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Sixteen Years of Florida Current Transport at 27° N

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Abstract.
Daily transports of the Florida Current have been inferred since 1982 through the use of submerged submarine telephone cables that measure the voltage difference across the Straits of Florida. Using all sixteen years of data, the annual cycle ranges from a minimum of 30 Sv in January, to a maximum of 33.5 Sv in July. The annual cycle is not stable throughout the entire period however: the first eight years show a slightly larger peak-to-peak annual range of 5 Sv, while the second eight years have a semi-annual cycle with a distinct minimum in July and peak-to-peak range of 4 Sv. Filtered Florida Current transports contain a two to three year variation between 2 and 3 Sv in amplitude and a decadal variation of about ± 2 Sv. The decadal changes in the Florida Current transport are significantly correlated (R=0.75 at 95% significance) to the North Atlantic Oscillation Index.

Introduction

The Florida Current contains both wind-driven subtropical circulation and the upper layer of the meridional thermohaline circulation that supplies the warm waters of the Gulf Stream system. Transport measurements between the coast of Florida and the Bahamas have long been supposed to be important for understanding global climate. Models have used the Florida Current annual cycle as a benchmark for their model validation. So many observational programs have been conducted in the Straits of Florida, one could argue that this current system is one of the best known in all the world's oceans. However, it is highly variable and continuous measurements are required to filter out the high frequency variability.

With new technologies in hand that allowed the direct determination of the absolute velocity, *Schmitz and Richardson* [1968] undertook the first detailed observational program of the Florida Current in 1964-1967 using the dropsonde technique. *Niiler and Richardson* [1973] later reanalyzed a more complete record of the transport between Miami and Bimini extending to 1970 and found a transport of 29.5 Sv with an annual cycle amplitude of 4.1 Sv and a maximum in July. More recently, an intensive observational program was undertaken under the auspices of NOAA's Subtropical Atlantic Climate Study (STACS) during 1982 to 1984 which included 16 cross sections using Pegasus velocity profilers and 7 months of current meter data [*Molinari et al.*, 1985a, b; *Lee et al.*, 1985; *Larsen and Sanford*, 1985; *Maul et al.*, 1985; *Schott and Zantopp*, 1985].

Herein, we present an update on the present state of observations of the Florida Current transport monitored through submarine telephone cables crossing the Florida Straits (Fig. 1). The cable monitoring system is outlined and the long term time series is presented. We derive a revised annual cycle estimate and then examine the long term trends in transport in relation to the North Atlantic Oscillation (NAO).

The Submarine Cables

Submarine cables provide a means, via the cable ends, for measuring the motional induced voltages in the ocean. Using these voltages and simple electromagnetic theory, the water column transport changes across the cable can be inferred. In his pioneering work Stommel described it simply as: "Due to the fact that the water in the ocean is a conductor, and that it is everywhere under the influence of the earth's magnetic field, we should expect, by the law of electric induction, that wherever the water is in motion electric potentials and currents will be established" [*Stommel*, 1948].

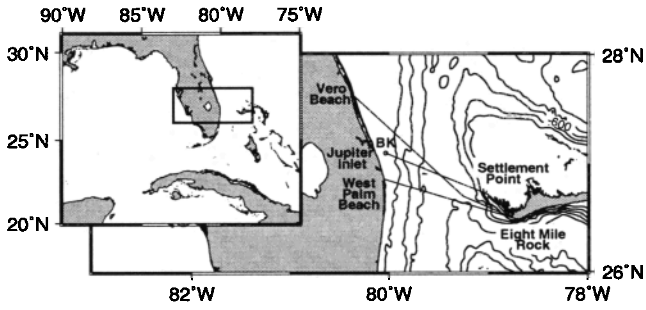

Figure 1. Locations of submerged cables used for transport monitoring.

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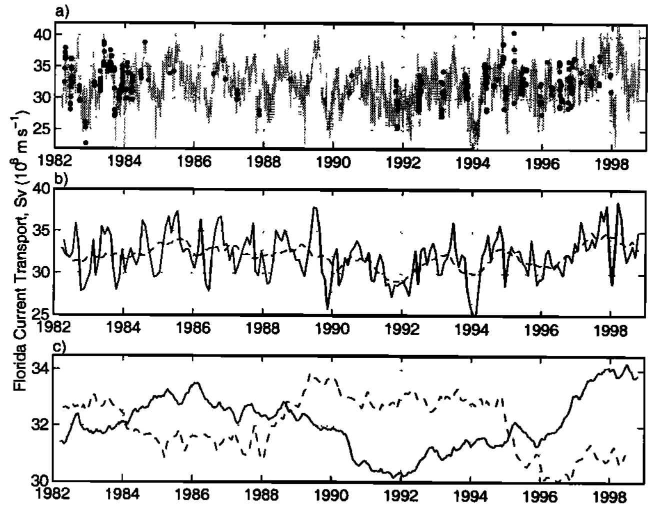

Figure 2. Time series of Florida Current transport inferred from the cable voltages including (a) the daily transport values (light grey line), (b) the monthly (solid line) and one-year (dashed) running mean transport (c) the two-year running mean (solid line) of the daily transport values. Panel (c) also includes the monthly mean NAO index of *Hurrell and Loon* [1997] (dashed line) which is rescaled for plotting to have the same mean and variance as the cable transport (unitless). Panel (a) includes in situ observations of Florida Current transport obtained to calibrate the cable and monitor voltage offsets (solid circles).

The conversion of the voltage measurements to transport and the errors associated with this conversion, such as geomagnetic fluctuations, temperature, and meandering effects, have been discussed in *Larsen* [1992]. Profiling-derived transports (i.e. in situ transport observations that measure the absolute velocity) are used to calibrate the cable-derived transports and also determine voltage offsets. These profiling-derived transports are shown as black dots in Figure 2 and are estimated to be accurate to better than 0.2 Sv [*Leaman and Molinari*, 1987, given that the Pegasus values are accurate to 1 cm/s].

Details of the cable history can be found in *Larsen* [1992]. Most recently, a cable between West Palm Beach, FL and Eight Mile Rock, Grand Bahamas Island has been used. These measurements continued until October 1998, when this cable was retired from telephone service and replaced by a cable between Vero Beach, FL and Eight Mile Rock, Grand Bahamas Island. When the first cable was retired, it was grounded at West Palm Beach with the expectation that voltages could be recorded only at the other end. Technical difficulties in the retirement of the cable led to the delay in instrumentation of this cable until March of 2000, resulting in a 17 month gap in the time series. In the future it should be possible to record voltages on the new active fiber optic cable using the insulated copper shield that could be grounded at Eight Mile Rock. Therefore, low cost voltage measurements of the Florida Current should be able to continue for many years.

Transport Time Series

Over 16 years of daily mean transports have been computed from the cable voltage recordings. Figure 2 shows the complete record of daily mean voltage-derived transports from April 1982 to October 1998 for the northern end of the Straits of Florida. Geomagnetic field variations and tidal signals were removed prior to computing the daily mean values. The profiling derived transports are also plotted for comparison. The long term mean transport is 32.2 Sv. The annual and two-year running mean values of the transport are also shown in Figure 2. It shows that the Florida Current transport slowly decreased by about 3.5 Sv from 1985 to 1992 and then slowly increased by about 4 Sv until the present. The yearly means show 2-to-3 year variations with changes as large as 4 Sv.

Annual Cycle

The annual cycle of the Florida Current was computed by forming a composite annual cycle of daily transports (i.e. all January 1's are averaged together), and is shown in Figure 3. This daily annual cycle was then smoothed using a 3rd order Butterworth filter with a half power cutoff at 25 days. The average daily values for all 16 years of data are shown with the thin solid line. The thick solid line includes the filtered version of this annual cycle using all 16 years of data. The heavy dashed line is an annual cycle computed from only the first 8 years of data (1982-1990) and is the equivalent

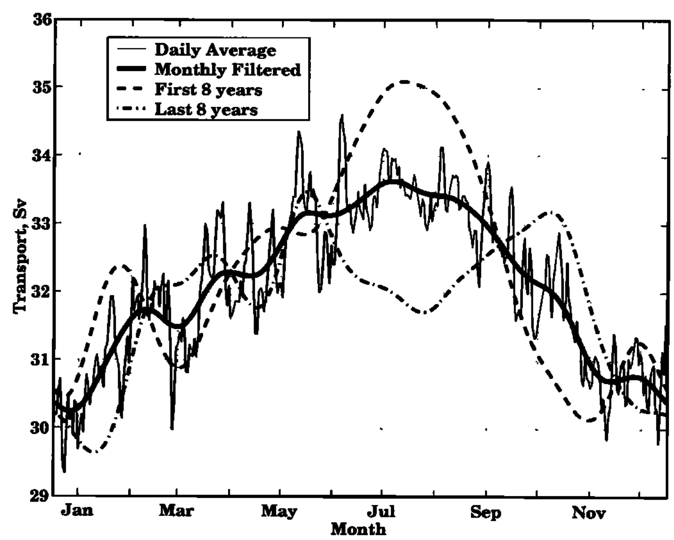

Figure 3. Annual Cycle (AC) of Cable-derived transport of the Florida Current computed and smoothed (see text) including: the complete sixteen year daily cable record (thin solid line), a smoothed version of the complete sixteen year AC (thick solid line), a smoothed AC from only the first 8 years (thick dashed line), and a smoothed AC from the last 8 years (thick chain dashed). The daily average AC (thin solid) and its standard error (which is about 1 Sv, not shown) give an indication of the level of high frequency noise and confidence in the means.

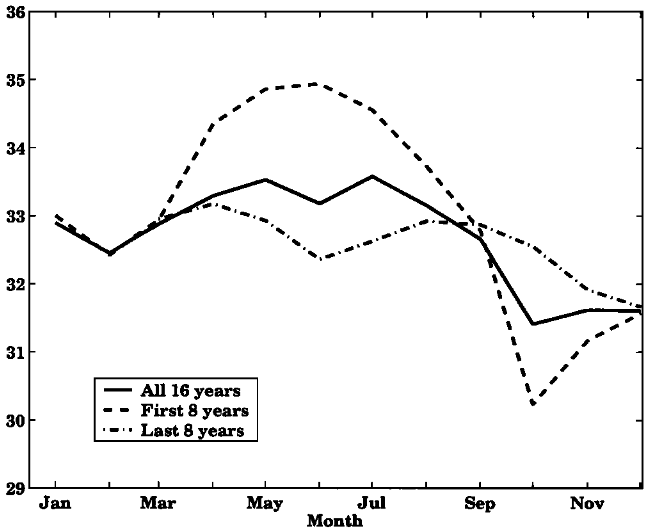

Figure 4. Annual Cycle (AC) of transport of the Florida Current computed and smoothed (see text) including: all direct in situ observations over the complete sixteen year record (thick solid line); observations taken in the first 8 years (dashed line); and observations taken from the last 8 years (chain dotted).

to the annual cycle described by *Larsen* [1992], which was also similar, although slightly smaller than, the annual cycle found by *Niiler and Richardson* [1973], *Sanford* [1982] and *Leaman and Molinari* [1987]. This line shows the well-known summer maximum in transport particularly in July and August and a pronounced rapid decrease in transport in early October. A surprising finding is the annual cycle computed from the last 8 years of data (shown as the thick chain-dashed line), which shows a much flatter annual cycle with some suggestion of two peaks with a secondary minimum in July-August sandwiched between two maxima in May-June and Oct-Nov. The overall range in monthly values is smaller (about 4 Sv peak-to-peak change vs. 5 Sv for the earlier period). The difference between these curves in the summer appears to be significant (the curves are different by more than twice the standard deviation). It is not clear what has caused this radical shift in the annual cycle. It is now clear however, that we cannot take the annual cycle of the Florida Current for granted.

Independent confirmation of the shift in the annual cycle of the Florida Current was obtained by forming an annual cycle from the in situ Pegasus transport observations (Figure 4). Pegasus transports were binned by month and averaged for all sixteen years, the first eight years and the last eight years. These monthly averages were then subjected to a median filter and the results plotted in Figure 4. These in situ transport observations confirm the shift in the annual cycle seen in the more complete cable transports. The prominent peak in mid-summer seen through the first half of the transport record is substantially diminished and even reversed in the second half of the record.

Interannual variations

Increasingly, climate studies have focused attention upon the natural variability of the coupled oceanic atmospheric system and in particular the atmospheric phenomenon known as the North Atlantic Oscillation (NAO). The NAO *index* is typically defined as the normalized sea level pressure difference between Iceland and the Azores [e.g. *Hurrell and Loon*, 1997], that approximately characterizes the behaviour of the large scale NAO. Variability in the NAO has been shown to have significant influence on storm tracks and European weather, marine life in Sweden and Norway, sea surface temperatures north of the Gulf Stream, and fish mortality off the northeastern United States [for a nice summary see *Hurrell and Loon*, 1997]. In view of the NAO's impact on so many important climate variables, it is a extremely important to understand what causes its variability and how the NAO forces other climate signals.

We have extracted the longer period fluctuations from the Florida Current transport time series (the longest time series of ocean transport) to compare to the NAO index [*Hurrell and Loon*, 1997] (Fig. 2c). The Florida Current time series of monthly transport values and the NAO index time series of monthly values were filtered using a 2-year running mean (Fig. 2c). The correlation of these two smoothed time series is large and negative (-0.75), with the NAO index leading the Florida Straits transport by about 18 months and significant at the 95% level. There is a wide range of lags with significant negative correlations with the NAO index leading the cable by between 1 to 25 months and hence the exact phase relationship is in some question depending on how the data sets are smoothed (not shown). Also, there exists a positive correlation (0.6 at >90% significance) near lags of about 45 months with the Florida Current transport leading the NAO index. Although this lag is barely resolved by the sixteen year time series, we note it here because it points to a potential forcing on the atmosphere through Florida Current changes and a possible coupled oscillation with a decadal time scale.

Discussion

This note examines the full sixteen years of Florida Current transport time series and shows that while the mean transport has not changed significantly (32.2 Sv), the annual cycle has changed dramatically. Low passed Florida Current transports also contain a two to three year variation of between 2 and 3 Sv (amplitude) and a decadal variation of about $\pm$ 2 Sv (fig. 2). A comparison of the two time series shows that the transport changes are similar to the long term changes in the NAO index. The sheer volume transport of the Florida Current must be kept in mind in assessing the climate impact of these interannual changes in transport. The Florida Current, at over 32 Sv, can replace all of the North Atlantic surface water down to 100 m within one year.

So, for example, a 2 Sv increase in transport over a two year period could cause an increase of about 1°C in the subtropical North Atlantic mixed layer temperature given that the Florida Current has a velocity weighted temperature of 19°C with a compensating return flow of 5°C. If the heat storage remains constant, then the surface heat loss would have to increase by 6 W/m^2. Put another way, a sustained 2 Sv transport increase would increase the heat content in the upper 3000 m of the ocean seven times that of the observed heat content changes from 1980 to 1995 described in *Levitus et al.* [2000]. These observations provide a new benchmark for validating numerical models and are challenging to our understanding of decadal climate fluctuations.

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