreasing) velocity at mooring 147 (149) and increasing temperature at both mooring 147 and mooring 149.

The meandering motion with antiphase across the stream's axis occurred with significant coherence at periods of about 10 days and 4 to 5 days. The 10-day fluctuation was more pronounced in the summer; the shorter period was more pronounced in the winter, in agreement with the average period of atmospheric cold-front passage. This is in agreement with the results of earlier work (*1, 15*), which reported east-west meanders of the Florida Current axis with periods of 4 to 14 days that produced large out-of-phase variations in currents across the axis that were associated with changes in total transport.

Current fluctuations at the eastern and western boundaries of the Florida Straits could not be accounted for by simple extensions of the interior meandering mode. Boundary waves appear to occur on both sides of the Current, and the overall coherence and phase pattern across the width of the Current is much more complicated than that reported earlier for near bottom flow (*12*). This is one reason why these earlier studies yielded spectra different from our transport spectrum (Fig. 2b) and why these researchers concluded that there was an energy gap over the period range from several weeks to seasonal.

To study possible effects of wind forcing on the current and transport fluctuations, we have analyzed wind data from the National Oceanic and Atmospheric Administration, Atlantic Tropical Oceanic Lower Layer (ATOLL) service, which are available on a grid 150 km by 150 km at half-day intervals. Local wind forcing is significantly different in summer and winter. During winter, wind energy is concentrated in shorter periods (order 5 days) due to cold-front passages, whereas in summer wind forcing shifts to longer periods. To evaluate these effects we calculated coherences between wind stress and transport for May through October (summer) and November through April (winter) separately (Fig. 2d).

For summer, the highest coherence of the downstream transport was found with the local meridional wind component at periods of 4 to 5 days and 8 days with a suggestion of coherence at a lower significant level at periods of 20 days. During the winter, the coherence between transports and the local meridional wind stress was greatest at 5 to 6 days and still significant at 10 days. There is also an indication of less significant coherence at periods of about 35 days.

Transport fluctuations occurring at periods of 10 days or longer were generally near in-phase with the local meridional wind. This is in agreement with an interpretation such that the northward wind causes eastward Ekman transport, which in turn establishes a westward barotropic pressure gradient that drives a northward geostrophic transport. The shorter period (3 to 5 days) transport variations tended to lag the meridional wind by about 90°. There is also significant coherence with the wind stress curl over the Straits at 15 to 25 days and 10 days during the winter but not at the shorter periods. Nor was any significant coherence found between the curl and the transport during summer. Duing *et al.* found coherence between wind stress curl from several coastal stations and moorings near the western boundary (*12*). We investigated possible effects of the wind stress curl east of the Bahamas and in the Caribbean with regard to the longer period transport fluctuations, but coherences were not higher than with the local wind.

This preliminary evidence suggests that the meandering motions and associated transport variations are probably caused or at least influenced by the local wind. However, because of the large coherence scale of the wind field, remote winds can also be coherent with the transport fluctuations at various frequencies. Thus to interpret results correctly it is necessary that one study the phase relations and probable propagation mechanisms to understand cause and effect; this study is still in its initial stage.

One question relevant to further monitoring of the Florida Current investigated was the minimum number of moorings and current meters required to obtain transport time series sufficient to serve as a check on cable transports, which were found to show occasional jumps of about 3 to 4 $\times 10^6$ m^3/sec (*4*). Obviously, since the vertical profiles of downstream velocities are close to linear, moorings do not have to extend up as high as in the first deployments (Fig. 2a). This in turn will increase mooring lifetime and thus the mooring deployment periods. If one uses transports derived from two moorings (moorings 157 and 159 in Fig. 2a), using the same method as described for five moorings, the standard deviation of the differences with Pegasus increases by a factor of 2 to 1.9 $\times 10^6$ m^3/sec for STACS III. The mean difference also increases by about a factor of 2, with the moored transports being lower by about 4 $\times 10^6$ m^3/sec. The correlation coefficient is 0.80. Using three moorings (moorings 156, 158, and 160) reduces the mean difference to -1.9×10^6 m^3/sec and the standard deviation of the differences to 1.2 $\times 10^6$ m^3/sec. The correlation coefficient becomes 0.91.

An improvement of the transport estimates based on the use of two moorings may be obtained if the two-mooring current meter estimates are regressed against Pegasus transports to derive a fitted transport. However, in this case, the standard deviation of the differences between the fitted two-mooring transports and Pegasus for STACS-III is still about 2 $\times 10^6$ m^3/sec. Regressing three moorings against Pegasus does not improve these results. Still, this transport accuracy would be sufficient, particularly if one is concerned about standard deviations of means over longer samples, to detect the aforementioned jumps in cable transports. If this approach were used, a transport-monitoring scheme could be devised that would include the use of a combination of occasional Pegasus sections, cable and tide gauge measurements, and a reduced array of two mid-depth current meter moorings. The Pegasus sections would be used to calibrate the cable transport estimates and to regress against transport derived from the two moorings. The corrected moored current meter transports would then serve as a continuous check on cable transports to detect voltage jumps. Downstream tide gauge pairs or bottom pressure recorders would provide an additional estimate of the barotropic transport for comparison with cable and moored current meter transports. The mooring data would also provide an estimate of heat flux that could be used to calibrate heat flux estimates from the cable.

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Florida Current Volume Transports from Voltage Measurements

Abstract. *The volume transport of the Florida Current is determined from the motionally induced voltage difference between Florida and Grand Bahama Island. Simultaneous measurements of potential differences and of volume transport by velocity profiling have a correlation of 0.97. The calibration factor is 25 ± 0.7 sverdrups per volt, and the root-mean-square discrepancy is 0.7 sverdrup. The induced voltage is about one-half the open-circuit value, implying that the conductance of the sediments and lithosphere is about equal to that of the water column.*

The cross-stream voltage between Jupiter, Florida, and Settlement Point, Grand Bahama Island (*1*), generated by the flow of the Florida Current through the earth's magnetic field, is measured over two submarine cable segments. This cable has been used for similar measurements (*2*). Because the submarine cable is broken in shallow water 10 km from Florida, the voltage differences were simultaneously recorded (as hourly mean values; Lycor integrating printer model 550B) between Jupiter and the cable break and between the cable break and Settlement Point. It is assumed that there is no bias to the combined voltages. The equality of the ground contact (steel armor) at Jupiter and Settlement Point was confirmed by an experiment in which reference electrodes (Ag-AgCl) were located at each end (*2*). There is, however, a constant bias on each of the individual cable segments of about 430 mV due to electrochemical differences between the measurement ground contacts and the exposed ends at the break. The cable record has been corrected for abrupt offsets in the voltage that have occurred intermittently since March 1983 (*3*) and for tidal and geomagnetic fluctuations (*4, 5*). Only the segment under the Florida Current (break to Settlement Point) will be discussed here. The purpose of this report is to compare the cable voltages with direct measurements of volume transport and to establish a calibration for the cable observations.

Velocity measurements at nine stations across the Straits of Florida, based on use of the Pegasus velocity profiling system (*6*), are described by Molinari *et al.* (*7*). We removed barotropic and laterally uniform tidal components in velocity, using a prediction from sea-level measurements. Profiling data were used to compute daily mean transport on the 63 days for which at least five profiling sites out of the possible nine sites between Jupiter and Settlement Point were occupied once during a 24-hour period. For each profiling site we computed the daily mean values for those days for which observations were made, assuming a linear change in flow between observations. This procedure provides about 75 percent of the possible 567 (63 times 9) observations; we computed 17 percent of the missing values by using the preceding or following ($\Delta t \leq 1$ day) values at a site and assuming a linear change of transport with time. We computed the remaining 8 percent of the missing values by assuming that the flow at any particular time can, on the average, be estimated from the weighted values of the flow at the two nearest sites.

Voltage differences ($\Delta\phi$) between the cable break and Settlement Point are related to the transport (T) by

$$T(t) = \frac{H_e[\Delta\phi(t) + B]}{F_z} \quad (1)$$

where t is time, H_e is the conductance depth, $F_z = -0.42 \times 10^{-4}$ tesla is the vertical component of the earth's steady magnetic field, and B is a constant offset voltage to account for differences in contact potential between the cable ends. This formula is an extension of that originally derived by Malkus and Stern (*8*), which did not account for shorting effects caused by electric currents leaking into the sea floor and temporal varia-

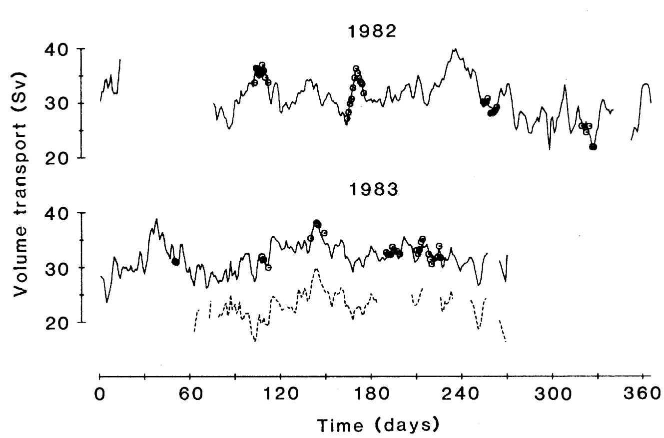

Fig. 1 (left). Daily means of the calibrated cable data in Sverdrups (1 Sv = 10^6 m^3/sec) plotted by 1-year segments as a solid line. The cable data before being corrected for offsets are plotted as the dashed line. The circles represent transport estimated from the profiler transects. The cable results agree with the directly measured transports at a correlation of 0.97 with a root-mean-square deviation of 0.67 Sv. Gaps are due to recorder malfunction or to the loss of data in the mail.

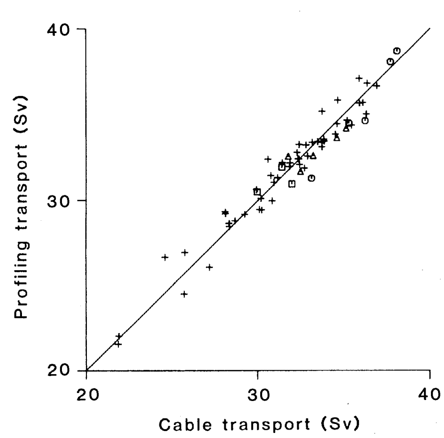

Fig. 2 (right). Comparison of 63 daily mean transports estimated from velocity profiling data and from simultaneous cable voltages, which are converted to transport units by subtracting 0.43 V and multiplying by the factor 25 Sv/V. The 13 values observed during anomalous offsets have been adjusted (see text) by the following amounts: squares plus 0.44 V; triangles plus 0.35 V; and circles plus 0.32 V.