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Florida Current transport variability: An analysis of annual and longer-period signals

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ABSTRACT

More than forty years of Florida Current transport estimates are combined to study annual and longer-term variability in this important component of the MOC and subtropical gyre. A detailed analysis with error estimates illustrates the difficulties in extracting annual and longer time scale variability given the strong higher frequency energy present. The annual cycle represents less than 10% of the total Florida Current transport variance in a 16 yr segment of the record, while interannual (13–42 month) variability represents only 13% of the total and periods longer than 42 months represents less than 10% of the total. Given the observed high frequency variability of the Florida Current, in order to get a monthly mean that is accurate to within 0.5 Sv (one standard error level) more than 20 daily observations are needed. To obtain an estimate of the annual climatology that is "accurate" to within 20% of its own standard deviation, at least 24 yr of data is needed. More than 40 observations spread throughout a year are required to obtain an annual mean that is accurate to within 0.5 Sv. Despite these daunting data requirements, there is sufficient data now to evaluate both the annual cycle of the Florida Current transport with a high degree of accuracy and to begin to determine the longer period transport variability. Comparison of the Florida Current, NAO and wind stress curl records shows that a recently described Sverdrup-based mechanism explains a significant fraction of the long-period variability primarily during the 1986–1998 time window, with other mechanisms clearly dominating before and after.

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1. Introduction

The North Atlantic subtropical gyre is distinguished from other subtropical gyres because the horizontal gyre is embedded within (or embeds) a climatically important full-water-column vertical gyre, the meridional overturning circulation (MOC). Decadal variations in the MOC, and the associated changes in ocean properties such as sea-surface temperature, have been tied to variations in precipitation over the neighboring continents and other socially important quantities (e.g. Alvarez-Garcia et al., 2008). Improved understanding of the variability in the MOC, and the role of the high frequency variability in extracting these annual and longer period variations from the MOC, is a key issue for long-term predictability (e.g. von Storch and Haak, 2008).

Off the east coast of Florida the bulk of both the warm surface limb of the vertical MOC and the majority of the western boundary component of the horizontal subtropical gyre are carried within the Florida Current as it passes through the Straits of Florida. Observations and estimations of the Florida Current have been made over a surprisingly long period of time, starting as early as the late 1880s (Pillsbury, 1887,1890). The importance of the Florida Current to the dynamical ocean–atmosphere system and as a flow with a significant history of observations has long been understood, leading to the establishment in 1982 of a nearly continuously program to provide long-term monitoring of the Florida Current (e.g. Larsen and Sanford, 1985; Molinari et al., 1985a; Leaman et al., 1987; Larsen, 1992). Among other things, the studies based on these measurements have demonstrated a small but significant annual cycle (e.g. Leaman et al., 1987) as well as higher frequency (3–10 day periods) variations that appear to be locally or near-locally forced coastally trapped waves (e.g. Mooers et al., 2005). Baringer and Larsen (2001) evaluated the annual cycle using 16 years of time-series data and they found an apparent shift in the annual cycle of Florida Current transport between the first and second half of their study period. Baringer and Larsen also showed that over the period 1982–1998 the low-frequency Florida Current transport variability (at periods greater than 2 years) appears to have a negative correlation with the atmospheric North Atlantic Oscillation (NAO), which has

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well-documented correlations with a multitude of other climatically important variations around the Atlantic basin. A subsequent study by DiNezio et al. (in press) developed a plausible mechanism to explain this anti-correlation based on fast propagation of first baroclinic mode Rossby waves forced by basin interior wind stress curl variability. The 16 yr time series studied by Baringer and Larsen (2001) included, however, less than two complete cycles of the low-frequency (roughly 12 yr) anti-correlated fluctuation and the authors noted that the significance of the anti-correlation was marginal. It has been observed that in the most recent few years this anti-correlation appears less certain (Baringer and Meinen, 2006; Beal et al. 2008), leading to questions about the robustness of the interannual/decadal mechanisms proposed to date to explain the observed Florida Current variability. In addition to the modern data used in most of these studies, there is a significant amount of older data that could also be used to test the relationships such as that between NAO and Florida Current proposed by DiNezio et al. (in press). Doing so, however, requires a careful review of temporal sampling, spatial sampling locations, and other issues with these data sets.

The purpose of this article is to review the available historical observations, compare them with the updated modern observations, and to use both types of data to evaluate the variations of the Florida Current over the full length of time during which observations have been made. The paper presents, for the first time, the data processing methods used on many of the measurements undertaken since 2000. The paper is organized as follows. First the data types available throughout the Straits will be reviewed, along with their strengths and weaknesses. Next, a consistent forty-year time series centered along 27°N within the Florida Straits will be compiled taking into account the appropriate offsets for the different instrument types. This is followed by a careful presentation of statistical tests using both simulated and actual data to estimate the errors associated with temporal undersampling, focusing first on the annual cycle and then on the interannual and longer variability. Finally the resulting time series will be compared to the NAO index and long-period wind stress curl forcing mechanisms and conclusions will be presented.

2. Summary of observations with the Florida Straits

Some of the very first ocean transport observations obtained anywhere in the world were made in the Florida Current/Gulf Stream in the 1880s (Pillsbury, 1887, 1890). Using extremely innovative techniques for the time, Pillsbury was able to estimate a transport of about 26 Sv (converting from his more archaic units) for the Florida Current near 26°N using velocity measurements made within the upper ~200 m over several months from an anchored ship.[3] Considering the probable accuracy of those early methods this transport estimate is surprisingly close to more accurate estimates made at 26°N 70–80 years later, such as the 30 Sv obtained for the period of 1964–1970 (Niiler and Richardson, 1973) and 33 Sv obtained during 1974 (Brooks and Niiler, 1977).

Since these pioneering observations, a host of different observational techniques have been applied to measuring the Florida Current transport ranging from geostrophic estimates (relative to an assumed level of no motion, e.g. Montgomery, 1941; Broida, 1969) to free-falling floats (e.g. Richardson and Schmitz, 1965; Brooks and Niiler, 1975) to a creative use of submarine telephone cables (e.g. Stommel, 1948, 1957; Broida, 1962, 1963). The latter measurements were in essence the earliest time series measurements of the Florida Current transport, and they were made in the southern Straits of Florida using a submarine cable that stretched from Key West, Florida to Havana, Cuba (Wertheim, 1954; Stommel 1957, 1959, 1961, Broida, 1962, 1963). However, interpretation of those early cable measurements is ambiguous due to difficulties with the application of the electromagnetic technique in an environment where the Florida Current could meander widely over different sediments (Schmitz and Richardson, 1968; Wunsch et al., 1969; Larsen, 1992). There were a number of estimates of the transport of the Florida Current during the 1960s using sea-level differences (e.g. Wunsch et al., 1969). The next *in situ* estimates that were made started in the mid-1960s near 26°N between Miami, Florida and Bimini, Bahamas (Niiler and Richardson, 1973; Brooks and Niiler, 1977). Subsequent to the work in the mid 1960s to mid 1970s, most of the observations were made a bit further north at 27°N between West Palm Beach, Florida and Grand Bahama Island. The more recent measurements have been taken at a location to the North of any inflow into the straits from passages opening to the Atlantic Ocean and where the Florida straits geometry tightly constricts the flow to a fairly shallow and narrow current where substantial meandering (as a percentage of the Florida Current width) is not possible.

The flow of the Florida Current at 27°N is fed through three primary sources. The largest is the flow through the Yucatan Channel, where transport estimates have ranged from 24 to 28 Sv (Johns et al., 2002; Sheinbaum et al., 2002). The next-largest inflow is through the Northwest Providence Channel, a narrow gap through the Bahamas bank centered at about 26.4°N (Fig. 1). Previous work in this area has found that the top-to-bottom westward transport through the Northwest Providence Channel ranges from about 1.2 to 2.5 Sv (Richardson and Finlen, 1967; Leaman et al., 1995; Johns et al., 1999). The only other passage feeding into the Florida Straits is the Old Bahamas Channel between Cuba and the Southern Bahamas Islands. This channel is extremely shallow but very broad. Estimates of the transport through the Old Bahama Channel have been about 2 Sv (Hamilton et al., 2005), however this value is highly uncertain given the

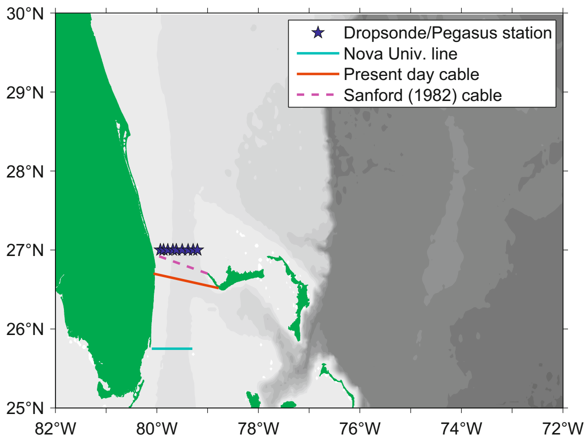

Fig. 1. Location of the observations collected in the Florida Current near 26–27°N. Dropsonde/Pegasus locations at 27°N have been essentially the same since 1982; the dropsonde casts collected by Niiler and Richardson (1973) and Brooks and Niiler (1977) were collected along the 'Nova Univ. line'. Both the cable used since 1993 (red) and the previous cable used from 1970–1972 and 1982–1993 (magenta) are shown. Gray-shading denotes the bottom topography (Smith and Sandwell, 1997) with 500 m contour levels; the Northwest Providence Channel enters the straits of Florida just south of the present-day cable location.

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[3] The assumption of zero flow at the bottom in the Pillsbury studies resulted in an underestimation of the total transport of the Florida Current. A subsequent reanalysis of the Pillsbury data resulted in a revised estimate of about 29 Sv (Schmitz and Richardson, 1968).

logistical difficulties of making accurate estimates of the flow. Note that there is an apparent discrepancy between the lower flow estimates of 24 Sv through the Yucatan Channel (Sheinbaum et al., 2002) and historical estimates of the 32 Sv Florida Current mean transport at 27°N (e.g. Larsen, 1992). Unfortunately there were essentially no measurements made at 27°N during the time when these lower Yucatan transports were observed. Addressing this apparent discrepancy would require both new observations in the various passages and a careful estimation of the errors in the transports estimated for each passage transport, which is beyond the scope of this paper. This paper will instead focus on the wealth of observations collected in the northern Straits of Florida near 26–27°N (Fig. 1).

3. Creating a consistent time series from disparate data sources

Assembling the longest possible time series of Florida Current transport by combining data from diverse observations requires careful consideration of the different processing techniques and the inherent accuracy of the different data sources. Detailed descriptions of the historical experiments will be left to the original references, however in roughly temporal order each of the measurement systems utilized herein will be presented, and any limitations or special considerations for each data type will be noted.

Aside from the Pillsbury (1887, 1890) measurements, the earliest observations of the total Florida Current transport in the northern Straits of Florida were made using an instrument called a ‘dropsonde’ between 1964 and 1970 (Niiler and Richardson, 1973). A dropsonde is a simple free-falling float that once deployed sinks at a constant rate, drops a weight when it reaches the bottom, then rises at a constant rate to the surface (Richardson and Schmitz, 1965). With the elapsed time and change in position between the start and the end of the cast, the vertical-mean horizontal velocity can be calculated. To determine the deployment and surfacing locations, the early dropsonde cruises used a shipboard system called “Hi-Fix”, which was a radio-based master-slave system that is less accurate than modern systems (Richardson and Schmitz, 1965). Over the seven-year period from 1964 to 1970 a total of 75 complete dropsonde sections were taken, each involving up to 13 dropsonde stations, across the Straits of Florida near 26°N between Miami and Bimini Island in the Bahamas (Niiler and Richardson, 1973; see Fig. 1 for section location). In 1974 an additional 44 dropsonde cruises were completed along the same line by Brooks and Niiler (1977). These measurements are the only data that will be discussed herein that were taken at 26°N rather than 27°N, and in order to ‘correct’ this data so that it can be used with the data at 27°N it is necessary to take into account the flow through the Northwest Providence Channel. To adjust the 26°N dropsonde observations for comparison with the 27°N measurements, 2 Sv was added to the measured Florida Current transport from each of the sections, recognizing that any small variations in the flow through the Northwest Providence Channel will therefore represent errors in the estimated transport at 27°N (error estimated to be ±1 Sv). Note also that the dropsonde data collected by Niiler and Richardson (1973) and Brooks and Niiler (1977) at 26°N were not corrected for tidal fluctuations and the raw data is no longer available to make this correction. Hence when compared to other 27°N data, the tide variations must also be represented as a larger uncertainty in the transport accuracy (this source of error is estimated to be approximately ±1 Sv based on the standard deviation of the difference between tidally corrected and non-tidally corrected dropsonde transports, see below).

The second data set used herein is from voltage measurements that were made on a submarine telephone cable from 1969 through 1975 (Sanford, 1982). Basic electromagnetic theory requires that when a charged particle, such as the salt ions carried in seawater, moves through a magnetic field, such as that produced by the Earth, an electric field is created perpendicular to the motion of the charged particles (e.g. Stommel, 1948; Larsen and Sanford, 1985). If a shielded, conductive wire is stretched along this electric field, a voltage will be induced along the wire and the magnitude of that voltage will be linearly proportional to the transport of charged particles through the magnetic field, and hence to the transport of sea water across the cable. The linear coefficients of the relationship between voltage and water transport depend on many factors, including the magnetic field strength, sediment conductivity, water conductivity, and cable length (e.g. Larsen, 1992). TheSanford (1982) study did not attempt to estimate these coefficients, and as a result only provided a scale-less estimate for transport variability. The data presented here are digitized from the figure in the Sanford (1982) article because the original data have been lost (Sanford, personal communication, 2007). It must be noted that the early and late portions of the Sanford cable record had major gaps and timing problems, so only the time period from 1970–1972 was considered to be research quality (Sanford, 1982).[4] It should be noted that the strength of the Earth’s magnetic field has significant fluctuations particularly at very high frequencies, and hence the voltage variability is ‘contaminated’ by fluctuations unrelated to ocean transport variations. Side-by-side magnetometer and electrometer observations made in the Pacific have demonstrated that the magnetic field fluctuations, which are primarily associated with ionospheric variations caused by solar storms, dominate the electric field fluctuations at periods shorter than three days, while oceanic variations dominate the electric field variability at periods longer than three days (Luther et al., 1991). Sanford’s cable data were not corrected for this ‘magnetic noise’ and cannot be corrected after the fact because the hand digitized record does not have sufficient time resolution. Therefore accuracy estimates for these data must take into account the unknown variability due to magnetic field variations at short time scales; the increased error is estimated from the present day cable system (to be discussed shortly) to be ±1 Sv.

The bulk of the data used in the present analysis was obtained from a major field program initially entitled the Subtropical Atlantic Climate Studies (STACS) project (e.g. Lee et al., 1985; Molinari et al., 1985a; Molinari, 1986; Leaman et al., 1987). The STACS program began in 1982 and involved a host of different observational systems, including a submarine cable, moored current meters, hydrographic sections, and direct temperature and velocity measurements obtained from a “Pegasus” acoustically-tracked profiler. The present study will focus on two types of measurements from the STACS era: the submarine cable and the Pegasus measurements (Fig. 1).

The same cable that had been used by Sanford (1982) during 1969–1975 was re-instrumented in 1982, and voltage measurements have been made on that cable and several replacement cables nearly continuously since that time (e.g. Larsen and

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[4] Note that the voltages induced on the cable are influenced by the structure and location of the current (due to horizontal variations in conductivity in both the sediments and the ocean). Hence a monitoring system using this method will substantially increase the signal to noise ratio when the flow feature (e.g. the Florida Current) is relatively confined and stable, such as near 27°N in the Northern Straits of Florida. This was the factor thought to be most responsible for the ambiguous nature of the data collected from the original cable system that was tested in the broader channel between Key West and Havana by Stommel (1957, 1959, 1961).

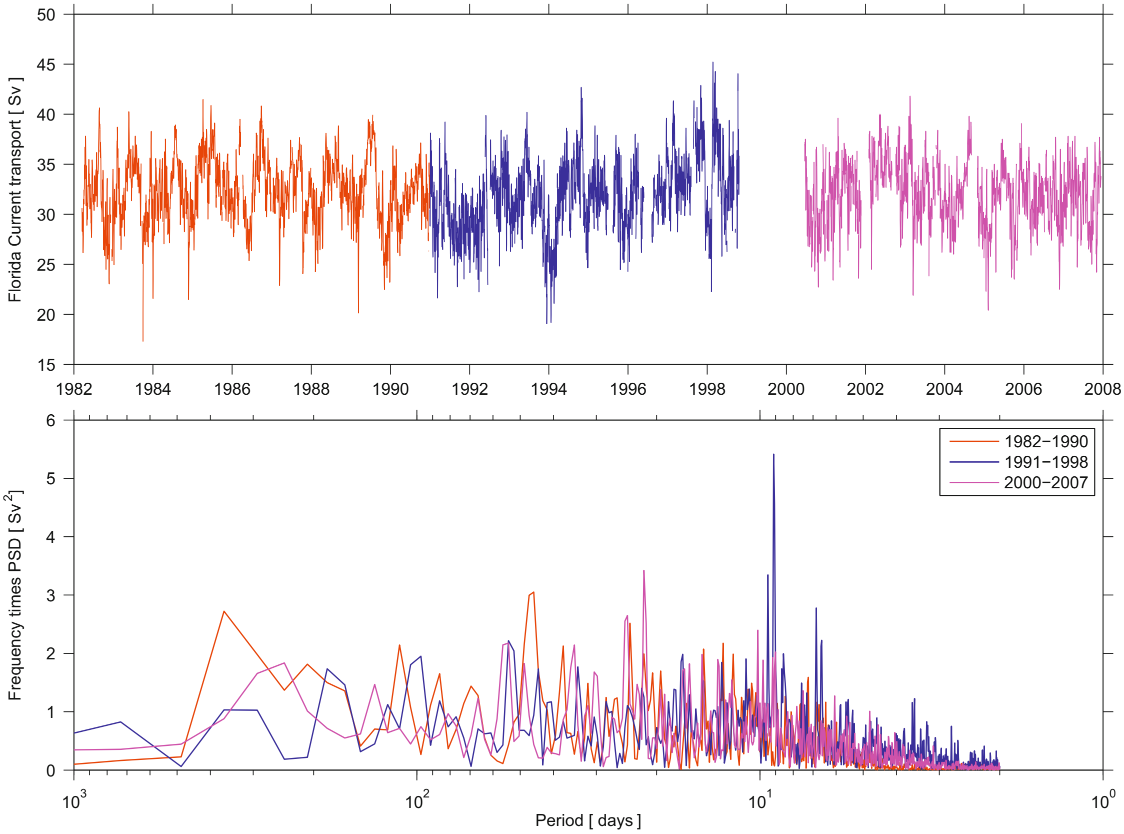

Fig. 2. Variance-preserving spectra of the Florida Current transport record from the submarine cable. The upper panel shows the color-coded segments of the cable record, while the lower panel shows the spectra for the similarly colored segments. Cable record is broken into three segments, the first two segments were both processed by Jimmy Larsen at PMEL using the methods described in Larsen (1992). The third segment was processed using the new automated system described in the text.

Sanford, 1985; Larsen, 1992; Baringer and Larsen, 2001). The only large gap occurred between 1998 and 2000 when funding for the project was temporarily cut and the building where the recording equipment was housed in West Palm Beach was closed. The second largest gap occurred in September–October 2004 when the building housing the recording system at Eight Mile Rock was severely damaged by Hurricanes Frances and Jeanne. During the first 16 yr of this cable project the recording system transitioned from a paper tape recorder to a computer based recorder, and the data were processed in a ‘research-mode’ that involved considerable hand-editing to try to remove the tides as well as the largest of the magnetic-field fluctuations using magnetic observatory data (Larsen, 1992). In the modern era (2000-present) the cable is now part of the NOAA Western Boundary Time Series program, and the system has transitioned to a real-time system that involves a computerized volt-meter that makes a measurement every minute and an automated processing system involving a three-day lowpass filter with a 2nd order Butterworth filter passed both forward and back for the removal of tides and the magnetic field variations. Both the ‘research-mode’ and ‘real-time’ processing methods make a daily average of the minute data as part of their processing. Comparison of the spectra of the daily cable data in eight year segments shows that differences in the resulting spectra between the modern (2000–2007) data and the earlier (1982–1998) data are smaller than the differences between the spectra of the first and second half of the original 16 yr record (Fig. 2)[5]. This suggests that the different processing methods for different cable periods are not resulting in particularly different spectra. Both the early records and the modern data have been daily averaged to provide means centered on noon UTC. During the original STACS period the calibration factors for the linear relationship between voltage and transport for this cable were determined using a series of 100+ Pegasus velocity sections (see details below and Larsen, 1992), and these coefficients are used essentially ‘as is’ for evaluating both the older Sanford (1982) data and for the modern era data.

It should also be noted that routine section validation is required for monitoring the performance and stability of the cable recording equipment. The cable measurements are subject to spurious drifts and offsets when electrodes and wires decay and fail and when the recording systems have problems. Since 2000 there has been roughly one problem with the system per year, all resulting in voltage step offsets except for one that was a voltage drift due to a tiny break in a wire over two months. Each drift/offset problem has been traceable to a specific hardware problem. Many of these changes have been due to a failure in the recording system itself (such as when it was destroyed by hurricanes in 2004), and when these systems have been replaced small voltage offsets (biases) have been observed. These offsets are caused by small but important differences from one voltmeter to the next, and the offsets are corrected using section data. Typically only the first 2–4 sections after any system change are used to determine the offset. It must be stressed that only a constant offset (based on

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[5] Note that the spectra for 1991–1998 demonstrates more high-frequency energy (less than 10 days) than the periods before and after. The raw voltage data from this time period has been lost (J. Larsen, personal communication), however

(footnote continued)

it is known that during much of the 1991–1998 time period the cable being used was simultaneously the active phone line and the telephone company was applying an active voltage that previous research has indicated causes extra noise in the voltage-to-transport conversion (Larsen, 1991).

the mean of the 2 to 4 differences between concurrent cable and dropsonde transports) is applied for any particular correction; the ratio between voltage and transport is never changed, so the time variability of the section data is still essentially independent for comparison with the cable. Correlations between the cable transports and truly independent sections (those not used for determining offsets) are basically the same as those between the cable and sections used for determining offsets ($r=0.88$ versus $r=0.91$, respectively). The root-mean-squared (rms) difference between the cable and dropsonde section values[6] is about 1.7 Sv for all of the sections since 2000; the differences for the sections used to determine the offsets to the cable and for those not so used are the same to within 0.3 Sv. Using the data only since 2004 (34 total sections) the rms differences have improved to around 1.1 Sv. Assuming the entire difference is due to errors in the cable data, a very conservative assumption, this difference can provide an error estimate for the daily cable values.

The other type of STACS data used herein, the Pegasus, is a free-falling acoustically tracked float that provides a full-water-column estimate of the absolute horizontal velocity at stations bracketed by subsurface acoustic sound sources (Spain et al., 1981). Data from 104 of the Pegasus sections from 1982–1984 have been found and reprocessed using methods consistent with the present-day systems; however only 60 sections satisfy the requirements that there are no more than two missing stations and both endpoint stations are available. Barotropic tidal variations are removed using the constituents derived by Mayer and Larsen (1986) from STACS current meter data. The transport differences associated with the tide corrections have a standard deviation of about ±1 Sv, and peak values as large as ±3 Sv. Florida Current transports are determined by horizontal integration of the Pegasus velocities across the Straits of Florida from the nine occupied stations at 27°N (the westernmost station was only added partway through the first year of observations, see Fig. 1 for locations). Maintaining the Pegasus acoustic sound sources proved too costly in the mid-to-late 1980s, and after 1984 the Pegasus instrument was used as a dropsonde, thereby only providing a measurement of the vertical mean horizontal velocity rather than a profile. A total of nine sections have been recovered and reprocessed using data from this time period (1986–1988).

Beginning in about 1991, section monitoring of the Florida Current transport transitioned from using Pegasus to using a true dropsonde similar to that developed in the 1960s. Rather than using Hi-fix, however, these dropsonde cruises utilized GPS for providing locations. From 1991 to 1993 the GPS was a handheld device on the ship, and surface locations were determined acoustically and visually from the ship. In 1994 a newer generation dropsonde was developed with an internal recording GPS, and this type of dropsonde has been used up to the present day. Note that when selective availability for GPS positioning was removed in the late 1990s the errors in GPS positioning decreased substantially (from 50 m to better than 5 m). This paper presents for the first time a total of 178 dropsonde sections from 1991 to the present that have been processed using consistent methods for GPS quality control, tidal correction, and spatial integration (with 6–10 new sections collected each year).

It should be noted that several other observational data sets are available in the Straits of Florida that were not used herein. These data sources include current meter records near 27°N during the 1982–1984 (e.g. Johns and Schott, 1987) and 1990–1991 (Hamilton et al., 2005) time periods, and biweekly transects that were collected across the Florida Straits near 26°N during 2001–2006 using a ‘ship of opportunity’ equipped with a shipboard ADCP (Beal et al., 2008). All of these data sets have some limitations for transport comparisons (horizontal integration from limited sites for the current meters, particularly in the 1990–1991 array, and installation and data quality problems in addition to being collected south of Northwest Providence Channel with the ADCP data). As the data are contemporaneous with the long-term cable record they are not used.

For comparison to the Florida Current transport time series, the North Atlantic Oscillation (NAO) index produced by NCEP is used. This monthly data set is made freely available on the web at www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml. Wind stress curl is estimated from the surface wind stress fields of the NCEP/NCAR reanalysis project (Kalnay et al., 1996).

4. Results and discussion

With over 300 shipboard sections (dropsonde or Pegasus) and more than 25 years of daily cable observations, the quantity of transport estimates available for the Florida Current is impressive (Fig. 3). The mean of the transport estimates at 27°N is 32.1 Sv, which is consistent with previous studies, the variance was about 11.2 Sv^2, the standard deviation was about 3.3 Sv, and the statistical[7] standard error of the mean is about 0.2 Sv. There is good agreement between observations of different types, with a correlation of greater than $r=0.8$ between dropsonde estimates collected since the year 2000 and the concurrent cable observations (see example in lower panel of Fig. 3). As is clear from the time series (and from the spectra in Fig. 2), the Florida Current exhibits variability on a wide range of frequencies, with a large amount of variance at high frequencies that would be considered “noise” in most climate-scale analyses. Detailed spectral analysis that would include long-period variability (beyond annual) is not possible because the longest segment of the existing continuous record (16 yr) does not contain sufficient realizations of these longer period variations for the spectra to be accurate. Using the nearly continuous 16 yr cable record from 1982–1998 (with short gaps interpolated), it is possible to more crudely determine how much of the total variance is contained within particular frequency/period bands (Table 1). The 16 yr near-continuous portion of the cable record was low, high, or band pass filtered within five period bands: less than one month, one month to 11 months, annual (11–13 months), interannual (13–42 months), and longer than 42 months. All filtering was done with a 2nd order Butterworth filter passed both forward and backward to avoid phase shifting, and the filtered time series were all detrended except for the lowest frequency band. The majority of the variance in the time series is found in either the one month to 11 month band (46%) or the submonth period band (24%), with the remaining variance split almost equally between the three other bands. Of course with a longer record it may be found that the percentage of long-period variance would be larger. Nevertheless with 70% of the total variance in the 16 yr record contained at periods less than annual, it is clear that any attempt to extract information about the annual cycle or interannual and longer variability must carefully consider how

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[6] Correlations and rms differences shown here are based on the comparison of dropsonde section data to the daily mean cable estimate from the same date. Correlations and rms differences for cable averages calculated over the actual ~8–10 h period of the dropsonde section, rather than daily cable averages, are essentially the same. This is not surprising given the application of the 72-h low-pass filter to the cable measurement time series.

[7] The measurement accuracy, or measurement error bar, on the mean transport value is less than 0.1 Sv; this is based on rms differences of 1.7 Sv between daily cable values and concurrent dropsonde cruises and the fact that there have been several hundred independent cruises and therefore degrees of freedom (e.g. Emery and Thomson, 2004).

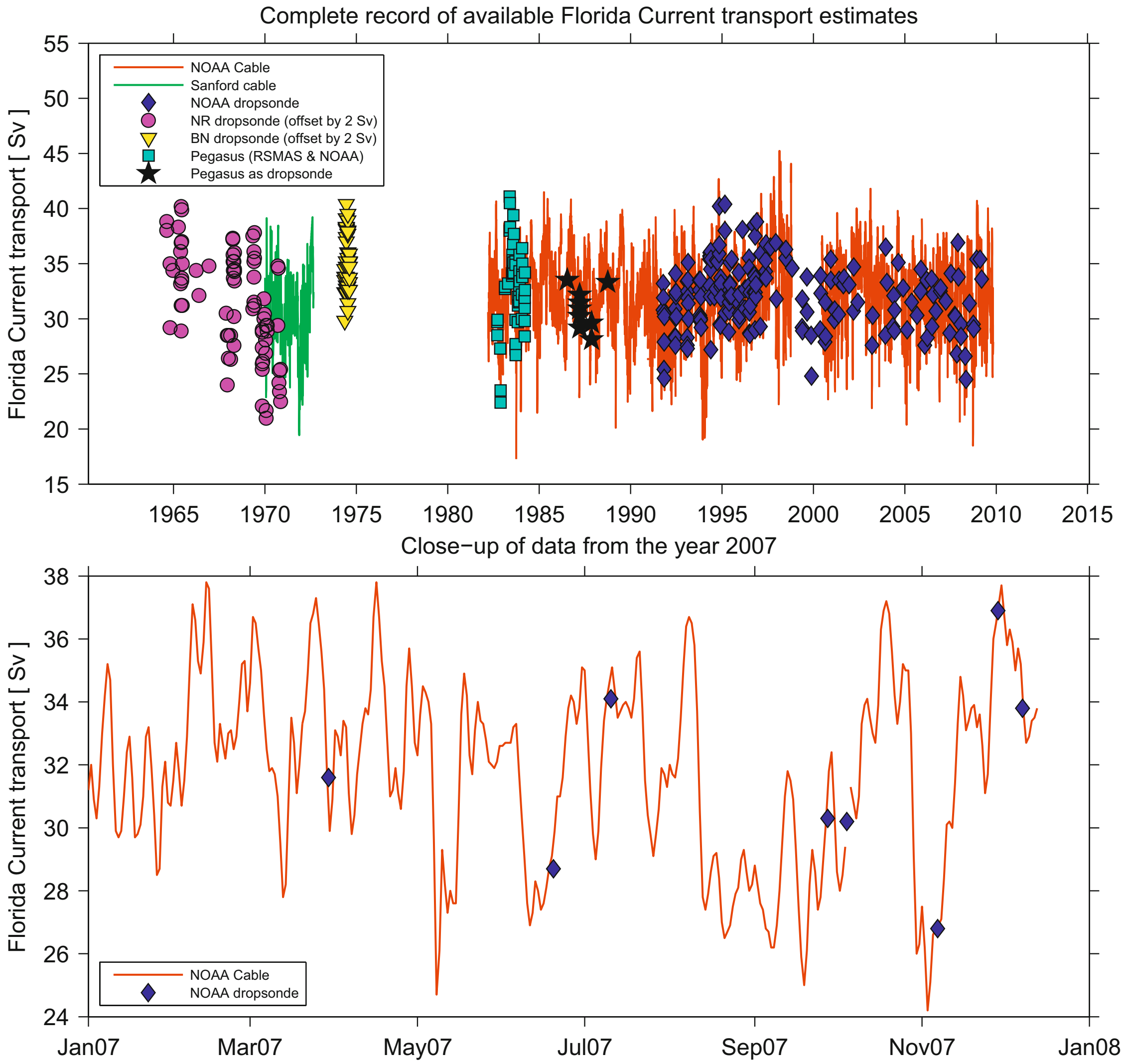

Fig. 3. Upper panel: Time series of Florida Current transport at 27°N demonstrating the range of observed values from each system, with the instrument types as noted in the legend. The Niiler and Richardson (1973) and Brooks and Niiler (1977) dropsonde estimates have been increased by 2 Sv to account for the Northwest Providence Channel flow as noted in the text. The Sanford (1982) cable voltages have been converted into transports using the linear coefficients determined by Larsen (1992), with the constant offset set to give the record-length mean a value equal to the long-term mean of the subsequent cable data (32.1 Sv). Lower panel: Close-up of the year 2007 illustrating the details of one year and the good agreement between cable and dropsonde data.

Table 1
Variance of the Florida Current associated with different period bands. Variance calculated with 1982–1998 cable record where time gaps have been filled with simple linear interpolation. First row is the variance, second row is the variance as a percentage of the total variance in the time series, which is roughly 10 Sv^2.

	Less than 30 days	Month to 11 month	Annual	13 month to 42 month	Greater than 42 month
Variance (Sv^2)	2.4	4.6	0.9	1.3	0.8
% of total variance	24	46	9	13	8

the high-frequency “noise” and the removal of said “noise” will affect the remnant time series. In what follows, the annual cycle will first be studied to determine to what extent the available data can be used to extract a mean annual cycle/climatology, and with what level of accuracy. Then the analysis will move to periods longer than annual to determine what climate variability can be meaningfully extracted from the time series.

4.1. Extracting an annual cycle (annual climatology)

The annual cycle of the Florida Current transport has been studied since the earliest work in the region using section data (e.g. Niiler and Richardson, 1973; Molinari et al., 1985b; Leaman et al., 1987), current meter data (e.g. Schott et al., 1988), sea level data (e.g. Schott and Zantopp, 1985) and cable data (e.g. Larsen, 1992), with most studies finding high transports in the late spring to summer and low transports in late fall to winter. Both numerical models (e.g. Anderson and Corry, 1985) and analytical models (e.g. Lee and Williams, 1988) have suggested that the annual variations in Florida Current transport are driven by local winds within (or just north of) the Straits, although observational studies have indicated that some caution should be used in interpreting these model results given the poor ability of the models to reproduce the observed variability at periods smaller than annual (e.g. Schott et al., 1988). Baringer and Larsen (2001)

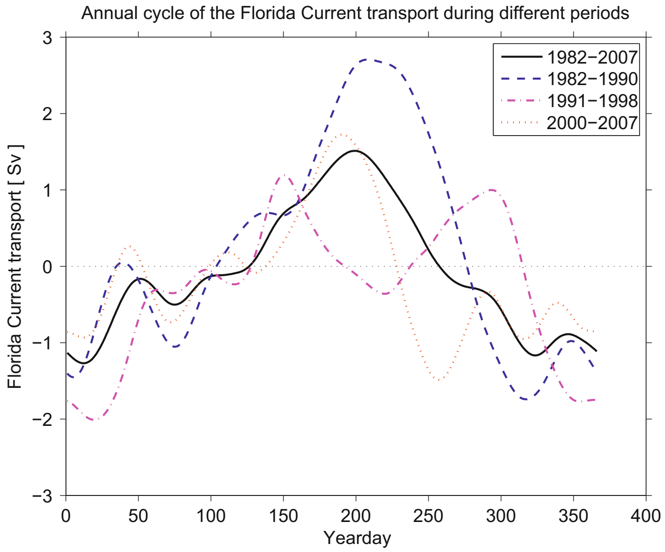

Fig. 4. Mean annual cycle/climatology of Florida Current transport determined over different years as noted in the legend. Plotted values are daily averages for the years noted (e.g. an average of all of the January 1st values, the January 2nd values, etc., where the averaged daily values have been subsequently smoothed with a 30 day low-pass filter to remove the highest frequency "noise". Measurement error bars on the 8 yr means would be about 0.2 Sv for reasonable estimates of the integral time scale and 0.1 Sv for the 25 yr mean; statistical error bars will be discussed shortly.

used cable observations of the Florida Current over the period 1982–1998 to evaluate the stability of the annual cycle in transport. They found that there was a marked difference between the annual cycle in the first half of the 16 yr window, when the Florida Current appeared to exhibit a clear annual cycle, and the latter half of the 16 yr window when the current variability was characterized more as a semi-annual cycle. Now that an additional 8 yr of cable observations are available from 2000–2007 the picture becomes even more confused, with the latter period showing a mean annual cycle that shows only a weak semi-annual component and has the highest transport occurring 30–50 days earlier than during the 1982–1990 window (Fig. 4). Since solar input at the top of the atmosphere, the only significant external forcing to the ocean–atmosphere system at the annual cycle, has not changed appreciably during this 25 year window, these significant variations in mean annual cycle lead to questions about possible mechanisms which could be modulating the observed annual cycle in Florida Current transport. Using observations and the results of a numerical model, a recent study has hypothesized that the variations in the form and phase of the annual cycle may be related to changes in the North Atlantic Oscillation and the associated wind pattern changes that go with it (Peng et al., 2009). Given the rather small measurement error bars that would be associated with these 8 yr mean values[8] it is clear that the largest uncertainties in the various estimated annual cycle would be the statistical accuracy (analogous to determining the statistical standard error of the mean). Therefore before investing too much into a discussion of the mechanisms behind these changes, it is important to evaluate the statistical significance of this variability given the high percentage of the total variance that exists at periods other than annual which may be aliased into any mean annual cycle/climatology determined from the data.

As noted earlier, about 70% of the total variance in the Florida Current is found to have periods shorter than annual (coastally trapped waves, etc.; e.g. Mooers et al., 2005), with about a quarter of the variance occurring at periods shorter than a month (Table 1). Baringer and Larsen (2001) showed that the strongest interannual or longer transport variations that can be identified in the 1982–1998 cable record have a period of roughly 10–12 years. Both this interannual-decadal variability and the high frequency variability (shorter than annual) can influence the accuracy with which the annual cycle can be determined. To evaluate the extent to which these other frequencies will pollute an estimate of the annual cycle/climatology, a Monte Carlo style approach was used. A simulated 100 year daily transport record was created as the sum of two sine waves (with annual and 12 year periods) and random noise. The amplitudes (standard deviation) of the simulated annual cycle and the simulated 12 yr cycle were both set to 1.0 Sv, consistent with the amplitudes determined from the real cable observations. The amplitude of the random noise was then selected so that the standard deviation of the simulated record equaled that of the true daily cable record (3.3 Sv). The random noise was added on a day-by-day basis, i.e. it has no temporal length scale beyond an individual day. Different spectral distributions of the noise, ranging from white noise to progressively redder-spectra (spreading the noise evenly across 1–10 days, 1–50 days, and 1–500 days), were tested; the effects were generally small, with wider spreads of noise generally having errors that were 0.05–0.30 Sv larger than those for the white noise used in the simulated record.

The Monte Carlo style evaluation was done as follows. Take, for example, the estimate for the statistical errors inherent in determining a mean annual cycle using four years of data. Four years would be randomly selected from the 100 yr simulated record, and a mean daily value for each day of the year would be calculated from the four years worth of "data". The differences between the resulting mean daily values and the 'true' simulated annual cycle (sine wave) was then calculated for the "raw" daily values as well as for daily values that have been smoothed using either a 30 or 60 day low pass filter. These differences were then saved and another random selection of four years was made and the process was repeated. A total of 10,000 random subsets of four years would be made, and once this was done the root mean squared (rms) value of the complete data set of daily differences would be calculated for the raw, 30 day low pass filtered, and 60 day low pass filtered annual mean records. This process was completed for random selections of one, two, four, six, eight, 10, 15, 20, 25, and 30 years (Fig. 5). This analysis indicates that an annual cycle/climatology determined using roughly 8 years (as was done by Baringer and Larsen, 2001), would have a statistical error bar of 0.4 Sv on each daily value simply due to the statistical "noise" from the higher and lower frequencies in the record (these values are nearly a factor of 2 larger than the measurement error bars). For a roughly 25 yr record, the daily statistical error bar is 0.2 Sv (again roughly a factor of 2 larger than the measurement error bars). While these seem like fairly small values, keep in mind that the standard deviation of the simulated annual cycle (which is based on the true cable-derived annual cycle) is only about 1.0 Sv, so a statistical error bar of 0.4 Sv is a 40% error bar on an annual climatology determined using only eight years of data. Applying these error bars to the annual cycles shown in Fig. 4 and looking at the observed differences, it is found that about 32% of the daily values in the annual climatologies determined using only eight years of data are further than "one standard error" level (or a 67% confidence limit) from the annual cycle determined using 25 years of data. Therefore these statistical estimations

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[8] The 1.1–1.7 Sv daily error bar discussed earlier would be reduced both due to the 30-day lowpass filter applied to the annual climatologies and due to the 8–25 years that are averaged together. Based on some reasonable integral time scale estimates of 3–10 days determined from the zeros in the autocorrelation function (following the methods of Emery and Thomson, 2004) this yields measurement accuracies of roughly 0.2 Sv for 8-year means and 0.1 Sv for 25-year means.

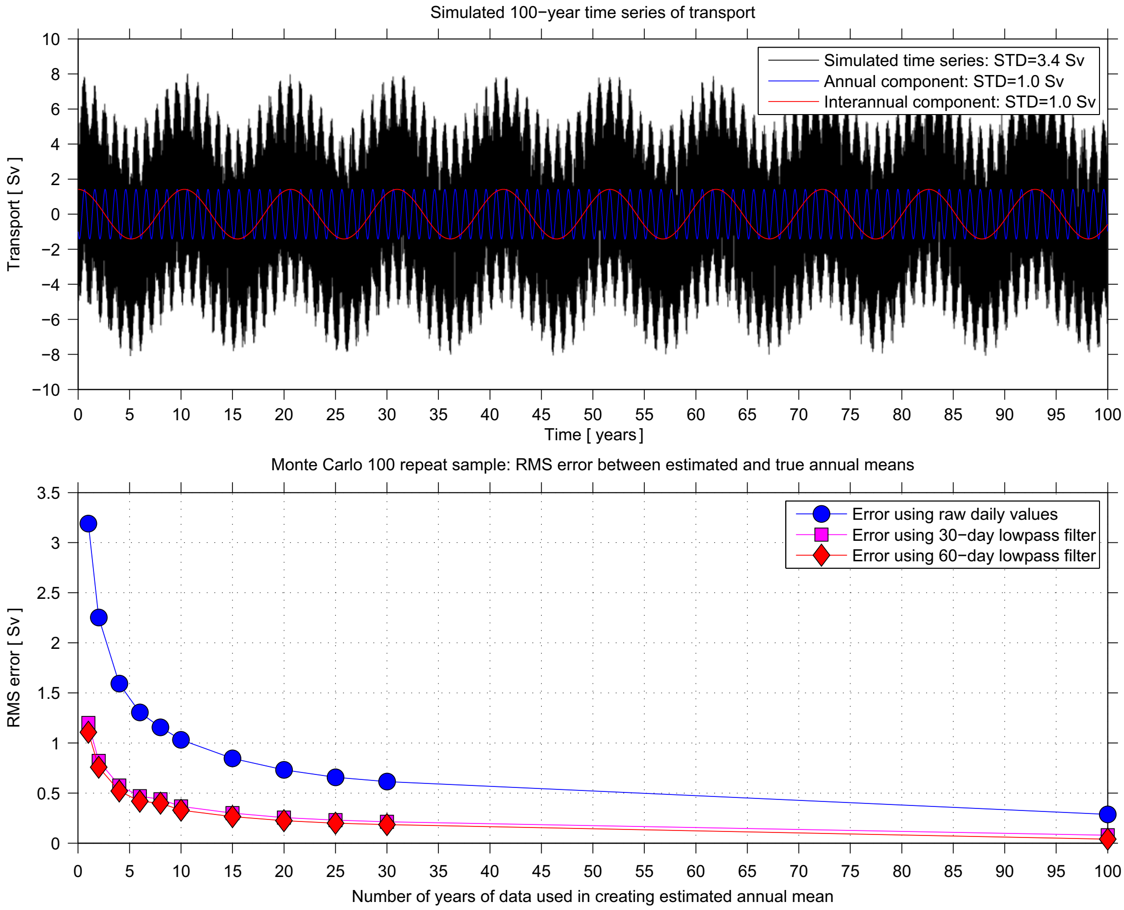

Fig. 5. Simulated 100 yr record in transport used in the Monte Carlo style estimation of the errors inherent in determining a mean annual cycle/climatology from a record where the annual variance is a small percentage of the total. Upper panel shows the simulated cable record (black) along with the annual (blue) and interannual/decadal (red) cycles upon which the simulated record was built. Lower panel shows the root-mean-squared (RMS) difference between the true daily annual mean values and those estimated using the indicated number of years worth of data from the simulated cable record. The different colors and symbols in the lower panel denote either the raw, 30 day, or 60 day low pass filtering that was applied to the data before determining the differences from the true annual cycle.

suggest that the differences in the annual cycles over the 1982–1990, 1991–1998, and 2000–2007 time periods are not different from one another in a statistically meaningful way. This of course does not mean that there is not a modulation of the annual cycle occurring as was suggested by Baringer and Larsen, (2001) and Peng et al. (2009), only that given the limited data presently available the differences between the annual cycles determined using subsets of the past 25 years are of marginal statistical significance and will require additional data for confirmation.

4.2. Extracting longer time scales from the data

Recalling that the percentage of variance at periods less than 42 months is more than 90%, aliasing of the other frequencies into the decadal band is also a problem given the short record. As noted previously, the largest fluctuation that can be identified at periods beyond a year or two is a quasi-decadal fluctuation with a period of roughly 12 years observed by Baringer and Larsen (2001) from the 1982–1998 cable data that was shown to be anti-correlated to variations in the North Atlantic Oscillation (NAO). DiNezio et al. (in press) further illustrated this anti-correlation using wavelet analyses over the period 1982–2007 and showed that the wind stress curl and the NAO were out of phase.[9] They proposed a physical mechanism using faster-than-linear wave propagation speeds for first baroclinic Rossby waves that could explain a significant fraction of the variability in the Florida Current on these time scales (DiNezio et al., 2009). The challenge of analyzing the Florida Current variability at these time scales, however, as was noted in earlier studies such as Sturges and Hong (1995), is that even with a roughly 25 year record, at most two realizations of the cycle would be captured in the near-continuous record.

In order to expand the available time series beyond the near-continuous daily time period (1982–2007), most studies of interannual to decadal variability have focused on using monthly, annual or biannual mean transports for the Florida Current (e.g. Baringer and Larsen, 2001). As with the annual cycle studies, it is important to analyze the accuracy to which these means can be calculated with sparse data when the continuous cable records are not available (e.g. see 1964–1982 and 1998–2000 in Fig. 3). This Monte Carlo style analysis was done similarly to that used for the annual cycle, however the actual cable data from the nearly continuous 1982–1998 period was used for estimating the errors in monthly, annual, three-year and five-year means rather than a simulated time series. For the monthly averaging, a random month of data was selected from the cable record, and then a

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[9] Note that although not expanded upon in detail in that study, the results of DiNezio et al. (2009) agree with previous research by Baringer and Meinen (2006)

(*footnote continued*)
and Beal et al. (2008) showing that the relationship between the NAO and the Florida Current transport is less evident in the most recent few years.

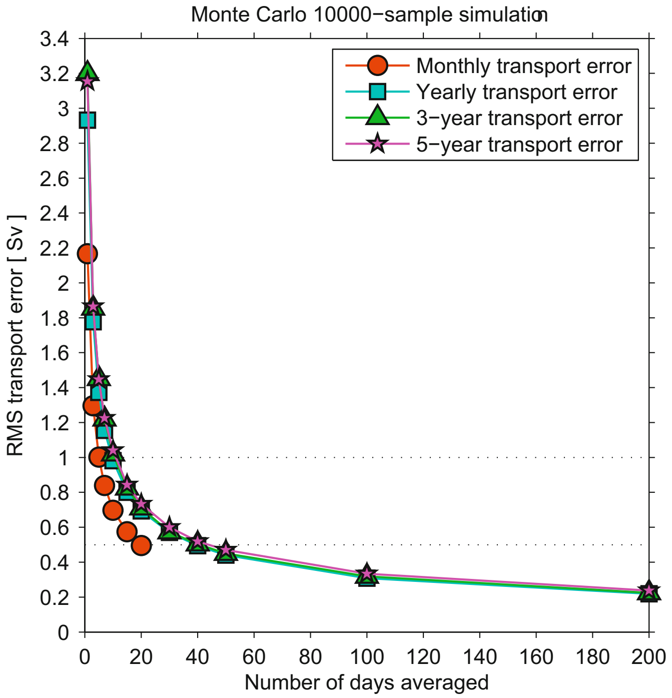

Fig. 6. Monte Carlo style estimates of the root-mean-square (RMS) error in estimating monthly, annual, three-year, and five-year means with only the indicated number of samples. Monthly estimates were made for one, two, five, eight, 10, and 20 days from the month, while annual, three-year, and five-year estimates were made with one, two, five, eight, 10, 20, 30, 40, 50, 100, and 200 days from each time window. The Monte Carlo style simulation was run for 10,000 random selections at each sample level. Note this error bar assumes a random distribution of days throughout the time window; errors would be larger if the distribution is not random (e.g. all data were collected in January and February when trying to estimate an annual mean).

randomly selected number of daily observations from that month (ranging from one to 20) were averaged and the difference between that average and the 'true' average of the complete set of daily values from that month was determined. The analogous procedure was used for annual, three and five year means. The results (shown in Fig. 6) suggest that in order to obtain a monthly mean value that is accurate to better than 0.5 Sv (one standard error, or 67% confidence level) at least 20 daily values from that month are required. In order to obtain an estimate of the annual mean transport of the Florida Current that is accurate to better than 0.5 Sv more than 40 observations are required in that year. Furthermore, these results presume that the observations were randomly spread throughout the year. If observations were clustered within one part of the annual cycle (as often occurred in the early portion of the record, e.g. all of the 1974 observations are in May–August when the annual cycle is nearing its peak) then the difference between the mean of those observations and the true annual mean could be larger because the annual cycle will be inadequately sampled by the observations.

This analysis does not suggest that the sparser data sets such as the dropsonde data in the 1960s and early 1970s cannot be used, it simply illustrates that monthly, annual, and multi-year mean estimates from the sparser data must be accompanied by larger error bars associated with the undersampling of the higher frequency variability in the Florida Current transport. For the study presented here, when annual means were based on observations that spanned less than six months of a particular year, the error bar on that annual mean was increased by the standard deviation of the annual cycle (1.0 Sv) in a square-root of the sum of the squares manner (i.e. the annual cycle error and the undersampling error are treated as independent of one another). For three and five year means, a similar sort of error can result depending on how many of the three or five years were sampled (for example, if a three-year average of 1981–1983 is desired but no data is available for 1981, then this three-year average will have an error associated with this). This final source of error was also evaluated using a similar Monte Carlo style technique and the associated errors were included in this analysis.

4.3. Relating Florida Current transport variations to other climate variability

The anti-correlation between the NAO index and the Florida Current transport discussed by Baringer and Larsen (2001) based on the 1982–1998 record can be seen by focusing in particular on the 1986–1998 time period in the three and five year mean records (Fig. 7). The maximum correlation between Florida Current transport and NAO index over the 1982–1998 window is a negative correlation with the NAO leading the Florida Current by one year; for the three (five) year centered means the peak correlation is roughly −0.5 (−0.6), however the lag-correlation peak is fairly broad. This lag between the NAO and the Florida Current is similar to some earlier results downstream of the Straits of Florida showing that the NAO leads Gulf Stream meridional shifts (the latter estimated from TOPEX altimetry data) by about a year during the similar period from 1992–1998 (Frankignoul et al. 2001), although a longer repeat bathythermograph dataset evaluated by Molinari (2004) showed little evidence for a lag between NAO and Gulf Stream meridional position over the longer 1950–2003 time period. During the 1982–1998 period the wind stress curl time series, which has been lagged from three boxes in the interior near 27°N based on the faster-than-linear group speeds derived by DiNezio et al. (2009), shows a high degree of positive correlation with variations in the NAO. The basic mechanism is that NAO variations cause changes to the interior basin wind stress curl field, and these wind stress curl variations force Rossby waves that propagate westward and result in changes in the Florida Current transport. The DiNezio et al. (2009) study demonstrated that the observations during 1982–2007 are consistent with this basic mechanism (although the relationship is weaker after 2000) and they determined that the necessary increase in first baroclinic mode group speeds required to explain the observed variability is consistent with previous observations from altimetry and in situ observations.

Looking outside the 1982–1998 window the marginally significant anti-correlation between Florida Current transport and the NAO does not appear to hold. As noted by Baringer and Meinen (2006) and Beal et al. (2008) there is little evidence of an anti-correlation in the most recent years, and before about 1984 (Fig. 7) even considering the large error bars it is clear from the data presented herein that there little sign that the NAO and Florida Current transport are correlated. The lack of correlation between the NAO and the Florida Current in the time periods outside 1984–1998, and the lack of correlation between the wind stress curl and the NAO, suggests that the anti-correlation found by Baringer and Larsen (2001) may have simply been fortuitous and that the mechanism proposed by DiNezio et al. (in press) may be only one of several mechanisms that can result in interannual and longer variability in the Florida Current.

The Meridional Overturning Circulation (MOC) upper limb is flowing through the Florida Current, so it is logical to expect that decadal variability in the MOC may also be impacting the Florida Current. There has been some speculation that the MOC is undergoing significant variability over the past few decades

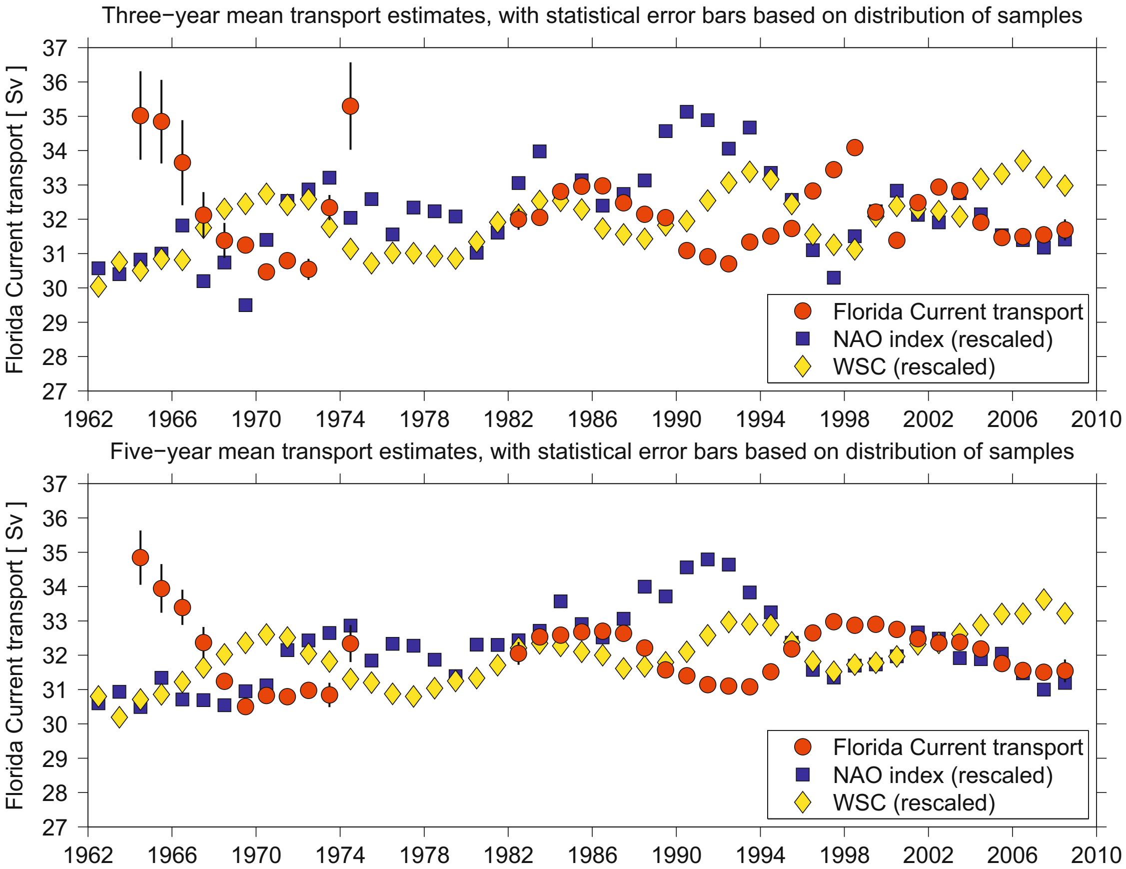

Fig. 7. Three and five-year centered-means of Florida Current transport (red), NAO index (blue), and lagged wind-stress-curl (yellow). Upper panel shows three-year means and lower panel shows five-year means. Wind stress curl (WSC) values have been averaged in bins in the basin interior at 26°N and then lagged based on the distance from the averaging regions to the Straits of Florida following the optimum lags derived in DiNezio et al. (in press). The NAO index and wind stress curl time series have been normalized and rescaled so that they could be plotted on the same transport axes. Vertical black bars indicate the estimated error bars on the three and five year mean Florida Current transports due to temporal undersampling.

(e.g. Bryden et al., 2005), however the types of statistical errors illustrated herein demonstrate the peril of trying to look at long-term trends with snapshot data (e.g. see also Wunsch 1999). Recent observations of the basin-wide integrated MOC, which are closing the total integral to within an accuracy of around 1 Sv at time scales beyond a few days, have suggested that there is also much more high frequency variability in the basin-wide full-water-column integrated MOC than had previously been expected (Cunningham et al., 2007; Kanzow et al., 2007). Furthermore measurements of the lower limb of the MOC show that there is little sign of any decadal variability in the deep flows near the western boundary (e.g. Meinen et al., 2006; Schott et al. 2006). Based on the 40+ years of observations of the Florida Current presented herein, it can be stated fairly conclusively that there is no clear sign of a change in the upper limb of the MOC near the western boundary either.

5. Conclusions

Observations of the Florida Current at or near to 27°N have been collected from historical and active programs from 1964 to the present to evaluate the variability of the Florida Current at time scales from annual to decadal. The longest near-continuous segment of observations, involving daily cable transport estimates from a submarine cable from 1982 to 1998, was used to illustrate that the majority of the variability in the Florida Current (at least to the extent that such can be determined with a 16 year record) is found at high frequencies, with roughly 70% of the total variance occurring at periods less than annual. The annual, interannual, and longer time scales each represent roughly 10% of the total variance (Table 1). The percentage of variance at high frequencies makes extracting fluctuations of importance to climate difficult, and only with long, high temporal resolution records such as that collected in the Florida Current through the submarine cable observations will this ever be possible. Detailed statistical analysis of the cable data suggests that the “modulation” of the annual cycle noted in Baringer and Larsen (2001) and Peng et al., (2009) cannot definitively be distinguished from aliasing of other frequencies onto the annual period, as a Monte Carlo style test suggests the differences from the long-term mean annual cycle are not statistically significant at even a one standard error level given the large amount of variance at high frequencies. At least 25 years of observations are required to achieve a mean annual cycle/climatology with an accuracy of 0.2 Sv, which is a 20% accuracy since the annual cycle has a standard deviation of 1.0 Sv. The annual cycle obtained from the full 25 years of data shows a slightly reduced amplitude (0.9 Sv), but similar phase (with a minimum in January and a maximum in July) as the earliest estimates of the annual cycle.

A similar Monte Carlo style analysis has shown that while the historical observations in the 1960s and the 1970s in the Straits of Florida can be used in concert with the modern data records, the sparseness of the data results in larger statistical uncertainty limits.

To achieve an annual mean estimate of the Florida Current transport that is accurate to within 0.5 Sv more than 40 daily estimates are required. Similar numbers of observations are needed to determine three and five year means of the Florida Current transport. Note all of these estimates presume that the observations are randomly spread throughout the year (or 3-year span, or 5-year span). If the observations are clustered in a small subset of the averaging window the errors can be considerably larger. Nevertheless, despite the large error bars which must be placed on the early data records, it can be shown that the relationship between the North Atlantic Oscillation and the Florida Current first discussed in Baringer and Larsen (2001) and expanded upon by Peng et al. (2009) is not consistent over time. During the time window from 1984 to 1998 there is an anti-correlation between the two time series, but outside of that window there is no such clear relation.[10] The sporadic nature of the relationship between the North Atlantic Oscillation, the wind stress fields and the Florida Current transport likely reflects the fact that the Florida Current plays a role both in the wind driven horizontal “Sverdrup” gyre and the thermohaline vertical gyre associated with the Meridional Overturning Circulation. The data shown herein provide no evidence for a long-term trend in the Florida Current transport, and the variability that does exist on decadal time scales is generally quite small (order 1 Sv during 1982–2007). Perhaps the most interesting inference from this analysis, however, is that there is an absolute necessity for measuring the components of the MOC both continuously in time (i.e. not with snapshot sections) and for long periods of time (i.e. not for just a few years) if there is any hope of extracting the true long-period variability of the ocean circulation.

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References

Alvarez-Garcia, F., Latif, M., Biastoch, A., 2008. On multidecadal and quasi-decadal North Atlantic variability. J. Clim. 21 (14), 3433–3452, doi:10.1175/2007JCLI1800.1.

Anderson, D.L.T., Corry, R.A., 1985. Seasonal transport variations in the Florida Straits: a model study. J. Phys. Oceanogr. 15 (6), 773–786.

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

Baringer, M.O., Meinen, C.S., 2006. Thermohaline circulation, in State of the Climate in 2005Bull. Am. Met. Soc. 87 (6), s1–s102, doi:10.1175/BAMS-87-6-shein.

Beal, L.M., Hummon, J.M., Williams, E., Brown, O., Baringer, W., Kearns, E., 2008. Five years of Florida Current structure and transport from the royal caribbean cruise ship Explorer of the Seas. J. Geophys. Res., doi:10.1029/2007JC004154.

Broida, S., 1962. Florida Straits transports: April 1960–January 1961. Bull. Mar. Sci. Gulf Carib. 12, 168.

Broida, S., 1963. Florida Straits transports: May 1961–September 1961. Bull. Mar. Sci. Gulf Carib. 13, 58.

Broida, S., 1969. Geostrophy and direct measurements in the Straits of Florida. J. Mar. Res. 27 (3), 278–292.

Brooks, I.H., Niiler, P.P., 1975. The Florida Current at Key West: summer 1972. J. Mar. Res. 33 (1), 83–92.

Brooks, I.H., Niiler, P.P., 1977. Energetics of the Florida Current. J. Mar. Res. 35 (1), 163–191.

Bryden, H.L., Longworth, H.R., Cunningham, S.A., 2005. Slowing of the Atlantic Meridional Overturning Circulation at 25°N. Nature 438, 655–657.

Cunningham, S.A., Kanzow, T., Rayner, D., Baringer, M.O., Johns, W.E., Marotzke, J., Longworth, H.R., Grant, E.M., Hirschi, J.J.-M., Beal, L.M., Meinen, C.S., Bryden, H.L., 2007. Temporal variability of the Atlantic Meridional Overturning Circulation at 26.5°N. Science 317, 935, doi:10.1126/science.1141304.

DiNezio, P.N., Gramer, L.J., Johns, W.E., Meinen, C.S., Baringer, M.O., 2009. Observed interannual variability of the Florida Current: wind forcing and the North Atlantic Oscillation, J. Phys. Oceanogr. 39 (3), 721–736, doi: 10.1175/2008JPO4001.1.

Emery, W.J., Thomson, R.E., 2004. Data Analysis Methods in Physical Oceanography. Elsevier, Amsterdam 638pp.

Frankignoul, C., de Coëtlogon, G., Joyce, T.M., Dong, S., 2001. Gulf Stream variability and ocean–atmosphere interactions. J. Phys. Oceanogr. 31 (12), 3516–3529.

Hamilton, P., Larsen, J.C., Leaman, K.D., Lee, T.N., Waddell, E., 2005. Transports through the Straits of Florida. J. Phys. Oceanogr. 35 (3), 308–322.

Johns, E., Wilson, W.D., Molinari, R.L., 1999. Direct observations of velocity and transport in the passages between the Intra-Americas Sea and the Atlantic Ocean, 1984–1996. J. Geophys. Res. 104 (C11), 25805–25820.

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

Johns, W.E., Townsend, T.L., Fratantoni, D.M., Wilson, W.D., 2002. On the Atlantic inflow to the Caribbean Sea. Deep Sea Res. I 49, 211–243.

Kanzow, T., Cunningham, S.A., Rayner, D., Hirschi, J.J.-M., Johns, W.E., Baringer, M.O., Bryden, H.L., Beal, L.M., Meinen, C.S., Marotzke, J., 2007. Observed flow compensation associated with the meridional overturning at 26.5°N in the Atlantic. Science 317, 938, doi:10.1126/science.1141293.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, B., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteor. Soc. 77 (3), 437–470.

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

Larsen, J.C., 1991. Transport measurements from in-service undersea telephone cables. IEEE J. Oceanic Eng. 16 (4), 313–318.

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. Phil. Trans. R. Soc. Lond. A 338, 169–236.

Leaman, K.D., Molinari, R.L., Vertes, P.S., 1987. Structure and variability of the Florida Current at 27°N: April 1982–July 1984. J. Phys. Oceanogr. 17 (5), 565–583.

Leaman, K.D., Vertes, P.S., Atkinson, L.P., Lee, T.N., Hamilton, P., Waddell, E., 1995. Transport, potential vorticity, and current/temperature structure across Northwest Providence and Santaren Channels and the Florida Current off Cay Sal Bank. J. Geophys. Res. 100 (C5), 8561–8569.

Lee, T.N., Schott, F.A., Zantopp, R., 1985. Florida Current: low-frequency variability as observed with moored current meters during April 1982 to June 1983. Science 227, 298–302.

Lee, T.N., Williams, E., 1988. Wind-forced transport fluctuations of the Florida Current. J. Phys. Oceanogr. 18 (7), 937–946.

Luther, D.S., Filloux, J.H., Chave, A.D., 1991. Low-frequency, motionally induced electromagnetic fields in the ocean 2. Electric field and Eulerian current comparison. J. Geophys. Res. 96 (C7), 12797–12814.

Mayer, D.A., Larsen, J.C., 1986. Tidal transport in the Florida Current and its relationship to tidal heights and cable voltages. J. Phys. Oceanogr. 16, 2199–2202.

Meinen, C.S., Baringer, M.O., Garzoli, S.L., 2006. Variability in Deep Western Boundary Current transports: preliminary results from 26.5°N in the Atlantic. Geophys. Res. Lett. 33, L17610, doi:10.1029/2006GL026965.

Molinari, R.L., Maul, G.A., Chew, F., Wilson, W.D., Bushnell, M., Mayer, D., Leaman, K., Schott, F., Lee, T., Zantopp, R., Larsen, J.C., Sanford, T.B., 1985a. Subtropical Atlantic Climate studies: introduction. Science 227, 292–295.

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

Molinari, R.L., 1986. Subtropical Atlantic climate studies (STACS) revisited. EOS 67 (5), 59–60.

Molinari, R.L., 2004. Annual and decadal variability in the western subtropical North Atlantic: signal characteristics and sampling methodologies. Prog. Oceanogr. 62, 33–66.

Montgomery, R.B., 1941. Transport of the Florida Current off habana. J. Mar. Res. 4 (3), 198–220.

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[10] This is also evident in the most recent few years in the wavelet analyses of DiNezio et al., 2009, although they did not evaluate the signals before 1982. The lack of correlation in recent years was also noted by Baringer and Meinen (2006) and by Beal et al. (2008).

Mooers, C.N.K., Meinen, C.S., Baringer, M.O., Bang, I., Rhodes, R., Barron, C.N., Bub, F., 2005. Cross validating ocean prediction and monitoring systems. EOS 86 (29), 272–273.

Niiler, P.P., Richardson, W.S., 1973. Seasonal variability of the Florida Current. J. Mar. Res. 31, 144–167.

Peng, G., Garraffo, Z., Halliwell, G.R., Smedstad, O.-M., Meinen, C.S., Kourafalou, V., Hogan, P., 2009. Temporal variability of the Florida Current transport at 27°N. In: Columbus, F. (Ed.), Ocean Circulation and El Nino: The New Research. NOVA Science Publishers, Hauppauge, NY in press.

Pillsbury, J.E., 1887. Gulf Stream Explorations – Observations of Currents – 1887. Rept. Supt., US Coast Geod. Surv., Appendix 8, 173–184.

Pillsbury, J.E., 1890. The Gulf Stream—a description of the methods employed in the investigation, and the results of the research. Rept. Supt., US Coast Geod. Surv., Appendix 10, 461–620.

Richardson, W.S., Finlen, J.R., 1967. The transport of Northwest Providence Channel. Deep Sea Res. 14, 361–367.

Richardson, W.S., Schmitz Jr., W.J., 1965. A technique for the direct measurement of transport with application to the Straits of Florida. J. Mar. Res. 23, 172–185.

Sanford, T.B., 1982. Temperature transport and motional induction in the Florida Current. J. Mar. Res. 40 (Suppl.), 621–639.

Schmitz Jr., W.J., Richardson, W.S., 1968. On the transport of the Florida Current. Deep Sea Res. 15, 679–693.

Schott, F., Zantopp, R., 1985. Florida Current: seasonal and interannual variability. Science 227 (4684), 308–311.

Schott, F.A., Lee, T.N., Zantopp, R., 1988. Variability of structure and transport of the Florida Current in the period range of days to seasonal. J. Phys. Oceanogr. 18 (9), 1209–1230.

Schott, F.A., Fischer, J., Dengler, M., Zantopp, R., 2006. Variability of the deep western boundary current east of the grand banks. Geophys. Res. Lett. 33, L21S07, doi:10.1029/2006GL026563.

Sheinbaum, J., Candela, J., Badan, A., Ochoa, J., 2002. Flow structure and transport in the Yucatan Channel. Geophys. Res. Lett. 29 (3), 1040, doi:10.1029/2001GL013990.

Smith, W.H.F., Sandwell, D.T., 1997. Global Sea floor topography from satellite altimetry and ship depth soundings. Science 277 (5334), 1956–1962.

Spain, P.F., Dorson, D.L., Rossby, H.T., 1981. PEGASUS: a simple, acoustically tracked, velocity profiler. Deep Sea Res. 28A, 1553–1567.

Stommel, H., 1948. The theory of the electric field induced in deep ocean currents. J. Mar. Res. 7, 386–392.

Stommel, H., 1957. Florida Straits transports: 1952–1956. Bull. Mar. Sci. Gulf Carib. 7, 252–254.

Stommel, H., 1959. Florida Straits transports: June 1956–July 1958. Bull. Mar. Sci. Gulf Carib. 9, 222–223.

Stommel, H., 1961. Florida straits transports: July 1958–March 1959. Bull. Mar. Sci. Gulf Carib. 11, 318.

Sturges, W., Hong, B.G., 1995. Wind forcing of the Atlantic thermocline along 32°N at low frequencies. J. Phys. Oceanogr. 25, 1706–1715.

von Storch, J.-S., and H. Haak, Impact of daily fluctuations on long-term predictability of the Atlantic Meridional Overturning Circulation, Geophys. Res. Lett., 35, L01609, 10.1029/2007GL032385, 2008.

Wertheim, G.K., 1954. Studies of the electric potential between Key West, Florida, and Havana, Cuba. Trans. Am. Geophys. U. 35, 872–882.

Wunsch, C., Hansen, D.V., Zetler, B.D., 1969. Fluctuations of the Florida Current inferred from sea level records. Deep Sea Res., Suppl. 16, 447–470.

Wunsch, C., 1999. The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations. Bull. Am. Met. Soc. 80 (2), 245–255.