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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

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

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-

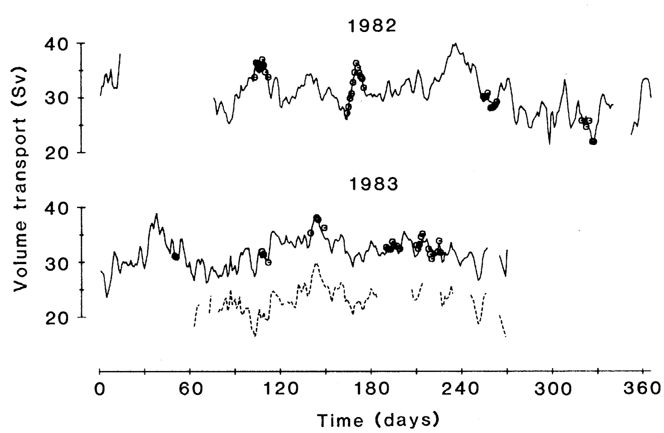

Fig. 1 (left). Daily means of the calibrated cable data in Sverdrups (1 Sv = 10^6 m^3/sec) plotted by 1-year segments as a solid line. The cable data before being corrected for offsets are plotted as the dashed line. The circles represent transport estimated from the profiler transects. The cable results 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.

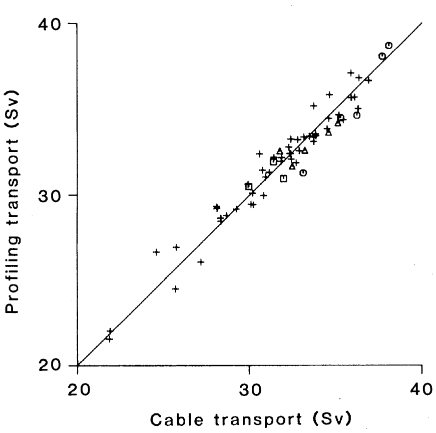

Fig. 2 (right). Comparison of 63 daily mean transports estimated from velocity profiling data and from simultaneous cable voltages, which are converted to transport units by subtracting 0.43 V and multiplying by the factor 25 Sv/V. The 13 values observed during anomalous offsets have been adjusted (see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

tions in the flow structure. Although Eq. 1 is found to be appropriate in the present case, this form is not generally valid (*2, 9*).

The principal reasons that Eq. 1 is valid are discussed in (*10*); these include the absence of significant lateral (east-west) current shifts and downstream variations (on the scale of the channel width), a favorable lateral distribution of the bottom conductance, and a nearly constant temperature distribution.

The daily mean values of the voltages from the break to Settlement Point for the 63 days of profiling transport estimates yield $H_e = 1050 \pm 30$ m and $B = -0.43 \pm 0.03$ V. Thus, a change of 1 Sv is equivalent to a change of 40 ± 1.1 mV in the cable voltage. The value and sign of B indicate that the armor is the seawater contact at Settlement Point and that copper is the seawater contact at the cable break.

The daily mean values of the calibrated cable data (in sverdrups) are plotted in Fig. 1 as the solid line in 1-year segments. The record during periods of voltage offset is plotted as the dashed line. Adjustments to the data were made only for these intervals. The transport estimates from the 63 profiling days are represented by the dots. The excellent agreement between the two transport estimates shows that the cable voltages track the day-to-day fluctuations of the Florida Current transport.

The transport values estimated from the profiling data and the cable voltages are compared in Fig. 2. The profiling data were weighted by the number of observations made on each occasion. The root-mean-square deviation is 0.67 Sv, which is 2.2 percent of the mean; the correlation is 0.97.

The results from Fig. 1 show that there are substantial changes in the transport of the Florida Current of up to 15 Sv (50 percent of the mean flow of 30 Sv) lasting up to 40 days. These results are in conflict with the presently accepted belief that the variations are mainly confined to periods shorter than 14 days with a small 10 percent annual variation. In fact, the volume transport of the Florida Current is highly variable. Thus continuous day-to-day recordings of transport are necessary for an accurate observation of the Florida Current, and observations over many years are needed to determine statistically the mean annual variation. In time, such data will provide a valuable record of annual and interannual fluctuations that are important to studies of the influences of the Florida Current–Gulf Stream on climate. That record, for example, will be vital to a study of the relation between western boundary current transport and basinwide wind stress and of the meridional heat transport of the North Atlantic at 27°N.

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3. Abrupt changes in the cable voltages began after 2 March 1983. Changes of 0.2 to 0.4 V occurred within an hour, creating a new base level for periods from a few hours to days. Identical voltage changes were observed on a second system attached to the cable conductor in which a lead electrode was used for ground. These unexpected voltage changes are most likely caused by the switching of the cable-seawater contact at the broken end between the steel armor and the copper center conductor. The voltage difference between the armor and copper is −0.75 V in seawater. The changes may be caused by corrosion, bottom currents, or sediment movements at the break site. It was possible to correct the data for these abrupt changes. The magnitude of the jump (after the geomagnetic noise and tidal variations are first removed) is the difference in the projected values at the jump, based on two linear trends that use all available data 24 hours before or after the jump. The magnitude of the offset was found to be essentially constant during a disruption and was therefore given by the mean of the magnitudes of the jump obtained at the start of the disruption and at the return to normal. There were 142 days of cable data that were corrected by adding these estimated offsets. Of course, the most direct way to eliminate these offsets is to repair the cable break.
4. There is significant contamination in the cable data due to geomagnetic disturbances caused by the time-varying, large-scale electric currents flowing in the ionosphere and magnetosphere (*5*). In fact, geomagnetic disturbances and ocean tides are the major source of variations in the cable data for periods less than 2 days. The tidal variations can be estimated and removed by the usual tidal analysis. One can largely remove the geomagnetic variations by using the north magnetic components at Fredericksburg, Virginia, and San Juan, Puerto Rico, which have a coherence squared of 0.82 with the cable voltage and leave a residual variability of 17 mV root-mean-square.
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10. In general, the cross-stream voltages will be given by the horizontal integral of the conductivity-weighted mean flow less any voltages due to large-scale electric currents (*9*):

$$\Delta\phi = \int_0^W F_z\, \bar{v}^*(x)\, dx - \int_0^W J_x^*/\sigma\, dx$$

where W is the stream width, $\mathbf{J}^*$ is the electric current due to nonmotional sources and nonlocal motional induction, σ is the electrical conductivity, and $\bar{v}^*$ is the vertical mean of the conductivity-weighted downstream component of velocity. From (*9*),

$$\bar{v}^* = \frac{\int_{-H}^{0}\sigma v\, dz}{\int_{-Z}^{0}\sigma dz} = \frac{\overline{\sigma v}}{\bar{\sigma}\bar{v}} \cdot \frac{\bar{v}}{1+\lambda}$$

where H is the water depth and $\int_{-Z}^{0} \sigma dz$ is the conductance of the seawater and sediments down to a depth Z (essentially, all electric currents flow at depths shallower than Z); λ is the ratio of the earth's conductance to depth Z to the ocean's conductance. If there were no electric current flowing into the sea floor, λ would be zero. If there were a shallow zone of nonconducting sediments starting at $z = -H_s$, then $Z = H_s$. But, in general, $Z \leq W$, since little current penetrates deeper than a depth equal to the channel width. The nonlocal motionally induced voltages caused by remote variations in the Florida Current can be shown by a simple model to be insignificant because the depth is uniform downstream and the width of the stream is narrow and locally straight.

The conductivity weighting can be expressed as

$$\frac{\overline{\sigma v}}{\bar{\sigma}\bar{v}} = <\frac{\overline{\sigma v}}{\bar{\sigma}\bar{v}}> + \left(\frac{\overline{\sigma v}}{\bar{\sigma}\bar{v}}\right)'$$

where <> represents a cross-channel average and ( )′ represents deviations from average. The <> term for the 63 days is 1.06 ± 0.02; this value is based on the profiling velocity and temperature data and on the assumption that conductivity is a linear function of temperature. It is therefore nearly constant in time; the root-mean-square of the deviation term is 0.04 and will be ignored. Since <> term has been found to be nearly constant in time, the effects of temperature are negligible. Hence,

$$\Delta\phi(t) = <\frac{\overline{\sigma v}}{\bar{\sigma}\bar{v}}> \int_0^W \frac{F_z \bar{v}(x,t)\, dx}{1+\lambda(x)}$$

where nonlocally generated electric currents ($\mathbf{J}^*$) have been ignored. Since the transport is given by

$$T(t) = \int_0^W H(x)\, \bar{v}(x,t)\, dx$$

Eq. 1 implies that

$$H_e <\frac{\overline{\sigma v}}{\bar{\sigma}\bar{v}}> \int_0^W \frac{\bar{v}(x,t)\, dx}{1+\lambda(x)} = \int_0^W H(x)\, \bar{v}(x,t)\, dx$$

where F_z is assumed uniform. Since the Florida Straits at the cable site are relatively narrow and shallow, we expect the flow within the Straits to be dominated by temporal changes in the intensity of the flow rather than by changes in the cross-stream velocity structure. One can then write

$$\bar{v}(x,t) = X(x)\, V(t)$$

where $X(x)$ is the cross-stream velocity profile and $V(t)$ is the time dependence of the flow. In this case,

$$H_e <\frac{\overline{\sigma v}}{\bar{\sigma}\bar{v}}> \int_0^W \frac{X(x)\, dx}{1+\lambda(x)} = \int_0^W H(x)\, X(x)\, dx$$

which defines H_e in terms of the depth H, the cross-stream profile X, and the conductance ratio λ. This formulation shows that H_e will then be a time-invariant, geometric factor.

One of the long-standing controversies about submarine cable measurements is the influence of lateral shifts in the position of the current. This effect has been blamed for voltage changes that appear to be unrelated to volume transport variations. This influence is small in the present case. The reason for this is that the conductance depth $H(x)[1 + \lambda(x)]$ has been observed in recent Pegasus and expendable current [T. B. Sanford, R. G. Drever, J. H. Dunlap, E. A. D'Asaro, *Univ. Washington Appl. Phys. Lab. Rep. 8110* (1982)] profiling to be nearly uniform along the submarine cable. One cause for this behavior is that in shallow water H is small but λ is larger because the sediments are thick; in deep water H is large and λ is smaller. To the extent that $H(1 + \lambda)$ is nearly uniform across the Straits, it can be brought outside the lateral integral. Then the expression for $\Delta\phi$ is:

$$\Delta\phi \doteq <\frac{\overline{\sigma v}}{\bar{\sigma}\bar{v}}> \frac{F_z}{<H(1+\lambda)>} \int_0^W H\, \bar{v}\, dx =$$

$$< \frac{\overline{\sigma v}}{\bar{\sigma}\bar{v}} > \frac{F_z T}{<H(1+\lambda)>}$$

Thus $\Delta\phi$ is related to transport by the time-invariant, geometric factor and tracks transport even if there is some east-west shift of the current, provided the shift is confined to the

deeper parts of the Straits. An analysis of the profiling data shows that the root-mean-square of the variations in transport is 3.1 Sv due to strength changes and 0.7 Sv due to velocity structure changes. Occasionally, such as during 1982 Julian day 164–169, the intensity and structure changes are nearly equal. Even during this event the cable tracked the transport. One expects that the cable voltage will be better correlated with conductivity-weighted transport than with the simple volume transport. In fact, there is no significant difference, and we chose to express the cable voltage in terms of volume transport.

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Sea Level Variation as an Indicator of Florida Current Volume Transport: Comparisons with Direct Measurements

Abstract. *Sea level measurements from tide gauges at Miami, Florida, and Cat Cay, Bahamas, and bottom pressure measurements from a water depth of 50 meters off Jupiter, Florida, and a water depth of 10 meters off Memory Rock, Bahamas, were correlated with 81 concurrent direct volume transport observations in the Straits of Florida. Daily-averaged sea level from either gauge on the Bahamian side of the Straits was poorly correlated with transport. Bottom pressure off Jupiter had a linear coefficient of determination of* $r^2 = 0.93$, *and Miami sea level, when adjusted for weather effects, had* $r^2 = 0.74$; *the standard errors of estimating transports were* $\pm 1.2 \times 10^6$ *and* $\pm 1.9 \times 10^6$ *cubic meters per second, respectively. A linear multivariate regression, which combined bottom pressure, weather, and the submarine cable observations between Jupiter and the Bahamas, had* $r^2 = 0.94$ *with a standard error of estimating transport of* $\pm 1.1 \times 10^6$ *cubic meters per second. These results suggest that a combination of easily obtained observations is sufficient to adequately monitor the daily volume transport fluctuations of the Florida Current.*

Monthly changes in the Florida Current volume transport have been related to departures in monthly mean sea level from the historically averaged monthly mean sea level at certain coastal stations (*1*). In the Straits of Florida, monthly mean sea level departures from the historical mean at Miami or at Key West were much larger than at Cat Cay, Bahamas. It was reasoned that changes in the mean sea level at Cat Cay reflect changes in the western Sargasso Sea, whereas at Miami and Key West sea level changes reflect variations in the surface discharge through the Straits (*2*). Techniques of spectrum analysis have also been applied to hourly sea level records and to bottom pressure records in the Straits (*3*), but correlations with volume transport were generally inconclusive because of a lack of accurate transport measurements. Recent advances in navigation and current profiling (*4*) provide transport measurements of sufficient accuracy with which to reassess the role of sea level as an indicator of Florida Current variability.

Sea level slope is an indirect but generally accepted first-order measure of ocean surface current velocity in extratropical regions. The basis for this measure is the relationship

$$f[V(0) - V_a(0)] = g\, dh/dx$$

in which $V(0)$ is the south-north surface velocity, $V_a(0)$ is the ageostrophic surface velocity and includes temporal and frictional effects, g is gravity, f is the Coriolis parameter, dh is the differential height of the sea above an equipotential surface where the vertical coordinate $z = 0$, and dx is the differential east-west dimension. The average surface current across a section is

$$<V(0)> = \Delta hg/fL + <V_a(0)>$$

where L is the width of the section at the surface and Δh is the difference in the sea level height. The distribution of northward flow in the Straits may be written as

$$V(x,z) = <V(z)> + V'(x,z)$$

where

$$\iint V'(x,z)dxdz = 0$$

Then the true volume transport (T) may be expressed as

$$T = \int_0^H \int_a^b V(x,z)dxdz = \Delta hg/fL \left[\int_0^H (b-a)G(z)dz\right] + \int_0^H (b-a)<V_a(z)>\, dz \qquad (1)$$

where $(b - a)$ arises from application of the mean value theorem to the cross-stream integral from $x = a$ to $x = b$, H is the maximum depth of the section over which the stream-wide transport per unit depth is summed, and $G(z)$ is defined by $<V(z)> = <V(0)>\, G(z)$. Equation 1 shows that a linear regression of transport on sea level difference is a statistical determination of the equivalent barotropic depth of the current and of the ageostrophic effects in whatever detail is warranted.

Figure 1 shows time series from April 1982 to August 1983 of monthly means of Cat Cay sea level (CCSL) minus Miami sea level (MISL), Key West sea level (KWSL) minus MISL, inverted MISL, volume transport estimated from the electromagnetic cable (*5*), and volume transport estimated by moored current meters (*6*). Each of the monthly means shows the same basic pattern, but each also shows significant differences. Monthly mean differences between the cable and the moored current meters are

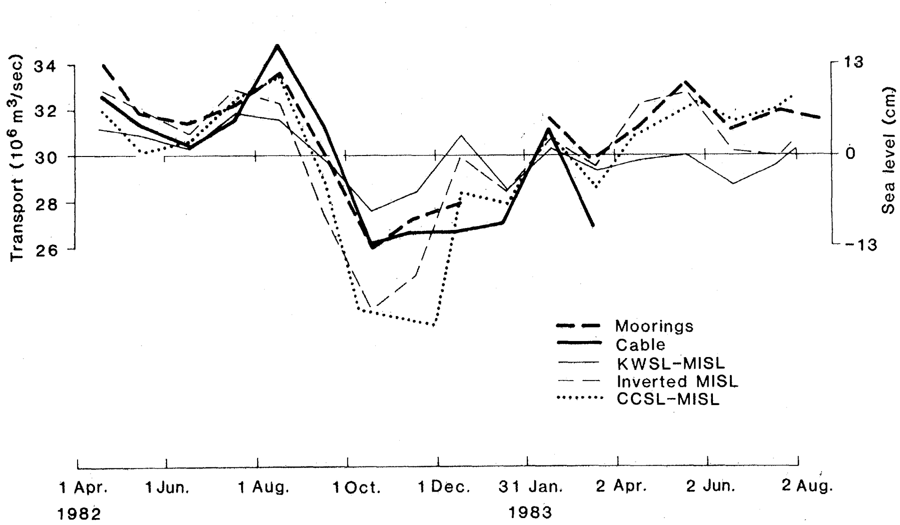

Fig. 1. Plot versus time of the mean monthly cable transports (*5*), mean monthly moored current meter transports (*6*), Key West minus Miami sea levels, Cat Cay minus Miami sea levels, and inverted Miami sea levels.