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## Energetic baroclinic super-tidal oscillations on the southeast Florida shelf

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[1] Historical and recent data reveal a very energetic regime on the shelf off southeast Florida. In addition to spin off eddies, large-amplitude tidal velocity fluctuations with amplitudes exceeding  $0.5 \text{ ms}^{-1}$  are observed. Recent exploratory measurements conducted as a part of the South Florida Ocean Measurement Center (SFOMC) show that the time scale of these oscillations is about 10 hrs. This period does not coincide either with the inertial period (27 Hrs) or with the semidiurnal  $M_2$  (12.42 hrs) or  $S_2$  (12 hrs) tidal constituents. In addition, these internal oscillations appear to be modulated seasonally. A possible explanation is that these oscillations are near-resonant internal seiches generated by barotropic tidal wave in the channel between Florida and Bahamas. **INDEX TERMS:** 4544 Oceanography: Physical: Internal and inertial waves; 4576 Oceanography: Physical: Western boundary currents; 4546 Oceanography: Physical: Nearshore processes. **Citation:** Soloviev, A. V., M. E. Luther, and R. H. Weisberg, Energetic baroclinic super-tidal oscillations on the southeast Florida shelf, *Geophys. Res. Lett.*, 30(9), 1463, doi:10.1029/2002GL016603, 2003.

### 1. Introduction

[2] Observations of large-amplitude tidal velocity fluctuations in the Florida Straits dates back to the work of J.E. Pillsbury in the late 19th century. He found that approximately twice a day the surface velocity changes by as much as 1 knot ( $0.5 \text{ ms}^{-1}$ ). Similar velocity fluctuations were measured by Parr [1937] and Schmitz and Richardson [1968] with current meters and free-falling profilers. Some other investigators [e.g., Smith *et al.*, 1969], however, did not observe such strong velocity oscillations in the Florida Straits. Recent long-term observations on the shelf off Southeast Florida as a part of the SFOMC show that these internal oscillations are of about 10-hr period and are seasonally modulated, being observed primarily during summer months. The experiment of Smith *et al.* [1969] took place in the fall and winter seasons when the 10 hr peak in the velocity spectrum does not appear to be prominent.

[3] In his book *The Gulf Stream*, Stommel [1965] suggested that an internal resonant seiche accounts for the semi-diurnal tidal velocity fluctuations in the Florida Current. The instrumentation capabilities in 1960s, however, were ill matched to the job of making definitive statements about the governing physics in such a region of complex motions as the Florida Straits.

[4] The new stage of studying the Florida Current begins in 1998 with establishment of the South Florida Ocean Measurement Center, near Port Everglades, Florida. As a part of SFOMC, a three-dimensional mooring array was deployed, with acoustic Doppler current profilers (ADCP) and a combination of recording temperature and salinity sensors on each mooring. These measurements were carried out since July 1999 and are a cooperative experiment between the University of South Florida and NOVA Southeastern University, [McCreary *et al.*, 2000].

### 2. Experimental Design

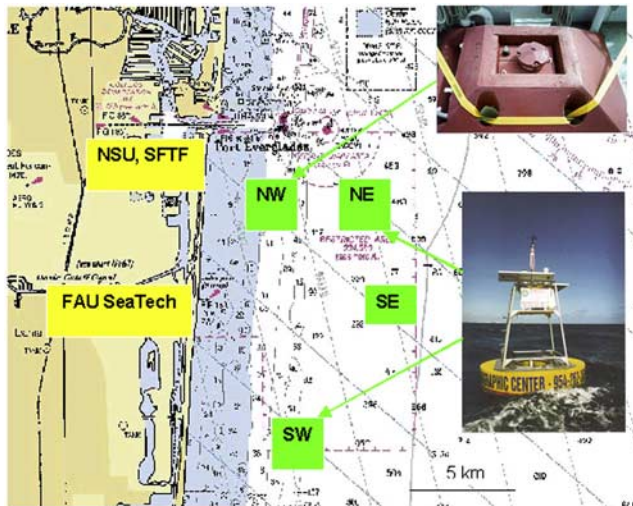
[5] The observing system, termed the Environmental Array, is designed to support SFOMC field tests of Autonomous Underwater Vehicles and to collect a complete seasonal cycle for describing western boundary current/continental shelf interactions, including extreme conditions during hurricanes. In addition, the array provides data useful for understanding a variety of scientific questions.

[6] The Environmental Array, deployment schemes, and data acquisition software were developed at the USF College of Marine Science and the NSU Oceanographic Center. The design of the array meets two objectives: It satisfies the monitoring needs of the other experiments on the SFOMC range; it also is able to provide data that can answer scientific questions like those posed above.

[7] The Environmental Array, including one bottom mooring (NW) and two surface moorings (NE and SW), was first deployed at the SFOMC range in June–July 1999 and continues to operate at present. This paper focuses on data collected during 1999 and 2000.

[8] The NW bottom mooring consists of a concrete anchor, a SBE-26 Wave and Tide Recorder, and an upward looking RDI Workhorse Sentinel 300 kHz ADCP. The NE and SW surface moorings mechanical construction consists of a surface buoy, three segments of chain, wire rope, and an anchor. A downward-looking WH Sentinel 600 kHz ADCP measures the vertical profile of horizontal velocity. A chain of inductively coupled SBE-37 MicroCats provides detailed information on the temperature ( $T$ ), salinity ( $S$ ), and density ( $\sigma_t$ ) fields. There is a Weather Pack (Coastal Climate, Inc.) on the NE mooring, providing measurements of wind speed and direction, air temperature, humidity, atmospheric pressure, and precipitation.

[9] The configuration of the mooring array during the SFOMC 1999 Experiment is shown in Figure 1. The NW bottom and the NE and SW surface moorings were deployed on 11-m ( $26^{\circ}04.23'N$ ,  $80^{\circ}05.65'W$ ), 50-m ( $26^{\circ}04.170'N$ ,  $80^{\circ}04.610'W$ ), and 20-m ( $19^{\circ}49.413'N$ ,  $71^{\circ}48.094'W$ ) iso-



**Figure 1.** The NSU/USF Environmental Array in the SFOMC experimental range during the Year of 1999. Here: NW is the northwest (bottom) mooring (11-m isobath), SW the southwest mooring (20-m isobath), NE the northeast mooring (50-m isobath), and SE the southeast (UM) acoustic mooring.

baths respectively (Figure 1). In addition, a 3-MicroCat chain of instruments was installed on the SE mooring in December 1999 and recovered in January 2000 as a part of the University of Miami (UM) acoustic experiment. In May 2000, the SW mooring was relocated northward to  $26^{\circ}04.24'N$ ,  $80^{\circ}05.36'W$ .

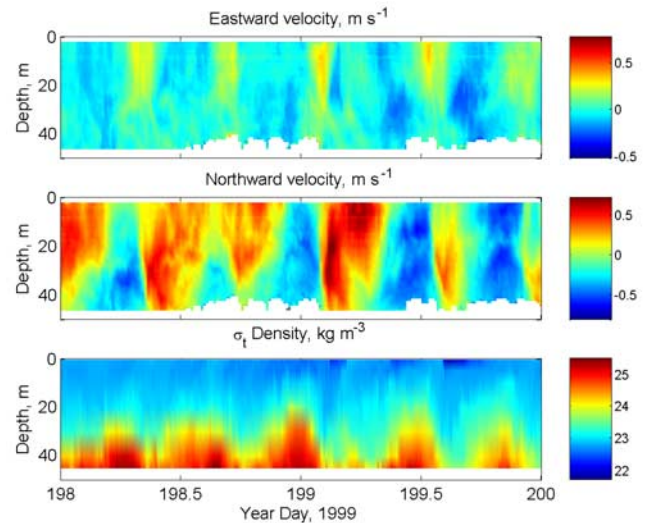
[10] The NW bottom array has been operating in a self-recording mode (pending cable connection to shore). The surface moorings (except the SE mooring) transmit data in real time via line-of-sight spread-spectrum radio, which are stored on a data acquisition computer at the NSU Oceanographic Center as well as internally in the instruments. The telemetered data were available in real time via the Internet, allowing for continuous quality control and assurance.

### 3. Observations

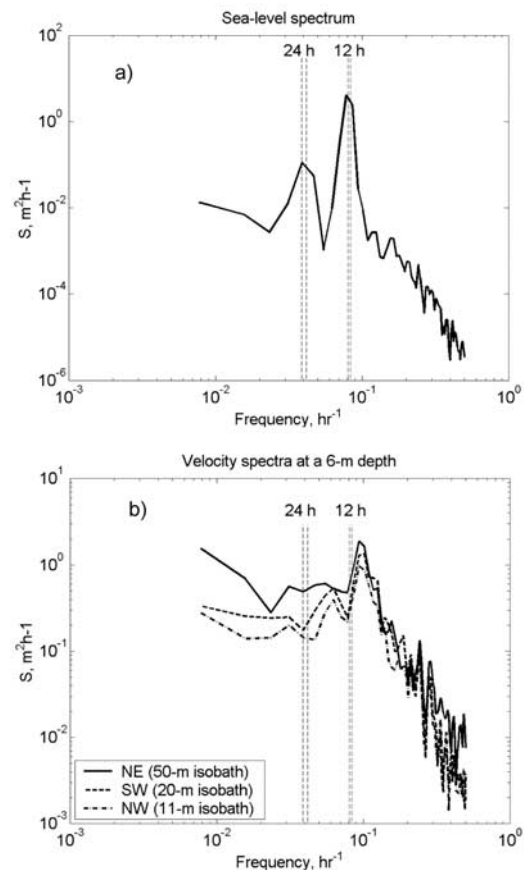
[11] Figure 2 shows an example of the velocity and density variability observed at the 50-m isobath (NE mooring) in July 1999. The velocity contour plot reveals  $\pm 0.5 \text{ ms}^{-1}$  velocity oscillations that are accompanied by strong vertical shear and density variations. This is an indication that the observed velocity oscillations are of baroclinic nature.

[12] The time period of the dominant oscillation in Figure 2 is about 10 hrs. Spectral analysis of the velocity signal (made on a two-week record including the time period shown in Figure 2) reveals a peak in the frequency spectrum corresponding to a 10-hr time period (Figure 3b). A peak at the 10 hr period is also observed on the respective density spectrum (not shown here). Spectral analysis of the simultaneous velocity records from the SW surface mooring and NW bottom mooring also shows a pronounced peak at a 10-hr time period (Figure 3b).

[13] Strong periodicity of the velocity and density variations in Figure 2 suggests that this oscillation is excited either by inertial or tidal forces. The inertial period at the



**Figure 2.** Internal oscillations with  $\sim 10$ -hr period observed in the velocity and density fields on the shelf off southeast Florida in July 1999 (NE Mooring, 50-m isobath).



**Figure 3.** Sealevel (a) and velocity (b) spectra in the SFOMC range according to measurements in July 1999. Note a 2-hr “blue” shift of the tidal peak in the velocity spectra compare to the sea-level spectrum. The tidal constituents near 24 hrs ( $O_1$  and  $K_1$ ) and near 12 hrs ( $M_2$  and  $S_2$ ) are marked by vertical dashes.

latitude of the SFOMC range (27 hrs), however, is substantially different from the 10 hr period of the observed velocity oscillation. The semidiurnal tidal constituents in the Florida Straits are  $M_2$  (12.42 hrs) and  $S_2$  (12 hrs). The sea level gauge mounted on the NW mooring shows a semidiurnal surface tide (barotropic wave) of about 40 cm amplitude. Spectral analysis of the sea level signal reveals a semidiurnal tidal peak close to the 12 hr time period (Figure 3a). The corresponding peak, however, is not seen in the velocity spectrum (Figure 3b); instead, a 10-hr peak is prominent.

[14] Analysis of the long-term velocity records obtained during the first two years of the SFOMC experiments shows a seasonal dependence of the velocity spectra (Figure 4a). These spectra are calculated from several-months long record segments. According to Figure 4a, the large amplitude velocity fluctuations with a 10-hr time period are primarily observed during summer months. During the fall and winter seasons, the 10 hr period oscillation is not prominent.

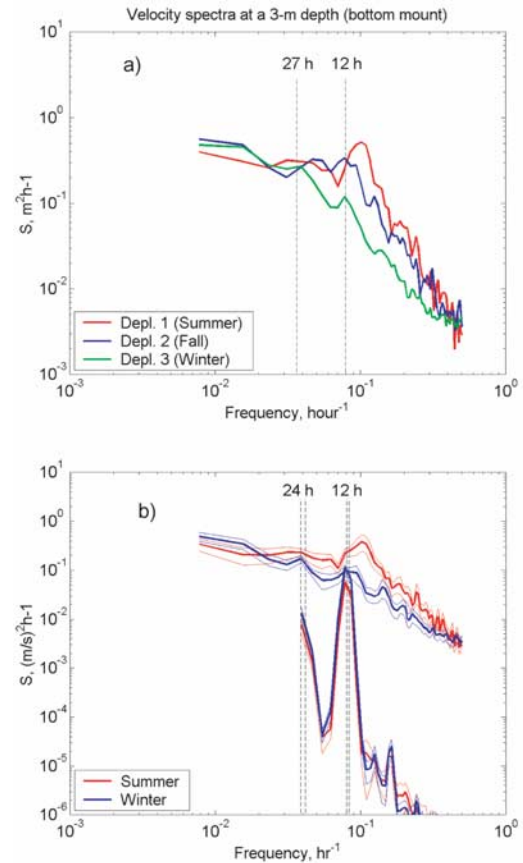
[15] The sea level variations are mainly related to barotropic motions, while the current velocities depend both on barotropic and baroclinic processes. The contribution of the barotropic component to the velocity signal is estimated in Figure 4b. This figure compares the velocity spectra in summer and winter with the corresponding velocity spectra calculated from the sea level records using long wave theory [LeBlond and Mysak, 1978]. Note that this theory does not work in the vicinity of the inertial period, which is equal to about 27 hours on the latitude of the SFOMC range. According to Figure 4b, the baroclinic signal in the velocity is strong in summer but weak in winter. The 10 hr velocity oscillation is also modulated over time scales of about 10 days or less (not shown here).

#### 4. Internal Oscillations

[16] Observations from the SFOMC Environmental Array demonstrate that there is a strong baroclinic velocity signal on the shelf off Southeast Florida. In fact, the baroclinic component may dominate the coastal circulation during summer months. The closeness of the velocity oscillation time period, 10 hrs, to the semidiurnal tidal constituents,  $M_2$  (12.42 hrs) and  $S_2$  (12 hrs), as well as the presence of the 10 hr peak in both density and velocity spectra, suggest that this is the type of motion excited by tidal rather than inertial forces.

[17] The surface (barotropic) tidal waves travel south through the Florida Straits (from North Atlantic to the Gulf of Mexico) at a speed of about  $80 \text{ m s}^{-1}$ . The maximum current oscillations associated with barotropic tidal waves are, however, only of about several  $\text{cm s}^{-1}$ . As it has been demonstrated in Figure 4b, the barotropic component is not prominent in the velocity signal.

[18] *Niiler* [1968] demonstrated that a strong cross-channel baroclinic tidal oscillation could be excited by a tidal surface wave traveling along the non-uniform channel. He investigated the tidal oscillation in the Florida Straits in the framework of the dynamics of a two-layer ocean with a free surface. The Florida Straits was modeled by a rotating channel which is very long and uniform in the north-south direction and of non-uniform depth in the east-west direction.



**Figure 4.** (a) Seasonal variability of the velocity spectra in the SFOMC range. The inertial (27 hrs) and semidiurnal (12 hrs) tidal periods are shown by vertical dashes. (b) The velocity spectra (two upper bold curves) are compared to the spectra of barotropic tidal velocities (two lower bold curves) calculated from the sea level spectrum. Thin lines are 95% confidence limits. Detail tidal constituents near 24 hrs ( $O_1$  and  $K_1$ ) and near 12 hrs ( $M_2$  and  $S_2$ ) are marked by vertical dashes.

*Niiler* [1968] approximated the depth profile across Florida Straits as follows:

$$H(x) = \begin{cases} d, & 0 \leq x < l, \\ D, & l < x \leq L, \end{cases} \quad (1)$$

where  $x = 0$  is the east coast of Florida and  $x = L$  is the island of Bimini. The channel's cross-section consisted of a shallow shelf of depth  $d$ , which drops off rapidly at  $x = l$  to a deep region depth  $D$ . The surface layer of warm water  $h$  is of density  $\rho_1$ , and the bottom layer of colder and denser water is of density  $\rho_2$ .

[19] In this theory, an abrupt change of the channel depth at the edge of the continental shelf is a critical factor in the exchange of energy between the surface and internal wave. Another factor determining the resonant properties of the channel is the vertical density stratification; in particular, the position of the stratified layer with respect to the continental shelf break. Baroclinic oscillations become large if the period of the surface wave is close to the natural period



of the internal seiche. The baroclinic seiche dominates in the velocity and density fields, while the barotropic component determines the sealevel variations.

[20] Approximating the depth profile across Florida Straits near the SFOMC range according to formula (1), we have derived from a 3-D bathymetry [*Maptech Maps and Charts*, 2002, <http://www.maptech.com>]  $d \simeq 250$  m,  $D \simeq 750$  m,  $l \simeq 20$  km, and  $L \simeq 100$  km. For the “effective” depth of the upper ocean layer  $h = 150$  m, it follows from Niiler’s [1968] equation (30) that the natural period of an internal seiche at the SFOMC range is  $T_s \sim 10$  hrs. This argues in favor of the internal seiche hypothesis.

[21] Seasonal changes in stratification affect the upper ocean layer depth  $h$  and, thus, the internal seiche period  $T_s$ . The spin-off eddies that are observed on the shelf off southeast Florida [e.g., *Lee and Mayer*, 1977; *Wunsh and Wimbush*, 1977; *Shay et al.*, 2000] can also modulate  $h$  and  $T_s$  over time scales of about 10 days or less. This provides a qualitatively explanation of the observed seasonal and shorter scale modulation of the 10 hr spectral peak.

[22] An alternative explanation for the 10 hr peak is that it could be the semidiurnal internal tide Doppler-shifted by the Gulf Stream [*Luther et al.*, 2001]. This hypothesis is based on the assumption that velocity fluctuations observed in the coastal area can be induced by motions outside this region (within Rossby radius). The intrinsic or Doppler-shifted frequency of a semidiurnal internal tidal propagating southward through Florida Straits (i.e., against the mean current) can be estimated from [Mooers, 1975b]:  $\sigma = \sigma_0 + \bar{v}k/(2\pi)$ , where  $\sigma_0$  is the wave frequency,  $\bar{v}$  the mean current speed, and  $k = 2\pi/\lambda$  the wavenumber component in the direction against the mean flow. For a typical wavelength of a low-order internal tidal wave  $\lambda \approx 100$  km and for a mean current-speed  $\bar{v} \approx 0.5 \text{ ms}^{-1}$ , the Doppler-shifted period of the semidiurnal tide is  $\sim 10$  hrs.

[23] Results of Mooers [1975a] suggest that the effective local inertial frequency is  $\sigma_f = [f(f + \bar{v}_x)]^{1/2}$ , where  $f$  is the Coriolis parameter and  $\bar{v}_x$  is the average vorticity. Rossby and Zhang [2002] reported values of  $\bar{v}_x \approx 0.5 f$  associated with the Gulf Stream (during New York-Bermuda sections). Vorticity at the western boundary of the Gulf Stream of  $\bar{v}_x \approx 4 f$  or higher has been reported in the SFOMC range [*Peters et al.*, 2002]. The inertial peak could therefore be shifted to a higher frequency due to significant vorticity, providing another possible explanation for the 10 hr peak.

[24] Though internal seiching is a plausible explanation for the energetic baroclinic super-tidal oscillations observed here we cannot reject the two other hypotheses. More detailed analysis including numerical modeling is required.

## 5. Conclusions

[25] The Southeast Florida shelf circulation is strongly related to the dynamics of the Florida Current. Superimposed upon the Florida Current are a variety of motions spanning a range of time and space scales, possessing both spatial inhomogeneities related to the topography, mean current structure, river discharges (at some extent), and temporal inhomogeneities related to the local meteorological forcing.

[26] The recent SFOMC data set covering a 2-year time period (1999–2001) shows strong baroclinic velocity fluctuation

(sometimes exceeding 0.5 m/s) with a 10-hr time period. These fluctuations are modulated seasonally as well as on a shorter time scales. This finding appears consistent with the Stommel hypothesis of a resonant cross-stream semidiurnal internal seiche in the channel between Florida and the Bahamas. The modulation on the seasonal time scale can be explained by the dependence of the channel resonant properties on the stratification and Gulf Stream position. The stratification is also affected by eddies, which may be another factor in modulating the 10-hr oscillation on shorter time scales.

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