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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

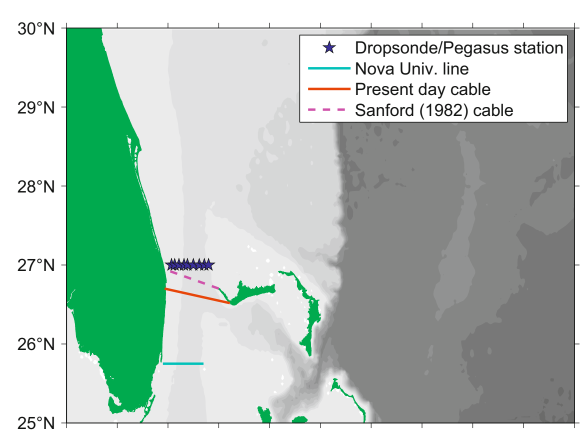

Fig. 1. Location of the observations collected in the Florida Current near 26–27°N. Dropsonde/Pegasus locations at 27°N have been essentially the same since 1982; the dropsonde casts collected by Niiler and Richardson (1973) and Brooks and Niiler (1977) were collected along the 'Nova Univ. line'. Both 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.

[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).