Deep-Sea Research Part I 125 (2017) 94–105

Contents lists available at ScienceDirect

Deep-Sea Research Part I

journal homepage: www.elsevier.com/locate/dsri

Southward flow on the western flank of the Florida Current

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ARTICLE INFO

Keywords:
Undercurrent
Surface countercurrent
Western boundary current
Alongshore pressure gradient
Ekman transport
Bottom boundary layer

ABSTRACT

A suite of long-term *in situ* measurements in the Straits of Florida, including the ADCP bottom moorings at an 11-m isobath and 244-m isobath (Miami Terrace) and several ADCP ship transects, have revealed a remarkable feature of the ocean circulation - southward flow on the western, coastal flank of the Florida Current. We have observed three forms of the southward flow - a seasonally varying coastal countercurrent, an undercurrent jet attached to the Florida shelf, and an intermittent undercurrent on the Miami Terrace. According to a 13-year monthly climatology obtained from the near-shore mooring, the coastal countercurrent is a persistent feature from October through January. The southward flow in the form of an undercurrent jet attached to the continental slope was observed during five ship transects from April through September but was not observed during three transects in February, March, and November. This undercurrent jet is well mixed due to strong shear at its top associated with the northward direction of the surface flow (Florida Current) and friction at the bottom. At the same time, no statistically significant seasonal cycle has been observed in the undercurrent flow on the Miami Terrace. Theoretical considerations suggest that several processes could drive the southward current, including interaction between the Florida Current and the shelf, as well as forcing that is independent of the Florida Current. The exact nature of the southward flow on the western flank of the Florida Current is, however, unknown.

1. Introduction

The Florida Current (FC) is a part of the North Atlantic Subtropical Gyre and the western boundary current system, which is represented by the Loop Current in the Gulf of Mexico, continuing as the FC in the Straits of Florida and the Gulf Stream in the North Atlantic (Stommel, 1965). Strong current flow over a rapidly changing three-dimensional topography contributes to the FC's great variety of motions (meandering, eddies, energetic internal tides, etc.) spanning a large range of time and spatial scales. The FC possesses both spatial inhomogeneities related to the topography and mean current structure, and also temporal inhomogeneities related to the local meteorological conditions.

The highly variable influx conditions for five key passages, Grenada, St. Vincent, St. Lucia, Dominica, and Windward Passages, may in part account for the considerable variability of the FC (Wilson and Johns, 1997). Schott et al. (1988) demonstrated that the FC and its variations are subject to both seasonal and interannual variability. Analysis of daily cable transport estimates from a submarine cable from 1982 to 1998 by Meinen et al. (2010) suggests that roughly 70% of the total variance in the FC occurs at periods less than annual.

One potential source of FC variability at periods less than annual includes eddies associated with the western flank of the FC. Lee and Mayer (1977) observed the spin off eddies associated with the western edge of the FC. Shay et al. (2000), Parks et al. (2009), and Archer et al. (2015) conducted observations of surface current manifestations in the nearshore zone with shore-based high-frequency radars, based on phased array principles. These measurements revealed submesoscale eddies, which were initiated by horizontal shear on the western flank of the FC, significantly contributing to short-term variability of nearshore circulation.

Changes in the FC on time periods of 2–20 days are often correlated

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http://dx.doi.org/10.1016/j.dsr.2017.05.002
Received 20 November 2015; Received in revised form 4 May 2017; Accepted 4 May 2017
Available online 18 May 2017

to local winds (Lee and Williams, 1988). Düing et al. (1977) correlated FC variations in the 2–15-day range with atmospheric forcing. The highest correlation was observed between the northward component of the current velocity and *curl* $\vec{\tau}$ (where $\vec{\tau}$ is the wind stress) on time periods of 2.5, 4.5, and 11.8 days. Lee et al. (1985) indicated strong transport variations in the FC in the 2–10-day period correlated with wind stress variations.

Soloviev et al. (2003a, b) reported strong oscillations in the current direction on the Southeast Florida shelf on time scales of approximately 10 h, which were presumably associated with a near-resonant seiching mechanism. Amplitudes of these current velocity oscillations were seasonally modulated with the maximum during late summer.

There have been sporadic observations of an undercurrent below the FC. Düing and Johnson (1971) and Leaman and Molinari (1987) observed strong variations in the current profile in the central and eastern Straits of Florida, resulting in southward flow with speeds up to 0.3 m s^{-1} in the lower half of the water column. Leaman and Molinari (1987) observed an undercurrent on the eastern flank of the FC. To our best knowledge there have been no detailed observations or attempts to simulate southward flow on the western flank of the FC. Such simulations require a higher spatial resolution than available in most regional numerical models.

In our work, we report the observations of the undercurrent and countercurrent in the western part of the Straits of Florida. We have observed three forms of the southward flow - a seasonally varying coastal countercurrent, an undercurrent jet attached to the Florida shelf, and an intermittent undercurrent on the Miami Terrace. The goal of this paper is to report and interpret our observations of the undercurrent and countercurrent on the western, coastal flank of the FC. The paper is organized as follows. Section 2 presents observations in the Straits of Florida. Section 3 provides the analysis of time scales of the ocean circulation variability on the western flank of the FC. Section 4 discusses observations of the coastal countercurrent, the undercurrent jet attached to the continental slope, the vertical structure of the undercurrent jet, and the intermittent undercurrent on the Miami Terrace. Theoretical considerations in Section 5 provide a possible explanation for the southward flow on the western flank of the FC. Section 6 is the discussion, and Section 7 summarizes the results of this work.

2. Observational data

Fig. 1 shows locations of the instruments on the Southeast Florida shelf. The acoustic Doppler current profiler (ADCP) mooring array location is shown in more detail in Fig. 2, superimposed on a synthetic aperture radar (SAR) image. The mooring array consisted of two bottom ADCP moorings deployed at 11-m and 244-m isobaths (Fig. 2). The SAR image indicates the frontal structure on the western flank of the FC. The position of the moorings relative to this frontal structure is also shown in Fig. 2.

The ADCP bottom mooring, deployed on the Dania Beach shelf at the 11-m isobath, has provided almost continuous current velocity data with 0.5 m vertical resolution from June 1999 to May 2013 (Table A1). The ADCP bottom mooring located on the Miami Terrace at the 244-m isobath operated from January 2007 to November 2010 (Table A2). It included a *Flotation Technology* buoy deployed 10 m above the bottom with the following instruments: upward looking Teledyne RD Instruments 75 kHz Long Ranger ADCP measuring vertical profiles of current velocity in the upper water column with 4 m vertical resolution; downward looking Teledyne RD Instruments 300 kHz Workhorse ADCP measuring vertical profiles of current velocity near the seabed with 0.5 m vertical resolution; *Benthos* acoustic modem for communication with the buoy; *Benthos* acoustic release used to facilitate mooring recovery; locator instruments (radio, light, ARGOS satellite). The theoretical standard deviation (accuracy) for the Workhorse and Long Ranger ADCPs due to instrumental uncertainty for hourly samples is

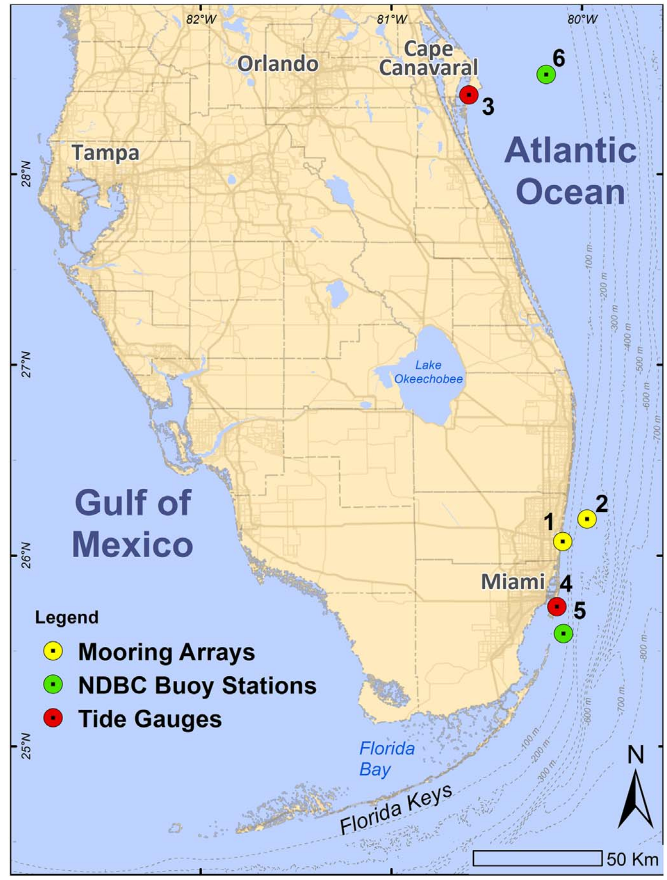

Fig. 1. Location of instruments: Label 1 is the bottom ADCP mooring at an 11-m isobath (26.073°N, 80.101°W); Label 2, the bottom ADCP mooring at a 244-m isobath 8 nautical miles (14.8 km) offshore, which was deployed at 26.191ºN, 79.974°W; Label 3, the Trident Pier tide gauge (28.415°N, 80.593°W); Label 4, the Virginia Key tide gauge (25.732°N, 80.132°W); Label 5, the meteorological station on NDBC Buoy Station FWYF1 - Fowey Rocks, FL (25.591°N, 80.097°W); and Label 6, the meteorological station on NDBC Buoy Station 41009 – Canaveral, 20 NM east of Cape Canaveral, FL (28.522°N, 80.188°W).

given in Table A2. There are three gaps in the time series due to interim mooring servicing, a total of about 58 h of missing data throughout the almost 4-year program.

In addition, seasonal cross-shelf transects were performed in 2007 from the R/V *F.G. Walton Smith* (University of Miami Rosenstiel School of Marine and Atmospheric Science) with the hull-mounted, Teledyne RD Instruments 75 kHz Ocean Surveyor ADCP. The transects shown in Figs. 7–8 ended close to the ADCP mooring located at the 244-m isobath 8 nautical miles offshore.

An additional transect with the station 4 km offshore (Fig. 10) was performed in 2011 from the R/V *Panacea* (Nova Southeastern University Oceanographic Center) using a downward-looking Teledyne RD Instruments 600 kHz Workhorse Monitor ADCP. The ADCP instrument was mounted to an aluminum arm that was raised and lowered into the water from the side of the vessel. Vertical profiles were created by lowering a Valeport Midas 606 CTD instrument through the water column to a depth of approximately 100 m while the vessel was stationary.

During active observational phases, the area was monitored with SAR satellites (see, *e.g.*, Soloviev et al., 2010), which helped to identify the position of the FC front in some cases (Fig. 2). No systematic SAR observations were, however, available during the thirteen years of mooring observations at the 11-m isobath location.

It should be noted that the FC front is not always seen in SAR imagery. In the infrared satellite imagery, the FC and the FC front may also vanish from satellite imagery during the summer months due to