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A continuous record of Florida Current temperature transport at 27°N

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[1] As part of a newly funded international program to monitor ocean heat transport at mid-latitudes in the North Atlantic, a continuous estimate of the temperature transport of the Florida Current is required. Since 1982, volume transports have been inferred from voltage measurements monitored by submarine telephone cables across the Straits of Florida. Electromagnetic induction theory suggests that the cable voltage should actually give a more direct measure of conductivity transport than pure volume transport. Due to the strong dependence of conductivity on temperature, this would in theory result in a direct and continuous estimate of the Florida Current temperature transport. This hypothesis is investigated using data from a large number of temperature and velocity sections (58) across the Florida Current at the cable location, leading to a new calibration of the voltage signal for the temperature transport of the Florida Current, crucial for trans-basin heat flux estimates. **Citation:** Shoosmith, D. R., M. O. Baringer, and W. E. Johns (2005), A continuous record of Florida Current temperature transport at 27°N, *Geophys. Res. Lett.*, *32*, L23603, doi:10.1029/2005GL024075.

1. Introduction

[2] The oceans play a central role in regulating global climate due to their large heat capacity compared with the atmosphere. In the North Atlantic, the peak heat transport occurs at approximately 25°N, where about 1.2 petawatts (~60% of the global oceanic heat transport) is carried polewards [*Bryden and Imawaki*, 2001]. This northward heat transport is dominated by the meridional overturning circulation (MOC). Variability of the MOC and its heat transport are thus key to global climate variability.

[3] Early 2004 marked the beginning of a four-year monitoring program to continuously measure the strength and variability of the North Atlantic MOC and heat transport at approximately 25°N [*Srokosz*, 2003]. Since the Florida Current contains most of the upper limb of the MOC at this latitude, Florida Current transport measurements are a vital part of this effort. However, to date no continuous estimates of the Florida Current temperature transport exist.

[4] At 27°N in the Straits of Florida a number of submerged submarine telephone cables have been used to measure the voltage difference across the Straits. Electromagnetic induction theory has been used to infer volume transports from these cable voltage measurements for over 20 years [*Larsen and Sanford*, 1985; *Baringer and Larsen*, 2001]. However, the theory actually suggests that cable voltages should be more strongly related to Florida Current temperature transport than volume transport. Here we investigate the hypothesis that cable voltages can provide a continuous time series of volume and temperature transport of the Florida Current and thus provide the necessary boundary current information required for the international program monitoring heat transport.

2. Data and Methodology

[5] The Subtropical Atlantic Climate Studies program (STACS) [*Molinari et al.*, 1985a] involved repeated sections across the Florida Current between 1982 and 1984. Vertical profiles of velocity and temperature were obtained using the free-falling acoustically tracked "Pegasus" profiler at 9 stations (Figure 1). For a description of methods and results on the mean velocity and temperature structure of the Florida Current from the Pegasus data see *Leaman et al.* [1987]. At approximately the same location, an abandoned submarine telephone cable (Figure 1) measured the voltage differential across the Straits generated by the flow of the Florida Current through the Earth's magnetic field [*Larsen*, 1992]. This voltage record can be used to infer Florida Current transport variability through calibration using the Pegasus observations to provide a continuous record of the transport [*Larsen and Sanford*, 1985].

[6] The theory of electromagnetic induction for wide ocean streams provides an equation for the motionally induced, cross-stream voltage difference, $\Delta\phi L$, [*Sanford*, 1971]:

$$\Delta\phi_L(t) = \int_0^L [F_z(x)/\tau(x,t)] \int_{-H(x)}^0 \sigma(x,z,t)v(x,z,t)dzdx, \quad (1)$$

where F_z is the magnitude of the vertical component of Earth's magnetic field, τ is the conductance of the ocean, sediments and conducting crust, σ is the electrical conductivity of the ocean, v is the along-stream velocity,

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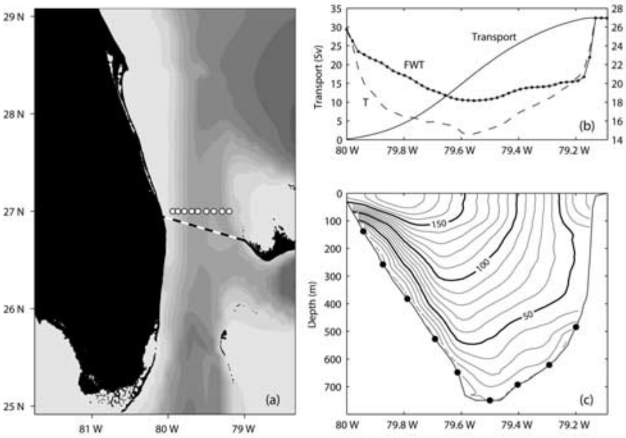

Figure 1. (a) Location of STACS Pegasus stations (circles) and submarine cable (dashed line). (b) Mean Florida Strait cumulative transport, temperature (T) and flow-weighted temperature (FWT), from all 58 Pegasus sections. (c) Mean Florida Strait northward velocity section (cm/s). Pegasus station positions are indicated by black circles.

L is the width of the Strait at the cable location, and H is the water depth. According to (1), and when F_z and τ are nearly uniform over L as is the case for the Florida Current [*Larsen*, 1992], to first order the variability of the cross-stream voltage should be related to the conductivity transport. Larsen and Sanford further simplified this relationship to find a constant scaling factor that related cross-stream voltage differences to transport alone, yielding a relationship of approximately 24.6 Sv/volt.

[7] From the STACS database a total of 58 sections of full water column velocity and temperature profiles were suitable for comparison with cable voltages. Volume and temperature transport estimates are computed directly from this data. A climatological temperature-salinity (T-S) relationship for the Straits of Florida which takes into account the cross-stream structure is used to recover salinity profiles. From these, conductivity and density may be estimated, and conductivity transport and temperature transport calculated. The transports reported in this paper are calculated as the cross-sectional integrals:

$$transport = \int_0^L \int_{-H(x)}^0 k(x,z)v(x,z)dz\,dx, \qquad (2)$$

where k = 1 for volume transport (V), k = σ for conductivity transport (C), k = θ (potential temperature) for temperature transport (T; in Sv°C), and k = $\rho C_p\theta$ for temperature transport (Q; in PW). The factor ρC_p is approximately constant and the mean value of ρC_p from all the Pegasus sections is 4.088×10^6 J m^{-3} $°C^{-1}$. Note that since there is a net northward transport through the Straits of Florida of ∼32 Sv [*Baringer and Larsen*, 2001], mass is not conserved in these integrals and temperature transport is dependent upon the temperature scale used [*Hall and Bryden*, 1982].

[8] The original minute cable voltage record was corrected for tidal and geomagnetic fluctuations, converted to transport and averaged daily [*Larsen and Sanford*, 1985]. Raw voltage corrections also involve an offset correction that is dependent on the electrical ground and recording system used [see *Larsen*, 1992], hence we scaled the cable-derived transports by 24.42 Sv/volt to regain a fully bias corrected voltage time series. To allow a direct comparison, daily cable transports were interpolated in time to match the mean Pegasus section times (a Pegasus section typically takes 20 hours). Model II geometric mean regressions, where both X and Y are independent, were used in the comparisons [*Ricker*, 1973].

3. Results

[9] There is a high correlation between Pegasus volume and temperature transports (Figure 2a; R^2 of 0.95) principally due to the velocity variability being in both integrals. They are not perfectly correlated because the temperature within the Straits is variable. The flow-weighted temperature (FWT) can be defined as the temperature transport divided by the volume transport. FWT varies from about 18°C to 20.5°C, but not proportionally to transport, as seen in Figure 2b (R^2 of only 0.03). In other words, although variations in temperature transport are due mainly to variations in volume transport, this is not the only factor. This means that temperature transport cannot be perfectly determined from volume transport alone.

[10] Using the computed volume transport from the 58 Pegasus sections, a simple linear model of temperature transport would be

$$Q = 0.0806 * V - 0.0405, \qquad (3)$$

where the estimated error in temperature transport is ±0.06 PW. Since the FWT and volume transport are

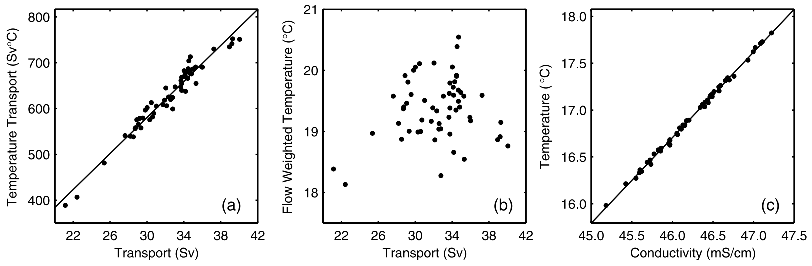

Figure 2. Florida Current: (a) volume transport vs. temperature transport, (b) volume transport vs. flow weighted temperature, and (c) section mean conductivity vs. section mean temperature, from Pegasus profiler sections undertaken during STACS (1982–1984).

Table 1. Regression Calculations of Cable Voltage vs. Observed Florida Current Volume, Temperature and Conductivity Transports

Cable Voltage vs. Florida Current	R^2	RMS Error	Mean % Error	RMS Error as % of Mean Transport
Volume transport (Sv)	0.92	1.06	2.6 %	3.3 %
Temperature transport (PW)	0.88	0.11	3.5 %	4.1 %
Conductivity transport (Sv mS cm^{-1})	0.90	58.94	3.0 %	3.7 %

essentially uncorrelated, this corresponds to assuming a nearly constant FWT of the Florida Current (~19.4°C). In the absence of any independent information on the temperature structure or its variability, this would be the simplest form of temperature transport estimation, whenever a transport value was available.

[11] To generate a continuous time series of temperature transport, the submarine cable voltages must be used. The measured cross-stream voltage should, in theory, be related to the conductivity transport, as shown by equation (1). Conductivity is highly correlated with temperature (Figure 2c; R^2 of 0.999) and thus we expect the voltage variability to be related to the Florida Current temperature transport.

[12] The regression calculations of cable voltage vs. Pegasus volume, temperature and conductivity transports (Table 1) actually show that volume transport gives the best correlation ($R^2 = 0.92$), although they are only marginally different at the 80% confidence level. The higher correlation of cable voltage with volume transport is contrary to our expectations, however, it does provide us with a means of calibrating the cable data for temperature transport.

[13] The regression between the Florida Current temperature transport values estimated from the profiling data and the simultaneous cable voltages is:

$$Q = A * \Delta\phi_L + B, \qquad (4)$$

where A is 2.302 ± 0.109 PW/V, and B is −0.523 ± 0.147 PW. The fit is shown in Figure 3a, where the cable voltages are scaled into their regression-derived temperature transport values for clearer comparison. The correlation is 0.88 and the RMS error is 0.11 PW. The uncertainty in the temperature transport estimation using cable voltages is larger than using section data directly due to the noise in the voltage measurements themselves, the associated influence of magnetic field variability, and variability of the conductance of the sediments and crust which is very poorly known [*Larsen*, 1992]. However, 0.1 PW represents only about 4% of the mean temperature transport. This applies for daily estimates of cable transports; errors would be reduced significantly by temporal averaging.

[14] An alternate approach to estimating the temperature transport from the cable voltages is to assume that the cable voltage is indeed a better proxy for the volume transport, as suggested by the regressions, and to use the associated transport value with an estimate of the FWT to determine the temperature transport. The mean Florida Current FWT from the 58 Pegasus sections is 19.37°C, whereas the spatially averaged mean temperature is 16.93°C. The FWT is higher than the mean because the near-surface warmer waters are in the faster flowing part of the current. The RMS error in Florida Current temperature transport associated with using the cable volume transport time series with a mean FWT of 19.37°C is 0.11 PW (Table 2), identical to a direct calibration of the cable voltages. An improved estimate of the temperature transport could be made if the FWT of the Florida Current could be independently predicted, for example, based on its seasonal variation. Figure 4 shows the seasonal distribution of FWT from the 58 sections. Although much of the variability appears to be random, there is an indicated seasonal cycle of warmer FWT in early fall (September–October) and colder FWT in late winter (March–April) that is consistent with the expected seasonal heating cycle. Using monthly values of FWT from the annual cycle shown in Figure 4 leads to a slightly improved estimate of the temperature transport from the cable, giving a correlation with the observed temperature transport of 0.90 and an RMS error of 0.10 PW.

[15] At first glance, the RMS errors in the cable temperature transport estimate seem significantly higher than the error of 0.06 PW estimated from volume transport observations, according to (3). However, this error does not account for additional error introduced by uncertainty in the transport itself. It represents how well transport alone determines

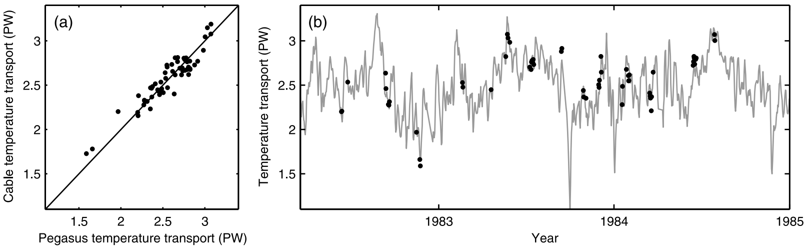

Figure 3. (a) Comparison of observed and cable estimated Florida Current temperature transport. (b) Cable voltage time series (to 1985) calibrated for temperature transport. Solid circles are in-situ observations from Pegasus profilers.

temperature transport (i.e. 0.06 PW is an estimate of the error induced by assuming a constant FWT). As noted by *Larsen and Sanford* [1985] and *Molinari et al.* [1985b], comparisons of Pegasus and cable estimates of transport suggest that the actual Florida Current volume transport uncertainty is probably of order 1 Sv. Assuming a ±1 Sv error in the transport estimated from the Pegasus sections, (3) leads to an associated error in the temperature transport of 0.08 PW. Combining this randomly with the error of 0.06 PW arising from the regression (i.e. the expected temperature transport error from FWT uncertainty) yields an overall temperature transport uncertainty of 0.10 PW; identical to the cable estimated Florida Current temperature transport uncertainty.

4. Discussion and Summary

[16] In summary, we find that the cable voltages can be used to generate a time series of Florida Current temperature transport, which is crucial for trans-basin heat flux estimates. The uncertainty in this temperature transport estimate is 0.1 PW, which is 4% of the mean Florida Current temperature transport (2.5 PW). Although *Larsen and Sanford* [1985] mentioned that one expects cable voltage to be better correlated with conductivity-weighted transport than with the simple volume transport, it had not been investigated until now. Contrary to the theory, it is found that volume transport is more closely related to the cable voltages than are conductivity and temperature transport, however the differences are very small. It is likely that the effect of the varying FWT is too small compared to the other noise sources in the system to emerge statistically, even though from the physics there is every reason to expect that the correlation should be better.

[17] As mentioned previously and discussed by *Larsen* [1992], there are a number of possible causes of error in cable-estimated transports, including those due to magnetic variations, lateral movement of the core of the current and eddy transports (which have spectral peaks in the weather band between 5 to 12 days [*Johns and Schott*, 1987]). Taking a conservative estimate that the time scale of variability of these small scale features (i.e., the decorrelation scale) is about 5 days, then it is possible to argue that monthly-averaged temperature transport values will have a reduced error by as much as a factor of 2.5 (~0.04 PW). This is of the same order or smaller than other terms in the trans-basin heat flux balance related to Ekman or interior baroclinic heat transport [*Hall and Bryden*, 1982].

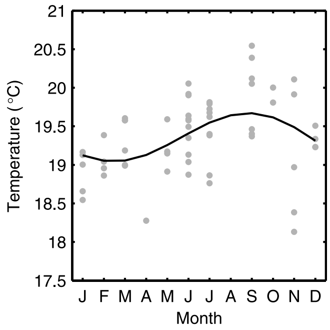

Figure 4. Mean annual cycle of observed Florida Current flow weighted temperature (FWT_{mm}; solid line), with the individual section data (Pegasus profiler sections) shown as grey circles.

Table 2. Comparison of Florida Current Temperature Transport[a]

Florida Current Pegasus Temperature Transport vs. Florida Current Cable Temperature Transport	R^2	RMS Error (PW)
Calibrated cable voltage ((volts*2.302) − 0.523)	0.88	0.11
Cable volume transport * mean FWT (19.37°C)	0.88	0.11
Cable volume transport * monthly FWT (FWT_{mm})	0.90	0.10

[a] Calculated using Pegasus observations compared with using (i) calibrated cable voltage signal, (ii) cable transport and a FWT of 19.37°C, and (iii) cable transport with monthly mean FWT (as shown in Figure 4).

[18] When considering basin-wide heat flux, the uncertainty from the Florida Current contribution is also arguably lower than the 0.1 PW error for a single value since any error in the cable-derived temperature transport that is related to an error in volume transport will be partly cancelled out by the subtraction of the same volume transport times the mean mid-ocean temperature. Therefore, the 0.1 PW error in Florida Current temperature transport is equivalent to a less than 0.08 PW contribution to the basin-wide heat transport error, which is about 7% of the mean heat transport value (1.2 PW).

[19] Since 2002, full water column Florida Current section data is being regularly acquired as part of NOAA's contribution to the Global Ocean Observing System; CTD/LADCP sections are being undertaken four or more times per year. These sections, combined with the new Atlantic heat transport monitoring program [*Srokosz*, 2003], will provide ample data to further compare and calibrate the cable-voltages for temperature transport and to determine what factors can increase the efficiency of the submerged cable to measure temperature transport.

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References

Baringer, M. O., and J. C. Larsen (2001), Sixteen years of Florida Current transport at 27°N, *Geophys. Res. Lett.*, *28*(16), 3179–3182.

Bryden, H. L., and S. Imawaki (2001), Ocean heat transport, in *Ocean Circulation and Climate: Observing and Modelling the Global Ocean*, edited by G. Siedler, J. Church, and J. Gould, pp. 455–474, Elsevier, New York.

Hall, M. M., and H. L. Bryden (1982), Direct estimates and mechanisms of ocean heat transport, *Deep Sea Res.*, *29*, 339–359.

Johns, W. E., and F. Schott (1987), Meandering and transport variations of the Florida Current, *J. Phys. Oceanogr.*, *17*(8), 1128–1147.

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. R. Soc. London, Ser. A*, *338*, 169–236.

Larsen, J. C., and T. B. Sanford (1985), Florida Current volume transports from voltage measurements, *Science*, *227*, 302–304.

Leaman, K. D., R. L. Molinari, and P. S. Vertes (1987), Structure and variability of the Florida current at 27°N: April 1982 – July 1984, *J. Phys. Oceanogr.*, *17*, 566 – 583.

Molinari, R. M., et al. (1985a), Subtropical Atlantic climate studies: Introduction, *Science*, *227*, 292 – 295.

Molinari, R. L., W. D. Wilson, and K. D. Leaman (1985b), Volume and heat transports of the Florida Current: April 1982 through August 1983, *Science*, *227*, 295 – 297.

Ricker, W. E. (1973), Linear regressions in fishery research, *J. Fish. Res. Board Can.*, *30*(3), 409 – 434.

Sanford, T. B. (1971), Motionally-induced electric and magnetic fields in the sea, *J. Geophys. Res.*, *76*, 3476 – 3492.

Srokosz, M. A. (2003), Rapid climate change: Scientific challenges and the new NERC programme, *Philos. Trans. R. Soc. London, Ser. A*, *361*, 2061 – 2078.

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