Temperature transport and motional induction in the Florida Current

by Thomas B. Sanford[1]

ABSTRACT

Differences of electrical potential across the Florida Current between Jupiter, Florida, and Settlement Point, GBI, are interpreted in terms of mean and seasonal temperature transports. The potential differences arise from the lateral transport of electrical conductivity through the vertical component of the earth's magnetic field. Using the temperature and conductivity relation in the Current, the conductivity transport can be converted to temperature transport. In contrast to previous measurements between Key West and Cuba, the present observations lack large (factor of two), short-period voltage fluctuations. The mean voltage of 1.2 V is about that expected from the known mean volume transport and bottom conductance. The corresponding mean temperature transport is about that reported from direct measurements. The annual or seasonal variation of 95 mV is about the same relative to the mean as found in tide gauge and ship drift measurements. The annual transport inferred from the cable voltage is about one-half that observed in direct transport determinations. The shorter period disturbances contain little energy excess in the 4-14 day period seen in previous observations. The continued use of this submarine cable is proposed in order to collect long-term transport and ocean climate observations.

1. Introduction

The Florida Current is the strongest, most localized and stable current in the North Atlantic Ocean. It plays a crucial role in the circulation (Worthington, 1976) and oceanic heat transport (Bryden and Hall, 1980) of the North Atlantic Ocean. Fofonoff (1981) reviews the considerable volume of Florida Current observations and notes that it "emerges as the part of the Gulf Stream System that is best documented, analyzed and understood." It is recognized, but regrettable, that even under the best of circumstances our understanding is based on meager data, sparsely sampled over brief periods of observation. Longer, more densely-sampled observational series are needed in the Florida Straits and elsewhere; for example, such are needed to measure the mean and fluctuations of heat and mass transport. One underutilized data resource is the motional electric field within the Florida

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Current. This field and its spatial integral, the potential difference across the Current, arise from and reflect the flow and its variations. The purpose of this paper is to present a 32-month time series of motionally-induced potential differences across the Current and to interpret these observations in terms of meridional temperature transport. Included in the analysis is a comparison of the present data with previous observations.

A considerable volume of submarine cable measurements predates the more modern direct observations (Fofonoff, 1981). Wertheim (1954) observed the potential differences between Key West, Florida, and a site outside Havana, Cuba. After early attempts to interpret the potential differences in terms of volume transport, it has been concluded that much of the fluctuation in potential is due to lateral shifts of the axis of the current over variable bottom topography (Schmitz and Richardson, 1968) and aliased geomagnetic interference. Based on this experiment, the motional induction approach using long submarine cables has largely been discredited.

Under the circumstances, a justification is needed for re-evaluating or continuing submarine cable measurements. They are, first of all, of long duration and frequently continuous. Second, the signal represents an integral over the flow which is related to bulk properties of the flow such as volume and temperature transport. Third, in many situations, the interpretation is straightforward and accurate. Fourth, alternative measurements are sparse, discontinuous or unavailable. It is recognized that continuous and long-duration measurements of oceanic flow are needed for a variety of purposes, especially in ocean climate research. It is not, however, well accepted that motionally-induced electric and magnetic fields can, in fact, provide a means of monitoring ocean mass and heat transports. The principal goals of this paper are to interpret a particular set of observations, to relate them to the theory of induction and to encourage similar observations in situations where alternatives are unavailable.

The present measurements were begun in 1969 on a submarine cable between Jupiter, Florida, and Settlement Point, Grand Bahama Island. The voltage between GBI and Florida was recorded for several years before the measurements were suspended in 1975 due to equipment failures. These measurements are not the first potential difference observations in the Florida Straits, but they are the only continuous, long-duration ones, and were obtained in a region of the Florida Current that is more stable (having less lateral or cross-stream movement), flowing in a channel of more rectangular cross section. Hence, in contrast to the previous measurements between Key West and Cuba, the present observation can be more accurately interpreted in terms of transport.

In this paper the theory of motional induction is reviewed, the roles of conductivity and its transport are discussed, and an assessment is made of the utility of such measurements. Discussion of the observations is followed by a section on data analysis and interpretation and a concluding summary.

2. Motional induction

Sanford and Schmitz (1971) presented the relationships among flow, electric currents and electric potential in the Florida Straits region off Miami. They found that the motionally-induced voltage between Miami and Bimini could be used to measure volume transport to an uncertainty of about 10%. However, no submarine cable exists at this section. The cable used for the present work is about 100 km north of the Miami-Bimini line.

The theory of motional induction as relevant to cable measurements is presented by Longuet-Higgins (1949) and Longuet-Higgins *et al.* (1954). The principal theoretical approach was to model channels as having elliptical cross sections overlying a subfloor structure of uniform electrical conductivity. Both this model and the rectangular channel, nonconducting, bottom model of Malkus and Stern (1952) predict a voltage-to-transport relation of the form

$$T_v = \frac{H_e \Delta\phi}{F_z}, \tag{1}$$

where T_v is the volume transport, $\Delta\phi$ the potential difference, H_e the equivalent depth (dependent on real depth, channel width, seawater and seabed conductivities, and the spatial distribution of current in the channel) and F_z the vertical component of the earth's magnetic field. The equivalent depth may be thought of as the depth of the channel plus the thickness of the sub-bottom layer normalized to be electrically equivalent to a layer of sea water averaged across the channel.

That the conductivity of the sea bottom can be important is clearly revealed in the present measurements. Using only the actual mean depth of 482 m and allowing for no sub-bottom conductivity, the expected voltage for the 29.5×10^6 m^3/s mean transport of Niiler and Richardson (1973) through a vertical magnetic field of -0.43×10^{-4} T results in an expected induced voltage of 2.6 V, about twice that observed. This result shows that bottom conductance, the vertical integral of the subsea conductivity along the Jupiter-Settlement Point submarine cable is equivalent on average to that of the water column (i.e., H_e is about two times the mean depth). Such large bottom conductances were not expected. The Miami-Bimini area studied by Sanford and Schmitz (1971) has a bottom to water conductance ratio of 0.1. Hence, there appears to be a large change in channel structure and properties over the 100 km between Miami and Jupiter. A large bottom conductance serves to reduce the influence of lateral shifts of the Gulf Stream axis since it is not the actual depth over which the current flows, but the equivalent depth, that determines the induced signal level. This point will be pursued later, but for now it is important to emphasize that a large bottom conductance not only reduces the induced signal strength (a disadvantage), but also reduces the effect of lateral shifts of the Stream over the channel depth (an advantage). The highly-conducting bottom situation is discussed further by Sanford and Flick (1975).

The channel model presented in Figure 1 is based on actual bottom depths (H).

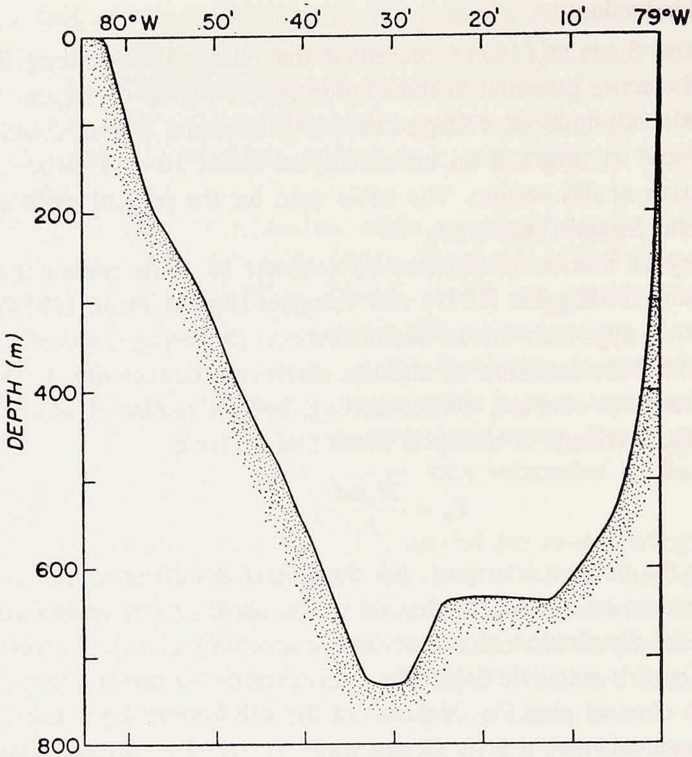

Figure 1. Channel between W. Palm Beach, Florida, and Settlement Point, Grand Bahama Island.

The electrical conductivity (σ) is a continuous variable in the domain $0 \leqslant z \leqslant -\infty$ with a finite conductance or vertical integral. The coordinate system is x, u directed across the Stream (East), y, v directed along the Stream (North), and z is up. The steady geomagnetic field is represented as $\mathbf{F}$. The relationships of Sanford (1971) and Sanford and Flick (1975) obtain in this situation. The potential difference ($\Delta\phi$) across the Stream ($0 \leqslant x \leqslant w$) is

$$\Delta\phi = F_z \int_0^w \bar{v}^* \, dx - \int_0^w J_x^*/\sigma dx\,, \tag{2}$$

where

$$\bar{\mathbf{v}}^*(x) = \frac{\int_{-H}^{0} \sigma(x,\xi)\mathbf{v}(x,\xi)d\xi}{H\bar{\sigma}[1+\lambda(x)]} \equiv \frac{\overline{\sigma\mathbf{v}}}{\bar{\sigma}(1+\lambda)}\,, \tag{3}$$

$$\mathbf{J}^* = \nabla x \frac{\nabla\sigma}{2\pi|\nabla\sigma|(1+\lambda)} \int_{-\infty}^{\infty} \int (\nabla \cdot F_z\bar{\mathbf{v}}^*) \ln[(x-x')^2+(y-y')^2]dx'dy', \tag{4}$$

$$\bar{\sigma} = \frac{1}{H} \int_{-H}^{0} \sigma d\xi \, , \tag{5}$$

and

$$\lambda = \frac{1}{H\bar{\sigma}} \int_{-\infty}^{-H} \sigma d\xi \, . \tag{6}$$

The induced potential difference is produced by a local contribution driven by $\bar{\mathbf{v}}^*$ and a nonlocal contribution ($\mathbf{J}^*$) caused by the spatial distribution from the flow of electric currents trying to "short circuit" zones of high potential gradient (i.e., large $\bar{\mathbf{v}}^*$) through regions of lower $\bar{\mathbf{v}}^*$. The analytical form for $\mathbf{J}^*$ is based on a laterally-unbounded ocean, and should be used with caution in the present situation. Nonetheless, its form reveals how the nonlocal currents arise due to the divergence of $F_z\bar{\mathbf{v}}^*$ and allows order-of-magnitude estimates of $\mathbf{J}^*$ to be made. To the extent that the channel is essentially two-dimensional, having no pronounced downstream variations to the flow or bottom topography or conductivity, then the $\mathbf{J}^*$ contribution will be small. This condition pertains in the Florida Straits, at least in the region bounded by Florida and the Bimini Islands, as has been shown by Sanford and Schmitz (1971).

Returning to the major term, $F_z\bar{\mathbf{v}}^*$, it is apparent that this is a conductivity flux term. Specifically, $H\overline{\sigma\mathbf{v}}$ is the flux of conductivity per unit cross-stream distance. A measure of the influence of conductivity weighting is the quantity $\bar{v}^*/\bar{v}$, which is composed of a water column term, $\overline{\sigma v}/\bar{\sigma}\,\bar{v}$, divided by the factor $(1+\lambda)$ depending on the relative water/sediment conductances. Recall that the total water column conductance is represented as $H\bar{\sigma}$ and that of the sediments as $H\bar{\sigma}\lambda$. Hence, the total water sediment conductance is $H\bar{\sigma}(1+\lambda)$. Sanford and Schmitz (1971) discussed the conductivity weighting and found for the Miami-Bimini section that the conductivity velocity correlation term (with respect to depth, not time) was about 1.1. The $1+\lambda$ term, however, was also about 1.1, essentially canceling the $\overline{\sigma v}/\bar{\sigma}\,\bar{v}$ effect.

That $\bar{\mathbf{v}}^*$ is a conductivity flux quantity has not been recognized in previous discussions of cable measurements. It has long been realized that $\Delta\phi$ is not a direct measure of volume transport, but the role played by σ has not been emphasized. The effect of σ is, in fact, secondary (in the Florida Current) to that of other influences, and its importance results primarily in that conductivity can be represented by a linear function of temperature. In this way, $\Delta\phi$ can be more usefully thought of as a temperature transport observation. An example of the temperature/electrical conductivity correlation is shown in Figure 2 for the Florida Straits.

The potential across the submarine cable is given by

$$\Delta\phi = \int_{0}^{w} \frac{F_z H\overline{\sigma v}}{H\bar{\sigma}\,(1+\lambda)}\, dx \, , \tag{7}$$

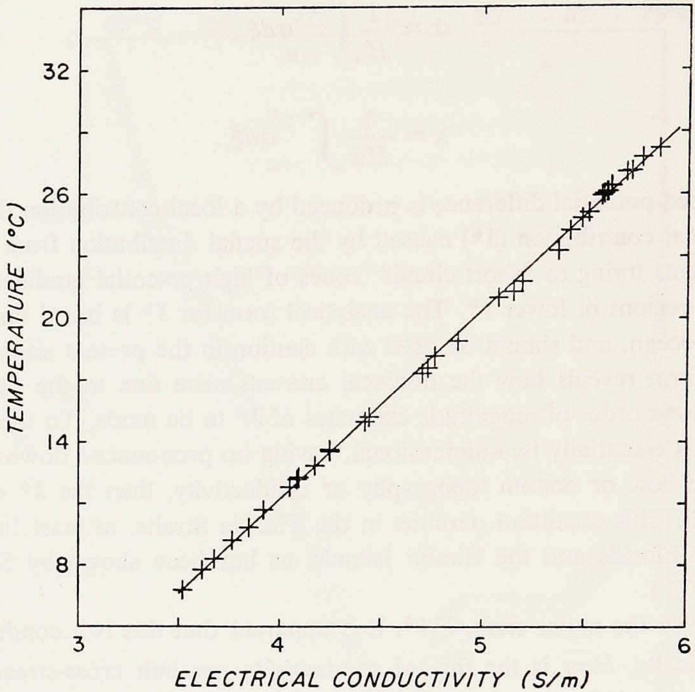

Figure 2. Temperature versus electrical conductivity for stations in the Florida Current between W. Palm Beach and Settlement Point. The least squares regression line is $t = 9.19\sigma - 25.5°C$. The rms deviation is 0.23°C.

excluding J* contributions. It is useful to separate the integrand into the cross-channel average and deviation contributions. That is, let

$$\overline{H\sigma v} = <\overline{H\sigma v}> + (\overline{H\sigma v})' \text{ and } F_z/H\overline{\sigma}(1+\lambda) =$$

$$\frac{1}{w}<[F_z/H\overline{\sigma}(1+\lambda)]> + [F_z/H\overline{\sigma}(1+\lambda)]' , \quad (8)$$

where

$$<(\quad)> = \frac{1}{w}\int_o^w (\quad)dx \quad (9)$$

and

$$\int_o^w (\quad)' \, dx = 0 . \quad (10)$$

Then

$$\Delta\phi = w<\overline{H\sigma v}><F_z/H\overline{\sigma}(1+\lambda)> + w<(\overline{H\sigma v})'[F_z/H\overline{\sigma}(1+\lambda)]'> . \quad (11)$$

The term $w<\overline{H\sigma v}>$ is the lateral transport of electrical conductivity, which will be denoted as T_σ, and the term $<F_z/H\overline{\sigma}(1+\lambda)>$ is a constant dependent on the earth's magnetic field and the channel electrical conductivity structures. Hence, the transport of σ is

$$T_\sigma = \frac{\Delta\phi}{<F_z/H\bar{\sigma}\,(1+\lambda)>} - \frac{w<(H\overline{\sigma v})'[F_z/H\bar{\sigma}(1+\lambda)]'>}{<F_z/H\bar{\sigma}\,(1+\lambda)>}. \quad (12)$$

Formulated in this way, it is easy to see that the deviation product term vanishes if H, λ and F_z are uniform over the cable or if $H\overline{\sigma v}$ is uniform. In nature, neither of these deviation terms is expected to vanish. At best, it is possible to estimate their contribution and choose measurement sites at which the second term on the right-hand side is small.

The time variability of H_e has led to the difficulties in understanding $\Delta\phi$ measurements such as those of Wertheim (1954). For example, Wertheim observed a factor of two range in $\Delta\phi$ while Schmitz and Richardson (1968) found a range of only about $\pm$10-15% about the mean of T_v. Sanford and Schmitz also reported for the Miami-Bimini section that $H_e(t) = 624$ m with a standard deviation of 39 m or about 6%. The "catastrophic" fluctuations in $\Delta\phi$ observed by Wertheim between Key West and Cuba are certainly caused by variations in H_e due to axial shifts of the Stream not present or significant in the Miami-Bimini section.

In the case of the Florida Current off Miami, Sanford and Schmitz (1971) evaluated a term similar to that defined here as $w<(H\overline{\sigma v})'[F_z/H\bar{\sigma}(1+\lambda)']>$ and found that the effects due to $\overline{\sigma v}$ canceled those from λ. Thus, an estimate of the term there can be obtained from the expression $w<(H\bar{v})'(F_z/H)'>$. Off Jupiter, the effects of σ and λ are not small and compensating, and the full expression for the cross-term of perturbations must be used.

3. The measurements

Starting in January 1970, a nearly continuous series of potential measurements has been made on a submarine cable between Jupiter, Florida, and Settlement Point, Grand Bahama Island (Fig. 3). The submarine cable was installed by the Western Electric Company.

The cable consists of a central core of copper surrounded by an insulation layer of polyethylene. Around the polyethylene are helical bands or tapes of copper to form the coaxial structure of the cable. A thick layer of natural fibers covers the copper tapes. Surrounding the whole are layers of steel armor. Besides the high isolation of the cable ($>10^6\ \Omega$) and low resistance ($150\ \Omega$), it is important to note that the copper tapes are in contact with sea water which is free to penetrate the wraps of the armor and the underlying fibers. The physical arrangements for the cable are diagrammed in Figure 4.

From the start of measurements through late November 1970, the cable measurements were made using silver-silver chloride electrodes at each end of the cable.

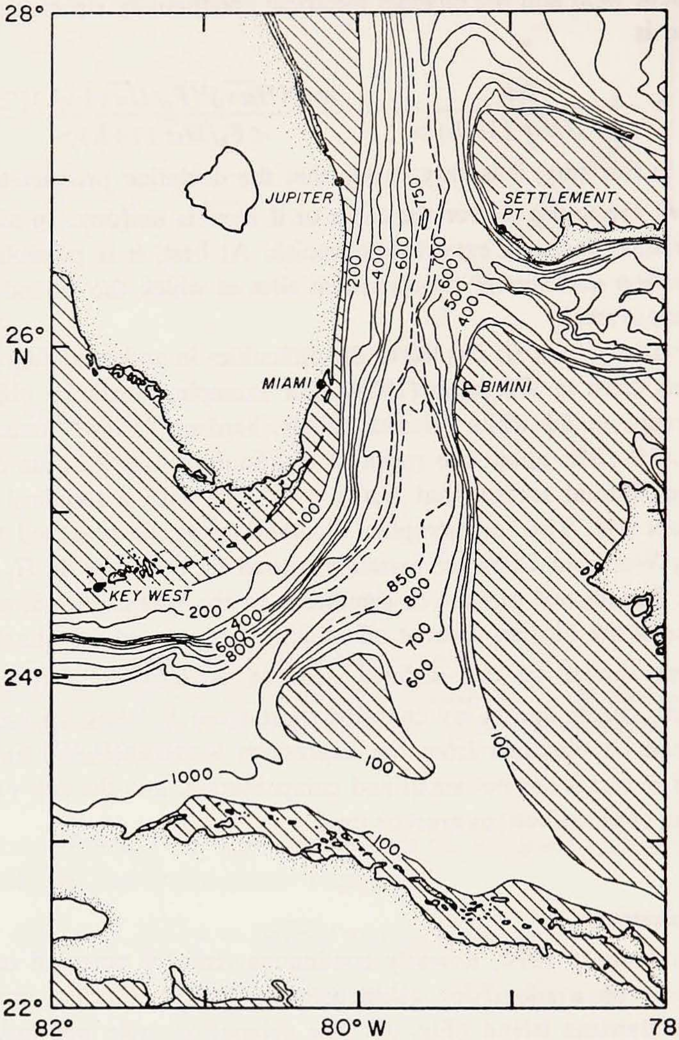

Figure 3. Chart of measurement location and bottom topography (in meters).

At Settlement Point the center conductor was attached to passive, low-pass filters to remove the high-frequency telemetry and voice signals, then to a cable section leading back to the sea and to a submerged silver-silver chloride electrode. At Jupiter, a cable section was buried from the filter hut back to the Intracoastal Waterway and terminated with a silver-silver chloride electrode. Hence, at Jupiter, the voltage between the cable conductor and the local electrode was the voltage between Florida and GBI plus any contamination such as electrode offsets and induction within the cable. The system performed well except that it was difficult

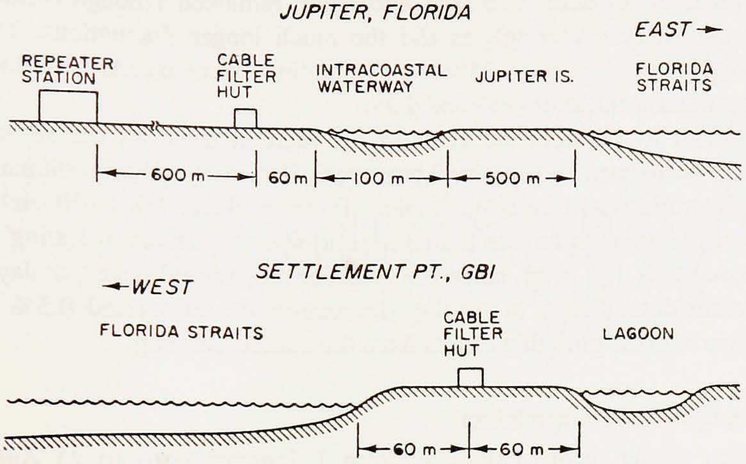

Figure 4. Sketch of the measurement configuration.

to maintain the electrodes. Some electrodes disappeared for no known reason; some solder joints became uninsulated; and once a barge tied up to the electrode housing, a PVC pipe partially exposed on the bank of the Intracoastal. After November 1970, it was decided to use the tapes at each end for electrodes. An experiment was conducted in which voltage measurements were made alternately between silver-silver chloride electrodes at each end of the cable and between the copper tapes. The voltages were equal to within 10 mV, or about 1% of the average signal level. From then on, the tapes were used as the local electrodes.

It is assumed that the potential distribution in the tapes is the same as that in the water, as confirmed by the above test against silver-silver chloride electrodes, but the use of tapes as electrodes (e.g., sensing volume, drift, etc.) needs more study.

The measurements were recorded on analog strip charts manually annotated with date and time. The date and time were written as frequently as every 8 hours at the start of this work and as seldom as once per several days toward the end. The recorders were installed in a cable support facility at Jupiter until June 1972. When this facility was no longer available, the recorders were installed at the U.S. Coast Guard Station at Jupiter. A special underground cable was installed from a point of access to the cable to the station. From mid-1972 until the measurements were suspended in early 1975, the recorders were looked after by Coast Guard personnel at Jupiter.

The records were digitized every hour, but an "eyeball" low-pass filter was applied by the author prior to digitization. Due to occasional large amounts of geomagnetically-induced variability on the record, it was thought best to filter visually these nontransport components. The filtering consisted of drawing a smooth curve over several hours of data. The tidal fluctuation remained (though certainly influenced by the ad hoc filtering), as did the much longer fluctuations. The drawn line was digitized every hour. Missing observations were inserted by linear interpolation between sections of recorded data.

It is difficult to estimate the error in the method since all the recording and logging were performed by untrained personnel. Errors in using the submarine cable tapes as electrodes have been mentioned as being about 1%, drift errors in the recorders are thought to be less than 1%, and operator errors in setting zero have been removed at a 1% level, since the recorder was zeroed once per day for most of the present data. Errors in reading the records do not exceed 0.5% rms. The major source of error probably results from the manual filtering.

4. Data analysis and interpretation

A portion of the record extending from 1 January 1970 to 23 August 1972 has been chosen for analysis. Additional data exist, but the quality of these data is inferior due to larger gaps and more time uncertainty caused by longer servicing intervals. The total record statistics are a mean voltage of 1.21 V and the standard deviation of 0.165 V. The ratio of rms variability to the mean signal is 13%, which is larger than the 9% observed by Schmitz and Richardson (1968) from direct measurements. Since about ¼ of the variance is due to tidal constituents [Düing *et al.* (1977)], and since the tidal period constituents are influenced by the data filtering used prior to digitization, a Groves (1955) D35 filter has been applied to the time series to reduce diurnal and semidiurnal components. The detided result is plotted in Figure 5. The standard deviation of this record is 0.129 V.

The cable measurements clearly show a seasonal signal with a minimum around November and a maximum in late summer, July through September. There exists a rapid deceleration of flow between September and November. The seasonal variations can be compared with the observations of ship drift by Fuglister (1951) and Cat Cay-Miami tide gauge differences by Pattullo *et al.* (1955). All three data sets are plotted in Figure 6 as the monthly values divided by the annual mean. For the tide gauge data, an annual mean of 66 cm due to the annual mean surface current is assumed (Wunsch *et al.*, 1969). Each set of observations shows the marked deceleration in the fall followed by a gradual growth to a maximum in late summer. The mean, annual and semiannual components of each measurement series are listed in Table 1.

These data indicate a seasonal variability to the cable voltages that agrees in amplitude and phase with other measurements. The phase (relative to 1 January) of the cable observations is slightly larger, indicating a small delay relative to the surface indications of the ship drift and tide gauge. This delay may result from the seasonal change of σ which can be inferred from the annual steric anomaly. The latter is 9.4 cm in amplitude (Table 1), which translates to a temperature change

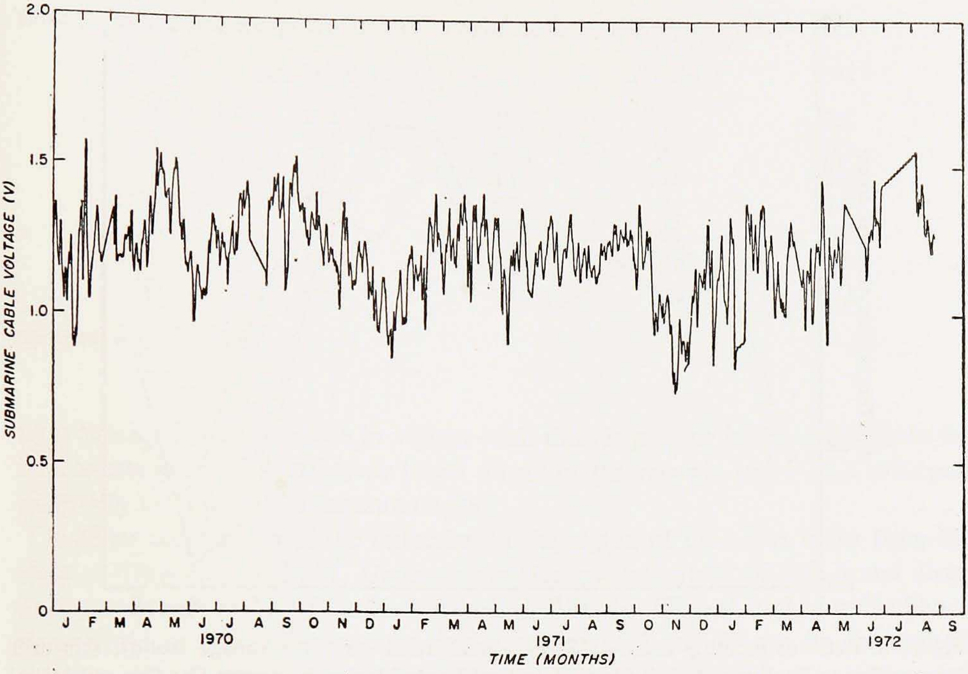

Figure 5. Detided cable voltages.

of 0.5°C at a phase of 256°. This small temperature change would shift the conductivity transport by ~ 10° relative to the volume transport.

In the Key West-Havana area, the cable voltages for the period 1952 through 1961 yield an annual cycle to mean ratio of 6.0% at a phase of 125° (Maul *et al.*, 1978).

More recent subsurface measurements reveal similar seasonal variability to the Florida Current. Niiler and Richardson (1973) reported an annual mean transport of 29.5 × 10^6 m^3/s with an annual component of 4.0 × 10^6 m^3/s or 14% of the annual mean at a phase of 155°. The moored current meter observations of Düing *et al.* (1977) contained an annual velocity component of 11% of the annual mean at a phase of between 120° and 140°. The cable ratio of annual variation to mean is 7.5%, and the phase is 175°.

Of all the data sets, the statistics of the dropsonde measurements of Niiler and Richardson (1973) should be the most comparable to the cable measurements. The other observations, except the Key West-Havana cable voltages, are of surface flows or at a single mooring site. The agreement with the dropsonde data, however, is reasonable in phase but about a factor of two different in the annual component to annual mean.

Because the Niiler and Richardson (1973) transport measurements are spread

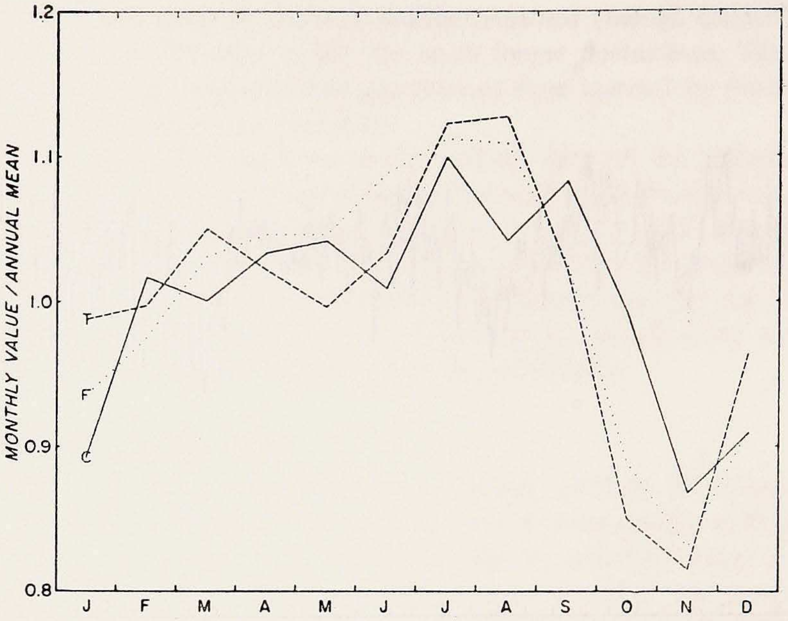

Figure 6. Ratio of monthly mean value to annual mean for cable voltage (solid), ship drift according to Fuglister (1951) (dotted) and sea-level differences between Cat Cay and Miami from Pattullo *et al.* (1955) (dashed) observations.

over a period of seven years, it is possible that the seven-year series should not be treated as statistically homogeneous. For example, all of the winter measurements occur in the second half of the series. It is, therefore, difficult to distinguish between a low winter value due to an annual cycle and one resulting from a long-

Table 1. Mean, annual and semiannual components; phase in degrees after 1 January.

	Mean	Annual Amp.	Annual Phase	Semiannual Amp.	Semiannual Phase
Cable	1.21 volts	0.095	175°	0.055	114°
Ship drift (Fuglister, 1951)	59 miles/day	6.5	161°	2.9	65°
Cat Cay-Miami tide gauge (Pattullo *et al.*, 1955)	66 cm	5.5	155°	5.4	58°
Steric anomaly Florida current (Pattullo *et al.*, 1955)	0.1 cm	9.4	256°	0.58	78°

Table 2. Results of the combined two sections of Chew *et al.* (1971).

Pos. (km)	Depth (m)	$\bar{v}$(cm/s)	$\bar{v}^*$(cm/s)	1+λ *
10	256	67	10	7.2
20	420	101	23	4.7
30	604	111	53	2.2
40	731	97	38	2.7
50	677	93	42	2.4
60	585	63	29	2.3
70	440	43	20	2.3

*Assumes $\overline{\sigma v}/\bar{\sigma}\,\bar{v} = 1.07$

term trend. A small decrease in voltage with time is present in the cable data: the time trends are −13.4 mV/year based on all of the records and −77.2 mV/year using only 1970 and 1971 measurements.

A direct comparison of the induction in the region of the cable exists from the work of Chew *et al.* (1971). Geomagnetic electrokinetograph (G.E.K.) and dropsonde measurements were obtained between Ft. Pierce, Florida, and Mantilla Shoal, Grand Bahama Island. From these data a section of $\bar{v}$ and $\bar{v}^*$ can be determined. The inferred G.E.K. velocity is taken to be $v_s - (\bar{v}^* - J_x{}^*/F_z\sigma)$, where v_s is the north component of surface velocity. Combining the G.E.K. and directly-measured surface current and multiplying by F_z yields $F_z\bar{v}^* - J_x{}^*/\sigma$, which has a cross-stream integral of 0.92 V. The value of $J_x{}^*/\sigma$ has not been separately measured, but Sanford and Schmitz (1971) evaluated it off Miami and found it to be negligible. The flow conditions are similar at the Ft. Pierce section, and $\mathbf{J}^*/\sigma$ will be ignored.

The influence of electrical conductivity according to (3) has two components. First, $\bar{v}^*$ is dependent on the velocity/conductivity covariance, which can be expressed in nondimensional terms as $\overline{\sigma v}/\bar{\sigma}\,\bar{v}$. This factor can be determined from the ratio of baroclinic to barotropic heat transports in the Florida Current from Bryden and Hall (1980) and the temperature/conductivity relation of Figure 2. The average value across the section is 1.07. The lateral integral of $F_z\overline{\sigma v}/\bar{\sigma}$ is the open circuit potential and amounts to 2.7 V. Second, the factor of 1+λ must be computed. Using the value of 1.07 for the conductivity correlation term, it is possible to determine λ from the measurements of Chew *et al.* (1971). Table 2 summarizes these results.

The open-circuit potential difference is reduced by the shorting effect of the seabed. Sanford and Schmitz (1971) found this effect to be of order 0.1 between Miami and Bimini. The data of Chew *et al.* (1971) indicate a highly-conducting seabed from G.E.K. and direct measurements of flow between Ft. Pierce and the northern tip of Little Bahama Bank. The ratio of open circuit to actual voltage is 3.1 in these data compared with 2.3 for the Jupiter cable inferred from (1), using a transport of 29.5×10^6 m³/s (Niiler and Richardson, 1973), a conductivity weighting factor of 1.07, and replacing H_e by $<H><1+\lambda>$ where $<H> = 482$ m. Hence, the trend toward increased bottom conductances found between Miami and Jupiter seems to continue on to Ft. Pierce. The source of the increased bottom conductivity appears to be a thick aquifer containing brackish water underlying the northern part of the Florida Straits (Manheim and Horn, 1968).

Assuming a uniform spatial gradient of bottom conductance between Miami and Ft. Pierce, the expected shorting factor is 2.3 at the cable site. Thus, two independent estimates of the influence of seawater and bottom conductances yield a value of 2.3; hence, the section-averaged λ is about 1.3.

5. Conductivity transport

The northward flux of electrical conductivity in the Florida Current can be computed based on the observed potentials, the inferred λ, the known seawater conductivity and the observed (Fig. 2) temperature/electrical conductivity relation. Let $t = t_o + \alpha\sigma$, where t is the temperature, and t_o and α are constants. Then the temperature transport can be expressed as $T_t = t_o T_v + \alpha T_\sigma$. The term $t_o T_v$ represents the transport of a constant, indistinguishable from a reference temperature. In a closed system in which the northward T_v is balanced elsewhere by an equal and opposite volume transport, this term vanishes (Montgomery, 1974; Bryden and Hall, 1980). The second term is based on conductivity transport and is the one of principal interest. For the Fort Pierce-Mantilla shoal area, hydrographic and the Chew *et al.* (1971) observations yield:

$$\alpha = 9.19°\text{C/S/m}$$
$$t_o = -25.5°\text{C}$$
$$\Delta\phi = 0.92$$
$$F_z = -0.43 \times 10^{-4}\text{T}$$
$$<1/H\bar{\sigma}(1+\lambda)> = 1.36 \times 10^{-4}\ \text{S}^{-1}$$
$$\overline{\sigma v}/\bar{\sigma}\,\bar{v} = 1.07$$
$$T_v = 31.6 \times 10^6\ \text{m}^3/\text{s}.$$

The second term on the right-hand side of (12) is small (<5%) of the first; hence, by (12) the conductivity transport is

$$T_\sigma = 1.58 \times 10^8\ \text{S m}^2/\text{s}.$$

The temperature transport is

$$T_t = (1.45 \times 10^9 - 25.5 \times 31.6 \times 10^6)\,°\text{C m}^3/\text{s}$$
$$= 0.65 \times 10^9\,°\text{C m}^3/\text{s}.$$

This value corresponds to a transport of 32×10^6 m³/s at an average temperature of 20°C, a value in agreement with the Bryden and Hall (1980) estimate of 19°C. The annual average temperature transport of the Florida Current is 0.55 × 10^9°C m^3/s. It should be acknowledged that this calculation is very sensitive to the distribution of λ used in (12) and too little is presently known about it.

Since the cable voltage is sensitive to conductivity as well as velocity variations, the annual signal also reflects the temperature changes of the stream. It would in general be expected that a semiannual component would arise from the annual variations in transport and temperature. Düing *et al.* (1977) report a small annual contribution to the temperature variation of about 0.06°C while the steric anomaly of Pattullo *et al.* (1955) indicates an annual component of 0.5°C, which is small compared with the mean or with the total temperature variance. Based on this annual temperature variability, one would not expect a large semiannual signal from this process. There is, however, a significant semiannual component (Table 1). A least-squares fit of the observations after the mean and annual components have been removed reveals a semiannual component of 5.5 × 10^{-2} V and phase of 114°. This is about 60% of the annual component, a value larger than would be expected based on the mean and annual values for transport and temperature.

A semiannual signal has not been found in the Key West-Havana voltages as analyzed by Maul *et al.* (1978), but Fuglister (1951) reports a semiannual component of 4.9% of the mean surface current and Pattullo *et al.* (1955) found an 8.2% signal between Cat Cay and Miami. The cable signal of 55 mV represents 4.5% of the mean voltage of 1.21 V.

At periods considerably shorter than semiannual, a variety of observations show 4-14 day variability (Fofonoff, 1981), whereas the cable spectrum shown in Figure 7 contains little or no excess energy or prominent peaks above the "red" background. Kielmann and Düing (1974), Wunsch and Wimbush (1977) and Brooks (1979) found lateral shifts to the Stream axis and transport fluctuation predominantly in the 4-14 day period range. Düing compared a 12-day portion of Jupiter cable voltage with his transport measurements. He found a visual correlation when the sign of the voltage fluctuations was reversed and the record shifted by 70 hours. This result is tenuous since the record length is comparable to the period of variation, and there is no 4-14 day enhanced energy in the total voltage record corresponding to that seen in pressure, temperature and velocity measurements.

This contradiction may stem from the absence of motions at this time scale off Jupiter or from attenuation of the signal. The former has been suggested by Wunsch and Wimbush (1977), in that interactions between the Stream and the topographic disturbance of the Miami Terrace may be responsible for the wavelike motion. On the other hand, Webster (1961) also reported fluctuations at these periods off Onslow Bay, north of the Jupiter site. If these flow variations are present, then

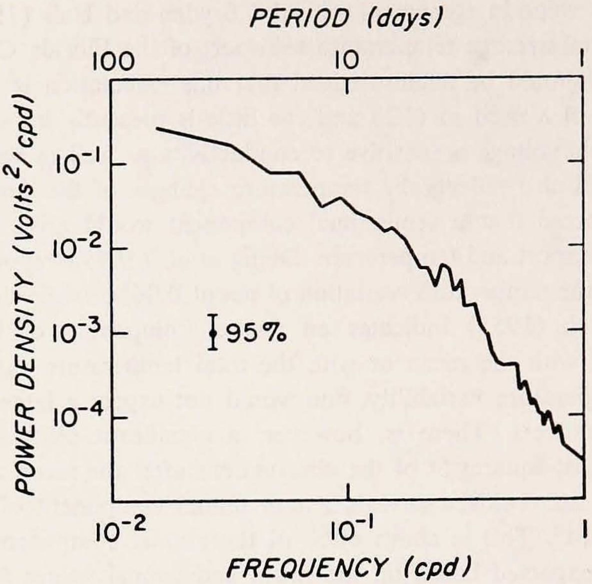

Figure 7. Power density spectrum of the cable voltage in the period range of 1 to 64 days. The mean annual and semiannual components were removed prior to spectral analysis.

there seems to be little evidence of them in the cable voltage. However, a wavelike flow will generate a much-reduced cross-current voltage if the horizontal wavelength is comparable to the section width. Wavelengths as short as 50-70 km (Wunsch and Wimbush, 1977) have been suggested. Barotropic waves of this horizontal structure will produce **J*** electric currents which will act to reduce the voltage observable. That is, the crest region will electrically interact with an adjacent trough portion to produce an electric current tending to reduce or neutralize the cross-stream voltage. In this case, the cable voltage variation could be much smaller than would be anticipated from the transport change at these periods and spatial scales.

6. Discussion

It has been shown that the voltage across the Florida Current represents that expected from the known mean transport over the independently-determined, regional bottom conductance. The open-circuit potential is expected to be about 2.7 V, whereas only 1.2 V is observed, a reduction by a factor of 2.3. The shorting effect of the sediments interpolated from adjacent regions also amounts to a reduction of 2.3. Thus, the calibration of the cable agrees well with the expectations.

On the seasonal time scale, the inferred transport agrees well in phase and in amplitude with the ship drift and tide gauge observations. The agreement is surprising in that the latter two measurements are typical of surface flow, whereas the cable represents a spatial integral and is more related to transport. A more comparable observation is the annual variation of transport reported by Niiler and Richardson (1973). They found a seasonal signal of 14% of the annual mean, or about twice the 7.5% found in the cable record.

At short time periods, little of the "catastrophic" voltage variation noted in the Key West-Havana records is seen here. The absence of these fluctuations results from the fact that the Florida Current off Jupiter occupies most of the available channel and lacks the lateral excursions over the sloping bottom off Key West.

Little of the dominant 4-14 day variability found in other observations, including some of total transport, is seen. The relatively high bottom conductances (i.e., $\lambda > 1$) tend to reduce the influence of axis shifts on the induced voltage, and $\mathbf{J}^*$ currents may arise which will "short out" those signals. Additional measurements should be able to resolve this issue.

In summary, the voltages induced between Florida and Grand Bahama Island are about half the calculated open-circuit potential and contain annual and semiannual fluctuations that agree well in phase and roughly in amplitude with other determinations. The smaller observed voltages compared with the open-circuit potential reflect the highly-conducting sea floor in this area. The superior features of cable measurements are that they are nearly continuous and represent transportlike, spatial averages of the flow. The disadvantages of the measurements are that the voltage to transport conversion depends on water and sea floor electrical conductivities and the distribution of flows within the conducting channel. Overall, the advantages, especially for the strength and other characteristics of the Florida Current off Jupiter, overcome the liabilities.

It is important to repair the submarine cable and resume continuous, long-duration measurements. Additional direct and electric measurements are needed to determine better the bottom conductances. Simultaneous cable voltage and land-based magnetic measurements are needed to understand and remove magnetotelluric interference, especially in the period range of hours to several days. It is expected that much of that research will occur over the next several years. Re-establishment of the submarine cable and the initiation of ancillary measurements will provide the means for long-term monitoring of transport and temperature flux in a region of vital importance to a better understanding of ocean climate and its fluctuations.

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