Accuracy of Florida Current Volume Transport Measurements at 27°N Using Multiple Observational Techniques

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ABSTRACT

For more than 30 years, the volume transport of the Florida Current at 27°N has been regularly estimated both via voltage measurements on a submarine cable and using ship-based measurements of horizontal velocity at nine historical stations across the Florida Straits. A comparison of three different observational systems is presented, including a detailed evaluation of observational accuracy and precision. The three systems examined are dropsonde (free-falling float), lowered acoustic Doppler current profiler (LADCP), and submarine cable. The accuracy of the Florida Current transport calculation from dropsonde sections, which can be determined from first principles with existing data, is shown to be 0.8 Sv ($1\,\mathrm{Sv} \equiv 10^6\,\mathrm{m^3\,s^{-1}}$). Side-by-side comparisons between dropsonde and LADCP measurements are used to show that the LADCP-based transport estimates are accurate to within 1.3 Sv. Dropsonde data are often used to set the absolute mean cable transport estimate, so some care is required in establishing the absolute accuracy of the cable measurements. Used together, the dropsonde and LADCP sections can be used to evaluate the absolute accuracy and precision of the cable measurements. These comparisons suggest the daily cable observations are accurate to within 1.7 Sv, and analysis of the decorrelation time scales for the errors suggests that annual transport averages from the cable are accurate to within 0.3 Sv. The implications of these accuracy estimates for long-term observation of the Florida Current are discussed in the context of maintaining this key climate record.

1. Introduction

The Florida Current is one of the most studied oceanic flows in the world, with targeted studies as early as the 1880s (Pillsbury 1891) and "routine" study of its transport beginning in the 1950s and continuing through today (e.g., Stommel 1957; Richardson and Schmitz 1965; Niiler and Richardson 1973; Molinari et al. 1985a; Leaman et al. 1995; Baringer and Larsen 2001; Rousset and Beal 2011). Each study over the years has utilized different instruments and methods for calculating the Florida Current transport. The accuracy of the transport calculation, therefore, has varied from study to study. As will be discussed in more detail later in the paper, some methods for determining the transport involved measuring velocity profiles at discrete stations and subsequently interpolating, extrapolating, and integrating those velocities, while other methods directly integrated the volume transport. For climate studies, wherein analysis of data over multiple decades is necessary, it becomes crucial to understand the different accuracies of these varying instruments and methods.

At present, three different measurement systems are being used simultaneously to monitor the variations of the Florida Current along 27°N. This provides the opportunity to carefully evaluate the accuracies of these systems and to test them against one another. Florida Current transports are being estimated regularly using shipboard measurements, with both dropsonde floats and lowered acoustic Doppler current profiler (LADCP) observations (Meinen et al. 2010; Szuts and Meinen 2013), at nine sites across the Straits of Florida (Fig. 1). Volume transports are also being estimated from voltage

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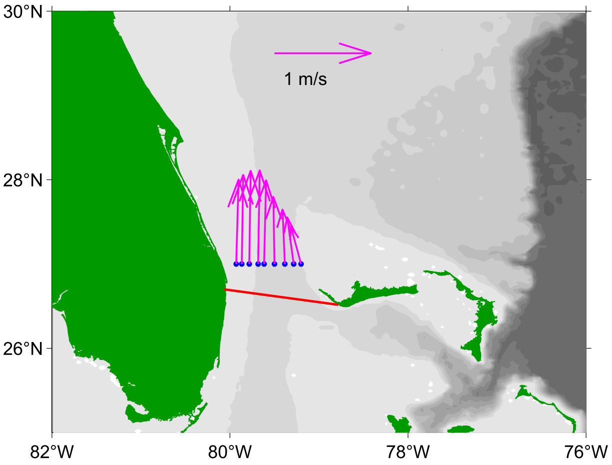

FIG. 1. Map of the Straits of Florida study area. Blue circles denote locations of the long-term Pegasus, dropsonde, and LADCP stations along 27°N. The red line indicates the approximate location of the abandoned submarine telephone cable between West Palm Beach, FL, and Eight Mile Rock, Bahamas. Magenta vectors indicate the time-mean vertically averaged horizontal velocities using all dropsonde data collected since 1994.

measurements on an abandoned submarine telephone cable spanning the straits at approximately the same location (Fig. 1; e.g., Baringer and Larsen 2001; Meinen et al. 2010). Furthermore, all of these present-day systems have previously been tested against one of the instruments commonly used in the 1980s, the Pegasus acoustically tracked free-falling float (e.g., Molinari et al. 1985a), which allows for comparison with that system as well.

Before continuing, it must be noted that ''measurement accuracy'' and ''statistical accuracy'' as used in this paper are not the same, and must be considered separately from one another. The accuracy of a single measurement of temperature by a thermometer, for example, is a measurement accuracy, whereas the determination of how well monthly snapshot measurements of temperature can represent the true annual mean temperature is a discussion of statistical accuracy. The focus of this paper is primarily on measurement accuracy—except where noted.

Ultimately, the absolute accuracy and precision of more complicated measurement devices tend to be determined through comparison with some other instrument. Because the dropsonde measurement is the most ''simple,'' it represents the best ''standard'' against which each of the other measurement techniques can be compared. The dropsonde measurement is considered simple because each aspect of the measurement can be evaluated on first principles to determine the contribution to the overall accuracy of the measurement. The purpose of this article is to present a careful evaluation of the accuracy of the dropsonde, LADCP, and cable observations, with a particular focus on the dropsonde float. Accuracies of the dropsonde and LADCP velocity measurements will be discussed and contrasted to earlier published Pegasus accuracies. Additionally, the section transport accuracies from the dropsonde and LADCP integrations across the Straits of Florida at 27°N will be presented and compared to the submarine cable measurements in order to derive the accuracy of the cable transport estimates.

The paper is organized as follows. Section 2 describes the instruments and data used in this study. Section 3 examines the accuracy in the measurement of velocity and the calculation of transport. Section 4 presents a discussion of the overall results and the implications of these accuracy estimates for climate studies of the Florida Current.

2. Instruments and data

A brief explanation of each of the data systems that will be discussed in this paper will be presented; only a short description will be provided with the appropriate citations for further information. Velocity measurement systems will be described first, followed by the sole naturally integrating transport technique presently in use.

a. Dropsondes

A dropsonde is a free-falling float that is deployed from a ship. Once deployed, it sinks to the bottom at a constant rate, drops a weight when it reaches the bottom (via a simple mechanical lever), and then rises back to the surface at a constant rate under its own buoyancy.[1] Knowing the elapsed time to complete the cast (i.e., the subsurface time interval), and the initial and final position of the dropsonde on the ocean surface at the start and end of the cast, it is possible to calculate the vertically averaged horizontal velocity as the total distance traveled divided by the time required for the cast. In a pioneering study, Richardson and Schmitz (1965) first described this type of technique and its use to make direct measurements of the ocean velocity and Florida Current volume transport. Many subsequent refinements have been made to improve dropsonde technology, but the concepts remain the same.

The accuracy of the vertical-mean horizontal velocity calculated from the dropsondes depends of the accuracy of the system(s) used to determinate the elapsed time of

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[1] The sinking and rising rates are constant in time but are not the same. Tests with a dropsonde carrying a pressure gauge have found that the sinking rate ($0.8\,\mathrm{m\,s^{-1}}$) and rising rate ($0.7\,\mathrm{m\,s^{-1}}$) are indeed constant to within $0.02\,\mathrm{m\,s^{-1}}$, or 2.5%, when the 1-Hz raw measurements are 1-min filtered to remove sensor resolution noise.

the cast and the geographical position of the instrument when it first begins to sink and first emerges back on the surface. Thus, the evolution of the dropsonde, as a direct ocean velocity measurement instrument, has been related to the evolution of the navigation systems from the 1960s until today. So, for example, the Hi-Fix (Decca Navigation System, Inc.) master–slave radio location system was used with the earliest dropsonde studies by Richardson and Schmitz (1965) and Schmitz and Richardson (1968). Subsequently, a Loran C system was used with the Partnership for Observation of the Global Oceans (POGO), an acoustically tracked drifter (considered at the time as the modern version of the dropsonde float) to measure water transport between the surface and a preselected depth in the Gulf Stream (Rossby et al. 1991). While these authors discussed the sources of errors involved in these earlier navigation systems, the accuracy of the dropsonde changed significantly with the advent of the global positioning system (GPS) in the late 1980s and early 1990s. This study presents the first rigorous ''first principle'' analysis of the accuracy of the dropsonde technique since the GPS was incorporated into the dropsonde system.

In the 1990s, dropsonde technology shifted to using GPS for determining float locations and cast elapsed times. From 1991 to 1993, the GPS used was a handheld device on the ship, and the dropsonde surface locations were determined acoustically and visually relative to the ship. In 1994 a newer-generation dropsonde was developed with an internally recording GPS embedded within the dropsonde itself (a design feature still in use today). Note that positioning accuracy from GPS has changed over the years. Prior to the year 2000, the system involved an intentional position degradation feature known as selective availability (SA); the SA degrading was removed in 2000, resulting in substantially increased GPS position accuracy (Grewal et al. 2007).

This study will focus on dropsonde data collected with floats internally equipped with GPS devices. Since 1994, 169 dropsonde sections (1521 total casts) have been conducted along 27°N, occupying the nine stations indicated in Fig. 1. The velocity variability observed by these dropsonde measurements is quite high, with the standard deviation of the observed flow at some stations exceeding 20%–30% of the mean value of the flow, particularly on the western side of the section (Fig. 2).

One additional measurement system related to the dropsondes will also be discussed briefly. The Pegasus acoustically tracked free-falling float (Spain et al. 1981) was developed as a modification to the early dropsondes, and was routinely used at the nine stations shown in Fig. 1 throughout the 1980s (e.g., Molinari et al. 1985b). The Pegasus float was considered very accurate because it was possible to carefully determine the locations of the sound source tracking moorings and to accurately estimate the acoustic sound speed profiles, resulting in highly accurate horizontal velocity profiles. Pegasus profilers were also used in a ''dropsonde mode'' during some of the Subtropical Atlantic Climate Studies (STACS) cruises in the late 1980s (Molinari et al. 1985b; Leaman et al. 1987). Unfortunately, the Pegasus system is also quite expensive to use, requiring numerous sound source moorings over a small horizontal distance and as such the system has fallen out of use since the early 1990s. Nevertheless, because all of the other systems that will be discussed herein have been directly compared to, and tested versus, the Pegasus system, it is logical to discuss these comparisons in the context of the accuracy estimates derived herein.

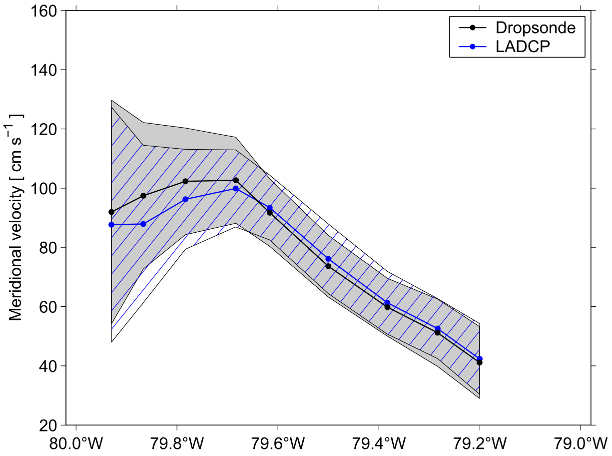

FIG. 2. Mean meridional velocities at the nine sites in the Florida Straits along 27°N from all dropsondes casts since 1994 (black) and all LADCP casts since 2001 (blue). Gray shading indicates plus or minus one standard deviation for the dropsonde data; crosshatch indicates plus or minus one standard deviation for the LADCP data.

b. ADCPs

Measurement of water velocities in the oceans has been greatly improved with the use of acoustic Doppler current profilers (ADCPs). The ADCP is an acoustic device that sends out sound pulses and measures the Doppler shift of sound energy reflected from particles in the water at different distances from its transducer array. This information is translated into relative velocities, and it ultimately yields a water velocity profile over some distance from the instrument. The maximum range is a function of the frequency of the ADCP, the acoustic pulse power, the sampling resolution of the instrument, and the spatial and temporal scattering content of the ocean (e.g., Thurnherr 2010). Many ADCPs are permanently installed on ships [hull-mounted/shipboard ADCP (SADCP)], where they sample the velocity field in the upper ocean along the ship's track, while other ADCPs are deployed on different types of fixed moorings. In most regions of the deep ocean (e.g., depths greater than 300–1500 m), neither hull-mounted nor individual moored ADCPs are capable of providing full-depth velocity profiles. To obtain full-depth velocity profiles in the deep ocean, sophisticated methods have been developed for processing data from ADCPs that are lowered from the surface while attached to a conductivity–temperature–depth (CTD) package (LADCP; e.g., Firing and Gordon 1990; Fischer and Visbeck 1993; Firing 1998; Visbeck 2002; Thurnherr 2010).

Shipboard surveys in the Straits of Florida have collected 48 LADCP sections (432 total profiles) since 2001 at the nine stations along 27°N (Fig. 1). Most cruises also collected SADCP data simultaneously during the surveys. As shown in Fig. 2, the vertically averaged horizontal velocity observations from the LADCP sections are also very highly variable, with standard deviations roughly equal to those of the more numerous dropsonde observations. The difference in the mean velocities (black and blue lines in Fig. 2) are not statistically significant, instead they reflect the fact that there are roughly 3 times as many dropsonde sections as there are LADCP sections.

It should be pointed out that, as was already established, one of the final goals for these station measurements is to combine them in order to estimate the volume transport of the Florida Current. While the LADCP profiles consistently provide sufficient observations to provide a full water column velocity profile that can be integrated horizontally to yield volume transport estimates, the SADCP data do not. The vertical coverage of the SADCP data is routinely insufficient to allow for a full-depth transport integration. Nevertheless, SADCP data from some of the cruises—that is, those that reach at least 500 m where the straits are deepest—are used in this study to estimate the errors associated with sampling the section horizontally at only nine discrete locations versus having continuous horizontal velocity measurements along the section.

c. *Cable voltage measurements*

Basic electromagnetic theory shows that charged particles, such as the salt ions in seawater, moving through a magnetic field will induce an electric field perpendicular to the motion (e.g., Stommel 1948; Sanford 1982; Larsen 1992; Szuts 2012). Because the earth has a strong magnetic field, and seawater is full of salt ions, horizontal flows in the ocean will induce horizontal electric fields perpendicular to the flow. Because seawater is a conductive media, the electric field induced by ocean currents will "short out" in the vertical, producing a vertically averaged field, and if a wire is stretched across this field, then the voltage induced on the wire will be approximately linearly proportional to the transport of ions through the field (see Larsen and Sanford 1985 for more details). Linear transfer coefficients between voltage and water volume transport can therefore be determined by comparison with direct ship section estimates at the cable site. This method has been investigated for use in measuring ocean transport since the 1950s (e.g., Stommel 1957, 1959), and it has been in routine and nearly continuous usage on active or inactive telephone cables in the Straits of Florida at 27°N since 1982 (e.g., Larsen and Sanford 1985; Baringer and Larsen 2001; Meinen et al. 2010). This method is inherently integrating over the length of the cable; cable voltages are calibrated into volume transport estimates through the use of concurrent ship-based velocity/transport measurements.

The linear transfer coefficients for the 27°N cable were originally derived using Pegasus observations in the 1980s (e.g., Larsen 1992). In the modern era, these coefficients are evaluated regularly using dropsonde cruises and a subset of the dropsonde section data have been used to make small adjustments to the coefficients. Approximately 40% of dropsonde sections since 2000 have been used for cable calibration adjustments (occasional constant offsets due to voltage recording system changes), and therefore about 60% are truly independent relative to the cable; for more information see Meinen et al. (2010).

3. Accuracy of velocity and transport estimates

Two types of measurement errors are pertinent to the discussion here—errors in the actual measurement of velocity by an instrument itself and errors introduced when combining velocity measurements at different sites to obtain a horizontally integrated transport. The velocity errors will be quantified first, with a focus on a careful evaluation of the dropsonde errors and on the comparison between dropsonde and LADCP, and this will be followed by a discussion of the transport accuracy issues. Once the individual errors are documented, total accuracies for the velocity and transport estimates are developed by combining the individual errors. For those errors that are independent from one another—that is, those errors that can be demonstrated to not be related—the total error is determined as the square root of the sum of the squares, following Emery and Thomson (2004):

$$\varepsilon_{\text{Total}} = (\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 + \cdots + \varepsilon_N^2)^{1/2}, \qquad (1)$$

where ε_i ($i = 1, 2, 3, \ldots, N$) are the individual random error sources and $\varepsilon_{\text{Total}}$ is the combined total error.

a. *Velocity accuracy—Dropsonde*

As mentioned earlier, the dropsonde measurement of velocity is simple—requiring accurate positions at the start and end of the cast and the accurate elapsed time. For the starting position, the accuracy is purely a function of the GPS accuracy itself. Several tests were conducted using two different models of GPS at fixed locations (i.e., securely fixed to structures); the resulting GPS location estimates were found to be accurate to within root-mean-square (rms) errors of 3–5 m. Note that this value is pertinent only to the time period after SA was disabled on the GPS system in the year 2000. Prior to that time, the GPS accuracy available to the public was noticeably worse with rms errors of 45 m (Farrell and Barth 1999). Regardless of whether SA was in place, the GPS position errors are random from one station to the next, and as such they represent a random scatter source of error to the calculated velocity, not a bias.[2] The velocity error at each location due to this source can be estimated as follows. First, the total distance error at each site is determined by multiplying the GPS position error by the square root of 2 (since the errors at both ends of the cast are independent). This total distance error is then divided by the average length of time for a given station (from 7 to 35 min depending on depth). The resulting velocity error estimates for the nine stations are then averaged to give an overall velocity accuracy for this source of error. The results are an accuracy of 6.1 cm s^{-1} before 2000 when SA was in place and only 0.6 cm s^{-1} since 2000 when SA was disabled.

The accuracy of the GPS location is not the only source of error that can be introduced to the dropsonde velocity measurement as a result of the GPS system. The modern GPS can obtain a position roughly once per second, so the time and location of the start of the cast are quite precise. Once the dropsonde submerges, however, it loses the GPS signal, and when it returns to the surface at the end of the cast, it takes a nonnegligible amount of time to reacquire the satellites and obtain a new location fix. During this time period, the dropsonde is drifting at the speed of the surface flow, biasing the vertical average toward the surface value. This drift has been an issue for every generation of dropsonde over the years—the early work by Richardson and Schmitz (1965) with the first dropsondes found this to be a 1% error in the resulting velocity in that generation of instruments.

A correction for the reacquisition time has always been applied to the dropsonde measurement as part of the standard processing; however, the application of the correction cannot be done perfectly. The error estimate associated with this imperfect correction was determined as follows for the modern data. A GPS receiver was subjected to 30 submergence tests with time lengths ranging between 5 and 30 min to determine the reacquisition time for casts of these lengths. A linear relationship between cast length and reacquisition time was found (not shown). For short dropsonde casts of about 5 min (i.e., depths of 100–150 m), satellite fixes returned after about 5 s, while for longer casts of around 30 min (i.e., depths of 600–700 m), reacquisition occurs after about 25 s. As noted above, these reacquisition times impact the dropsonde calculation as the surface currents advect the dropsonde during this 5–25-s period, thereby biasing the vertical averaging toward the surface velocity value. To address this problem, dropsondes are always left to drift on the surface for about 5 min at the end of the cast, and the surface velocity estimate obtained during those 5 min is used to project backward to the estimated actual surfacing location from the first good GPS location fix. The scatter about the linear fit mentioned above represents the accuracy of this surface drift correction. The rms difference from the linear fit was 7 s. This time "error" can be converted into a velocity error by differencing two estimates of the velocity: the velocity at the site (distance divided by time) minus the erroneous velocity at the site (distance divided by the time plus a 7-s error). The resulting accuracy for this correction, determined as the average of these values at the nine sites, is 0.5 cm s^{-1}.

The GPS location accuracy and GPS reacquisition correction accuracy are the two main sources of error that apply to the dropsonde velocity calculation.[3] Because these two sources of error are independent of one another, as one is based on satellite position accuracy and the other is based on ocean velocity drift accuracy, they can be combined in a square root of the sum of squares manner [Eq. (1)] to yield a total dropsonde velocity accuracy of 0.8 cm s^{-1} (6.1 cm s^{-1} before year 2000 due to SA). This overall velocity accuracy for the

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[2] Several multihour tests with GPS instruments fixed to structures were completed as part of this study; the results indicate that GPS position errors become uncorrelated after roughly 5–10 min (depending on GPS model).

[3] There is another source of error related to the vertical speed of the dropsonde through the water. The small (~10%) difference in sinking/rising rates (see footnote 1) can introduce a small bias due to the lag in time for the dropsonde to accelerate/decelerate to the ambient velocity at any level as it moves vertically. Estimates of this bias based on acceleration up to the surface speed at the end of the cast are negligible. Given the slow rising/sinking rates for the dropsonde used here (roughly a factor of 2 smaller than earlier studies, e.g., Richardson and Schmitz 1965; Richardson et al. 1969), this source of error is neglected hereinafter.

modern dropsonde is roughly a factor of 5 better than the early dropsondes, which had an estimated measurement accuracy of around 5% of the observed velocities (~100 cm s^{-1}; Schmitz and Richardson 1968).

b. Velocity accuracy—LADCP

As a modern and sophisticated ocean velocity measurement device, the LADCP can measure full-depth ocean velocity profiles rather than just the vertical average captured by the dropsonde. Because the LADCP measures water velocity relative to the instrument itself, which is on a moving package lowered on a long hydrographic wire tethered to another moving platform (the research vessel), an elaborate data processing technique is needed to remove the effects of the instrument motion from the velocity measurements and thereby transform the measured velocities into the earth's frame of reference (e.g., Thurnherr 2010). Two different "families" of methods have been developed for processing LADCP data: the "shear method" (e.g., Firing and Gordon 1990) and the "inversion method" (e.g., Visbeck 2002). The main difference between the two methods is that the inversion method allows ancillary data, such as concurrent SADCP measurements as well as pressure and sound speed information from a coincident CTD profiler, to be used to improve the resulting velocity profile, while the shear method analyzes the LADCP data independently. The LADCP velocity profiles presented herein were obtained using the inversion method incorporating all available ancillary data (CTD, SADCP, etc.). For more details on the processing of full-depth LADCP profiles using the inversion method, see Visbeck (2002) and Thurnherr (2010).

The LADCP measurement is more complicated than that of the dropsonde; while one can perhaps determine from first principles the accuracy of an ADCP fixed on the ocean floor or possibly even a hull-mounted SADCP, with the LADCP this is not feasible. As such, the accuracy of the LADCP-measured velocity has traditionally been estimated through comparison with another "simpler" velocity measurement device. Fischer and Visbeck (1993) used comparisons between LADCP profiles and concurrent Pegasus float profiles to evaluate the accuracy of the LADCP; the observed rms differences were about 5 cm s^{-1} in each velocity component. In a similar study, Hacker et al. (1996) compared only the depth-averaged velocity estimates by Pegasus and LADCP and obtained rms differences of less than 1.5 cm s^{-1}. A recent study by Thurnherr (2010) attempted to estimate accuracy for LADCP profiles by comparing different processing techniques from the two families mentioned above; the resulting accuracy estimate was less than 3 cm s^{-1} as long as multiple velocity-referencing constraints are imposed simultaneously. As part of the present study, during several cruises along 27°N in the Straits of Florida direct side-by-side comparisons were made between a dropsonde and concurrent LADCP profiles. A total of 22 concurrent casts were available, spread over six cruises (Fig. 3); in each case the dropsonde cast was started immediately upon the completion of the CTD-LADCP cast. The rms difference between the vertical-mean meridional velocities from the 22 casts was 3.8 cm s^{-1}. This observed difference should be a true measure of the combined error bars on the dropsonde and LADCP. These should be independent of one another—for example, dropsonde accuracy is principally dependent on the GPS accuracy, while LADCP is dependent on other things (acoustic backscatter strength, etc.). As such they can be combined in a square root of the sum of squares manner [via Eq. (1)]. Comparing the observed 3.8 cm s^{-1} differences to the estimated accuracy of the dropsonde measurements (0.8 cm s^{-1}) and subtracting, one can obtain an estimate for the accuracy of the LADCP vertical mean velocity. The resulting estimated accuracy for LADCP velocity data is 3.7 cm s^{-1}; note that because the LADCP accuracy is at least in part dependent on the scattering particle content in the region where the data is collected, this accuracy is most applicable in regions with particulate distributions similar to the Straits of Florida at 27°N. This 3.7 cm s^{-1} estimated accuracy result falls roughly in the middle of the aforementioned LADCP accuracy estimates—and it will be used throughout the rest of the paper.

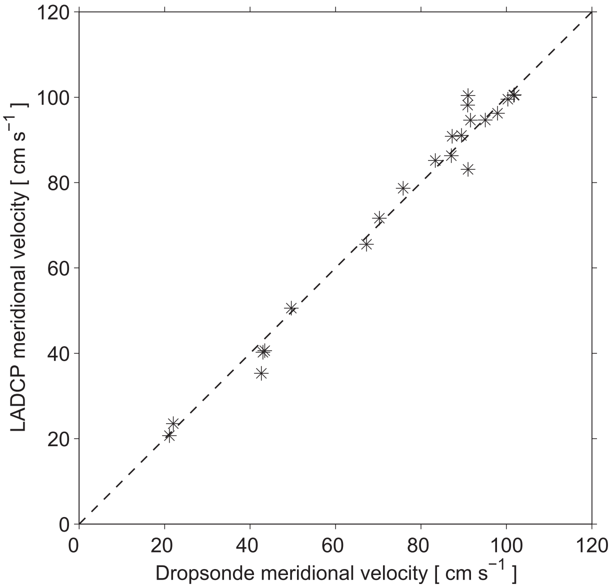

FIG. 3. Comparison of simultaneous vertical-mean meridional velocity measurements from dropsonde and LADCP casts; 22 total side-by-side comparisons were completed.

TABLE 1. Estimates of different sources of error (Sv) in calculating the Florida Current transport at 27°N using either dropsonde or LADCP section data. Numbers in parentheses relate to estimates using GPS prior to the removal of SA in the year 2000—see the text. The total estimated accuracy was determined in a square root of the sum of squares manner [see (Eq. 1)].

Errors sources	Dropsonde	LADCP
Velocity	0.1 (1.0)	0.6
Horizontal integration	0.1	0.1
Horizontal extrapolation	0.1	0.1
Horizontal sampling	0.2	0.2
Accuracy of tide removal	0.5	0.5
Asynopticity	0.5	1.0
Total	0.8 (1.3)	1.3

c. *Transport accuracy*

For transport accuracy, the estimates from ship sections of either dropsonde or LADCP have a common set of error sources. Both types of ship sections are subject to errors in the measured velocity, errors due to extrapolation out to the edges of the straits from the stations nearest to the shore (e.g., no slip, constant extrapolation), errors due to the horizontal resolution of only nine stations, errors due to interpolation between stations, errors due to imperfect removal of the tidal currents at each station, and errors due to the asynopticity of the observations (6 h to complete a dropsonde section or 12–14 h to complete a CTD-LADCP section). Each source of error will be quantified hereinafter in order to determine the overall transport accuracy from these systems (see Table 1).

First the measured velocity accuracy will be considered. The dropsonde velocity accuracy of 0.8 $\mathrm{cm\,s^{-1}}$ derived earlier (or 6.1 $\mathrm{cm\,s^{-1}}$ before SA was disabled in 2000) is translated into transport accuracy by multiplying the velocity error by an average station depth of 510 m and an average station spacing of about 10 km to get a "per station" error, and then the nine station errors are combined in a square root of the sum of the squares manner [see Eq. (1); since the station errors will be independent of one another—recall as stated earlier—GPS positions errors are uncorrelated after 5–10 min]. The resulting transport "error bar" due to the dropsonde velocity accuracy is 0.1 Sv (or 1.0 Sv before SA was disabled in 2000). The LADCP velocity accuracy of 3.7 $\mathrm{cm\,s^{-1}}$ is translated into transport accuracy in a similar manner, resulting in an error bar of 0.6 Sv.

The vertical mean velocities at the nine sites (Fig. 1) must be horizontally integrated in order to obtain the total transport. Historical estimates using dropsondes or Pegasus floats have traditionally estimated the integration errors as being less than 1% or 1 Sv when calculating the Florida Current transport either at 26° or 27°N, respectively (Schmitz and Richardson 1968; Molinari et al. 1985b). For the method discussed here, this integration involves both interpolations between the measurement sites as well as extrapolation out to the edges to fill out the complete 43.2 $\mathrm{km^2}$ (depth times width) of the straits at 27°N. The standard technique used to integrate the nine velocity values first involves interpolation onto a regular horizontal grid of 1000 points that corresponds to a high-quality bathymetry dataset previously collected at this location (Larsen 1992). Grid points inshore of the shallowest measurement site on either side of the straits are filled with constant values equal to the nearest measurement. Testing using a variety of extrapolation methods (e.g., constant fill, linear fit from final two measurements) indicates that the extrapolation method out from the final measurement points contributes transport uncertainties of less than 0.1 Sv. Similarly, changing the number of grid points between measurement sites (and thereby changing the "mean depths" associated with each of the nine measurements) also results in uncertainties of less than 0.1 Sv. This is consistent with dropsonde velocity observations at neighboring sites being fairly well correlated [correlation coefficients r between 0.6 and 0.8, all of which are significantly different from zero at the 99% confidence limit, as determined following the methods of Emery and Thomson (2004)].

A closely related question to these spatial integration issues is whether the nine stations used are sufficient for accurately capturing the transport. The interpolation/extrapolation error estimates just derived depend upon the nine stations being a good representation of the true transport. To evaluate how well the nine stations capture the true transport, a series of 19 high-resolution velocity cross sections collected via SADCP (using a Teledyne RD Instruments Ocean Surveyor 75-kHz system) were subsampled at only the nine locations and the transports were calculated alternately using either the full horizontal resolution captured by the SADCP sections or using only the profiles at the nine stations. The nine stations are found to capture the flow well, as the rms difference between the subsampled data and the full-resolution data was only 0.2 Sv (see Fig. 4).

Another source of error to the transport calculation relates to the fact that the ocean velocities are varying during the time while the section is being collected—this "asynopticity" of the observations introduces errors. The dropsonde and LADCP systems both measure the actual velocity observed at the time of the cast, and as such these velocities represent both the Florida Current signal at the specific time of the cast as well as any other signals present, such as tides. Tide velocities vary significantly over the period of time required to collect a section, and these tide signals must be removed prior to integrating the nine velocity measurements to obtain

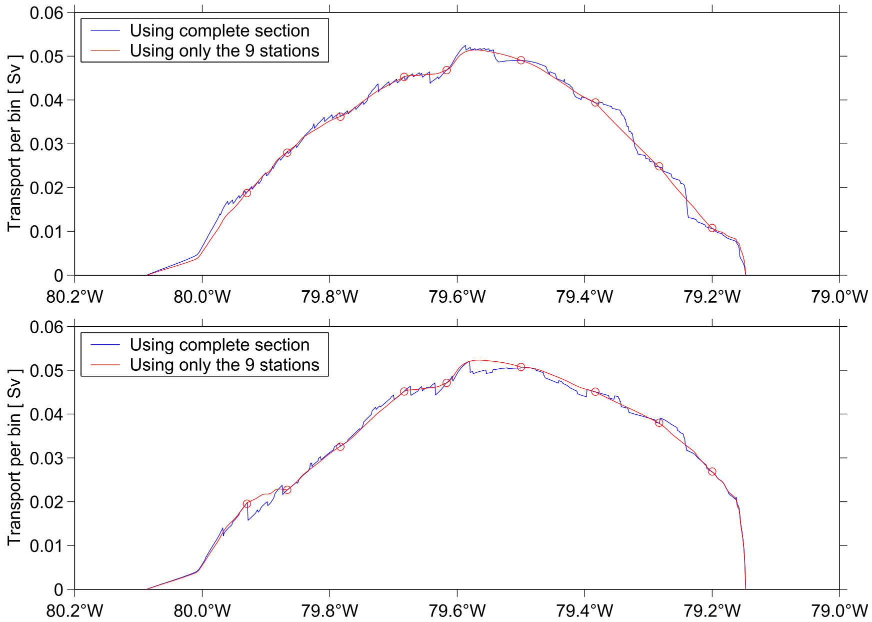

FIG. 4. Comparisons of meridional transports determined using SADCP data in two manners. The first method uses the full-resolution of 5-min bin-averaged data (blue lines), while the second method uses only those 5-min bin averages nearest to the nine long-term dropsonde/LADCP/Pegasus sites (red lines and circles). For both techniques the SADCP data are interpolated onto the same 1000-horizontal-point high-resolution (~90 m) bathymetry grid. Data are shown from two different cruises—(top) June 2009 and (bottom) September 2005—which illustrate the smallest and largest resulting interpolation errors, respectively.

a single transport value for the Florida Current. The tide signals can be estimated and removed (albeit imperfectly, see below), whereas other changes in the Florida Current transport that occur over the 6 h (for a dropsonde cruise) or 12–14 h (for a LADCP cruise) for a section cannot be predicted and removed.

Tide velocities for each of the nine stations are estimated using tide constituent phases and amplitudes derived previously from current meter and tide gauge data by Mayer et al. (1984). The meridional barotropic velocities associated with these tide corrections are determined via a harmonic analysis technique at the midpoint time of each cast (dropsonde or LADCP) using the t_tide package (Pawlowicz et al. 2002). The resulting velocities have a maximum amplitude of 10 cm s^{-1}, a mean value (as would be expected) of 0.0 cm s^{-1}, and an rms value of 3.7 cm s^{-1}. These tide amplitudes can, if assumed to be constant across the entire straits, translate[4] to a maximum transport of 4.6 Sv. This estimate is similar to previous estimates of tidal transports made using either Pegasus float data (e.g., 5.1 Sv; Molinari et al. 1985b) or a combination of current meter, tide gauge, and analytical tidal models (e.g., 5.1 Sv; Mayer et al. 1984). The key issue here, however, is not the size of the tide transport but the accuracy with which the tidal flows can be removed. Lacking new current meter mooring data at all nine sites across the straits at 27°N from which new tidal constituents could be determined, the best way to estimate the accuracy of these tidal corrections with existing data is to compare the barotropic tide corrections estimated using the Mayer et al. (1984) constituent phases and amplitudes to tide corrections determined using alternate estimates of the constituent phases and amplitudes. To estimate this, amplitudes and phases of the same tidal constituents were derived using tide gauges deployed at 14-m depth on either side of the straits at 27°N during the 2-yr period from July 2008 to July 2010. The transports of all 169 of the dropsonde sections since 1994 were then calculated three times using tide corrections based on each of these three sets of tidal phases and amplitudes. The variations between the resulting tide amplitudes at first appear fairly small, generally representing only 1%–2% of the signal (Fig. 5). The rms difference between the sets of transport values is 0.5 Sv however, which represents one of the largest sources of error to the dropsonde transport estimate (Table 1). Because the same tide correction method is applied to the LADCP velocities, the integrated

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[4] The tide-related transport is integrated from individual "random" velocity errors at the nine sites in the same manner as the transport integrations discussed previously.

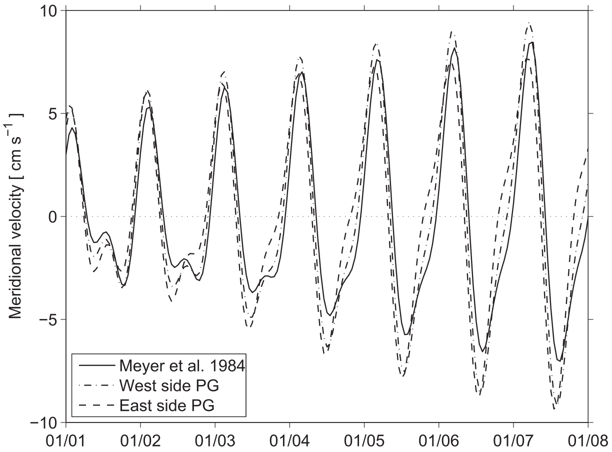

FIG. 5. Examples of meridional barotropic tidal velocities estimated using three different sets of tidal constituents: from Mayer et al. (1984) study and from the pressure gauges (PG) deployed on the west and east sides of the straits. Zero meridional velocity is denoted by horizontal dotted line. Data are plotted for the first week of an arbitrary year.

LADCP transports are subject to the same inaccuracy associated with the tide corrections although the LADCP section takes nearly twice as long, so it spans a different range of the tide cycle.

As mentioned earlier, the tidal velocities are not the only source of asynopticity in the section velocities. The Florida Current itself varies over fairly short time scales, at times as much as 10 Sv over as short a period as 3 days (e.g., Mooers et al. 2005). This will be a larger issue for the LADCP sections than for the dropsonde sections for the simple reason that the LADCP sections take roughly twice as long to occupy (12–14 vs 6 h). Estimating the magnitude of asynopticity errors for the section transports is difficult; ideally, this would be done by having nine current meter moorings, one at each dropsonde/LADCP site that would observe every ~30 min or better. With such moored data, one could explicitly calculate the asynopticity errors; however, such an array is not really feasible, and that resolution is far higher than is available from previous mooring experiments in the straits (e.g., Schott at al. 1988). With the available datasets, the best method that was found to estimate the asynoptic errors was to calculate the rms difference between consecutive days of transport data from the continuous cable observations and assume that this would be a reasonable "upper bound" error bar for asynopticity. This is one source of error that may be more quantifiable in the future.

The cable observations are collected every minute; however, the voltage signals are dominated by variations of the earth's magnetic field at time scales shorter than 3 days, and as a result the standard processing for the cable data involves a 72-h low-pass filtering and averaging to daily values (Meinen et al. 2010). The variations from one day to the next in the cable are thus somewhat weakened by the low-pass filtering; however, as the LADCP sections often span from one day to the next due to transits from port to the working area, these day-to-day differences provide a reasonable rough estimate for the errors that would be induced by asynopticity into the LADCP sections. The rms difference of the cable time series values in neighboring days during each of the LADCP sections was 1.0 Sv, so this will be used as the asynopticity error bar for the LADCP sections (a similar result is found by differencing all neighboring days in the complete cable time series). Because the dropsonde sections take roughly half as much time as the LADCP sections, the asynopticity errors in the dropsonde sections were estimated to be half that of the LADCP sections (roughly 0.5 Sv).

The various sources of error in either the dropsonde or LADCP section transports (see Table 1) are random relative to one another (i.e., the GPS position errors are unrelated to tidal correction errors, which are in turn unrelated to horizontal extrapolation errors, and so on). As such, the total accuracy of the transports from either type of cruise can be determined by taking the square root of the sum of the squares of the individual sources of error [Eq. (1)]. Combining the errors in Table 1, the overall accuracy of dropsonde transport estimates since 2000 is found to be 0.8 Sv (or 1.3 Sv before 2000), while the overall accuracy of the LADCP transport estimates is 1.3 Sv.

d. *Estimating the accuracy for the daily cable measurements*

As noted earlier, the daily cable transports themselves cannot be determined from first principles as was done with the dropsonde; however, with two independent systems with their own error bars (dropsonde and LADCP), it is possible to estimate a meaningful error bar for the daily cable transport estimates. The rms difference between the 48 LADCP section transports since 2001 with the concurrent daily cable-derived transport values is 2.2 Sv ($r = 0.75$), whereas the rms difference between the 44 independent dropsonde section transports (i.e., those not used for calibrating the cable voltages) from 2000 to the present and the concurrent daily cable transport measurements is 1.9 Sv ($r = 0.79$). In both cases the correlation coefficients are significantly different from zero at the 99% confidence level (Emery and Thomson 2004).

These rms differences are larger than the error bars estimated for the dropsonde and LADCP systems, which is to be expected because the cable itself must have its own error bar. Because the LADCP, dropsonde, and cable error bars should be independent of one another (as long as only those dropsondes that were not used for cable calibration are considered), the observed rms differences should be equal to the square root of the sum of the squares of the section error bar (either LADCP or dropsonde) and the cable error bar [i.e., Eq. (1)]. Knowing the total rms difference, the cable error bar can be derived as the square root of the difference in squared rms total difference and section error bar. [e.g., $\varepsilon_{\mathrm{cable}} = (\varepsilon^2_{\mathrm{Total}} - \varepsilon^2_{\mathrm{dropsonde}})^{1/2}$]. The resulting estimated accuracy for the daily cable measurements at 27°N is 1.7 Sv (1.8 Sv using the LADCP sections).

4. Discussion and conclusions

The dropsonde section, LADCP section, and daily cable transport accuracy estimates represent just 2.5%, 4.0%, and 5.3%, respectively, of the Florida Current historical mean of 32.1 Sv. Comparison of these values to previously published accuracy estimates indicates that the dropsonde accuracy is roughly a factor of 3 better than the historical estimated Pegasus section accuracy (2.5 Sv; Molinari et al. 1985b), while the LADCP is roughly a factor of 2 better. Modern reanalysis of 62 of the Pegasus sections and concurrent cable data following the same methods used herein finds an actual rms difference between cable and Pegasus of only 1.4 Sv, which suggests that the error estimate of Molinari et al. (1985b) was perhaps too conservative. By contrast, the earliest estimates of the accuracy of the daily cable transports (e.g., 0.7 Sv; Larsen and Sanford 1985) were perhaps not conservative enough.

In terms of climate variations and trends, these snapshot section accuracies and daily cable error bars are not particularly relevant. The climate system operates on time scales of months to years to decades. So, reaching an understanding of the temporal decorrelation scales of these errors is just as important as deriving the accuracy estimates themselves. For the section estimates, the first question that must be addressed is whether there are any sources of error that would consistently bias the sections in the same direction (e.g., would always bias the section transports low). For most of the sources of error in the sections (e.g., GPS position accuracy for the dropsondes, or tide removal from either dropsonde or LADCP velocities), it is obvious that these would be random from one section to the next. Evaluating the overall section errors, the simplest way to evaluate the randomness of the section errors is to study a histogram of the differences between the section transports and the concurrent cable values (not shown). Such histograms for both dropsonde and LADCP sections indicate that the distribution of the differences is roughly Gaussian in shape centered on zero. This indicates that the individual section accuracy estimates should be independent from one cruise to the next. As such, when calculating an annual average—for example, from the section data—the contribution of the various measurement errors to the resulting annual average accuracy would be reduced by the square root of the number of sections. Of course, when using a small number of sections to represent the mean for a year, the statistical sampling errors would likely far exceed the measurement errors.

Evaluating the decorrelation scale for the daily cable transport accuracy is more complicated. Clearly, as the cable data are processed using a 3-day low-pass filter (Meinen et al. 2010), one could not plausibly argue that the errors in transport measurements from neighboring days are independent of one another. To evaluate the length over which the errors might be correlated, the dataset of independent dropsonde sections was investigated to find cruises separated by varying lengths of time between 3 and 11 days. If the errors in the cable are independent at a particular time scale, then the "errors" in the cable at the times of the two cruises (i.e., the differences between cable and sections) should be uncorrelated. The number of pairs of sections collected from 1994 to the present ranges between 33 for cruises 3 days apart to 58 for cruises 11 days apart. Scatterplots of the differences in these errors from one cruise to the next become uncorrelated and histograms of the differences only become Gaussian in shape when the time difference between cruises reaches 10 days. This suggests that by 10 days the errors are independent.

Conservatively then, one could argue that the contribution of the measurement errors in the cable to the overall accuracy of a yearly mean value would be the daily value, 1.7 Sv, divided by the square root of the number of 10-day periods in a year, yielding 0.3 Sv. The overall error bar for the annual mean would, of course, have both a measurement component (the 0.3 Sv) and a statistical component based on having only a limited number of observations during the year. The cable collects nominally 365 daily mean measurements per year (i.e., daily averages of measurements every minute), and after low-pass filtering it has roughly 100 independent observations. Because of this high number of samples and the continuous nature of the measurements, the statistical error bar on an annual average is negligible. Therefore, one can argue that the cable measurements at 27°N in the Straits of Florida can produce an annual average transport accurate to within 0.3 Sv. This represents only 1% of the long-term mean Florida Current volume transport of 32.1 Sv.

Previous analysis of the cable time series and other historical measurements of the Florida Current volume transport has indicated that interannual and longer time-scale variations have amplitudes of roughly ±1 Sv (Meinen et al. 2010). These climate signals are small compared to the daily variations in the Florida Current transport; however, this study has now shown that the cable observations can produce annual means accurate to within 0.3 Sv, and as such the cable is fully capable of observing the small but important climate changes that may occur in the Florida Current transports. The accuracies of the sections collected using either dropsonde or LADCP will likely never be able to overcome the high-frequency variability in the transport record in order to be able to produce accurate annual and longer means; however, they are essential for monitoring the calibration of the cable voltage measurements for long-term climate measurements. Furthermore, future improvements in determining the section transports (e.g., improvements to tide removal) will lead to better calibration for the cable observations and may further improve the overall accuracy of the Florida Current volume transport estimates.

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