Coastal Engineering and Marina Developments

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Tidal and non-tidal characteristics of water levels and flow in the Apalachicola Bay, Florida

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Abstract

Apalachicola Bay is one of the most productive estuaries in Florida. Tidal forces influence water levels, current velocities and salinity mixing in the estuary. These parameters in return affect the aquatic habitats and their productivity. The tidal wave enters the bay in the east and exits it through several barrier island cuts in the west. Accordingly, the tidal amplitudes are higher in the eastern than in the western section of the estuary. The bay shows a mixed tidal type, mainly semi-diurnal in the eastern and central sections, but diurnal in the western part of the bay. The rotary tidal currents show complicated elliptical flow paths. Fluctuations of the tidal water levels result in short-term periodical variations of salinity and are responsible for the mixing of fresh river water and saline ocean water. Long-term mean currents influenced by the non-tidal shelf currents from the Gulf and density gradients created by fresh river water and oceanic saline water are responsible for the net current flow of the estuary.

1. Introduction

Apalachicola Bay is located on the northwest coast of Florida, adjacent to the Gulf of Mexico from which it is separated to a large degree through a set of barrier islands *(Fig. 1)*. The bay is one of the most productive estuaries in the entire northern hemisphere, yielding 10 percent of the oysters consumed in the US *(Johnson, 1993)*. Astronomical tidal forces cause periodic variations of the water levels and the current velocities and, in addition to shelf-currents, wind stresses, river discharge, storms, surface water runoff and groundwater

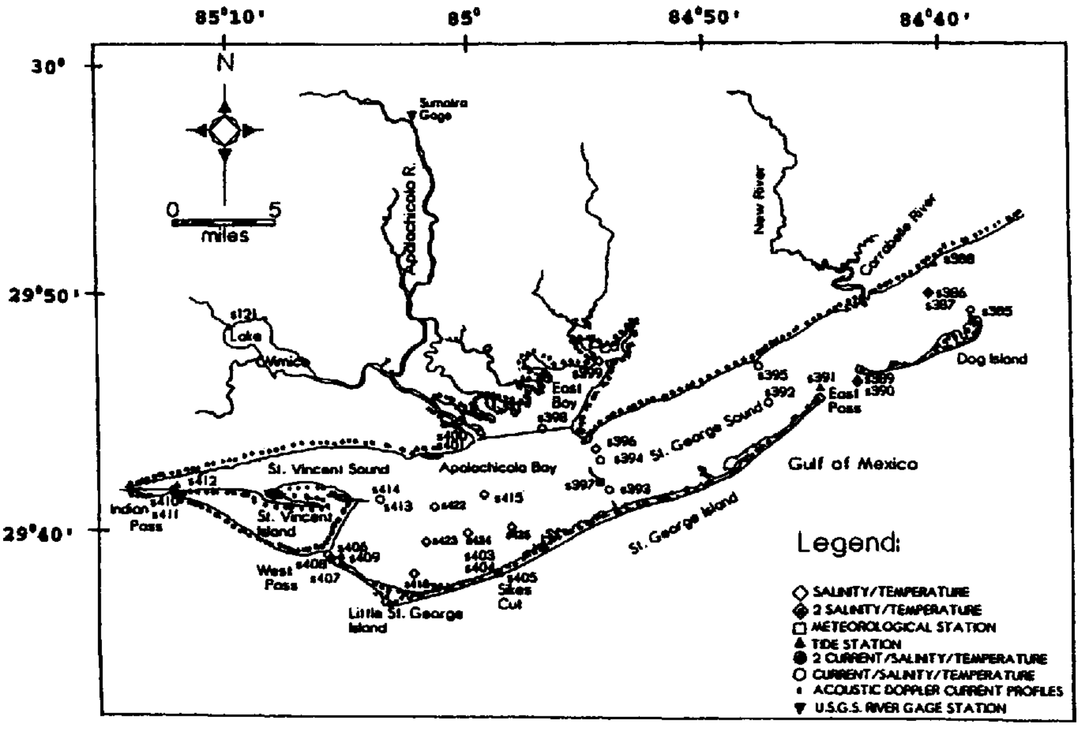

Fig 1: Locations of tidal and current measuring stations in the study area

recharge affect so the circulation and mixing of ocean and the fresh water, i.e. control the salinity variations in the bay *(Sun and Koch, 1996; Sun et al. 1999)*. Since the latter are the origin of the unique habitat environment of the bay that includes peripheral marsh zones which serve as important fish nursery areas, slight changes in the salinity as a result of changes of the named controlling factors may have detrimental effects on the seafood production.

A quantitative multi-variate analysis of the long-term control variables in the Apalachicola Bay was carried out by *Sun and Koch (1996)* and *Sun et al. (1999)*. A groundwater- ocean water interaction study of Apalachicola Bay was done by *Sun (1997)*. The current paper focuses mainly on the short-term periodical tidal dynamics and the non-tidal characters of the Apalachicola Bay. The results of the analysis proposed will help to better understand the hydrodynamic system and to improve the ecological management of the bay.

2. Harmonic analysis of currents and water levels

2.1 Data

Water elevation and current data were collected at various stations by the Northwest Florida Water Management District at half- hour intervals from April 1993 to August 1994. Examples of records of tidal heights and velocities are shown in *Fig. 2*. Daily precipitation data were obtained from the Florida Climate Center and the discharge of Apalachicola River at the Sumatra gauge from the USGS *(USGS, 1993-1994)*. Thirteen current gage stations and 19 water level gauge stations were analyzed.

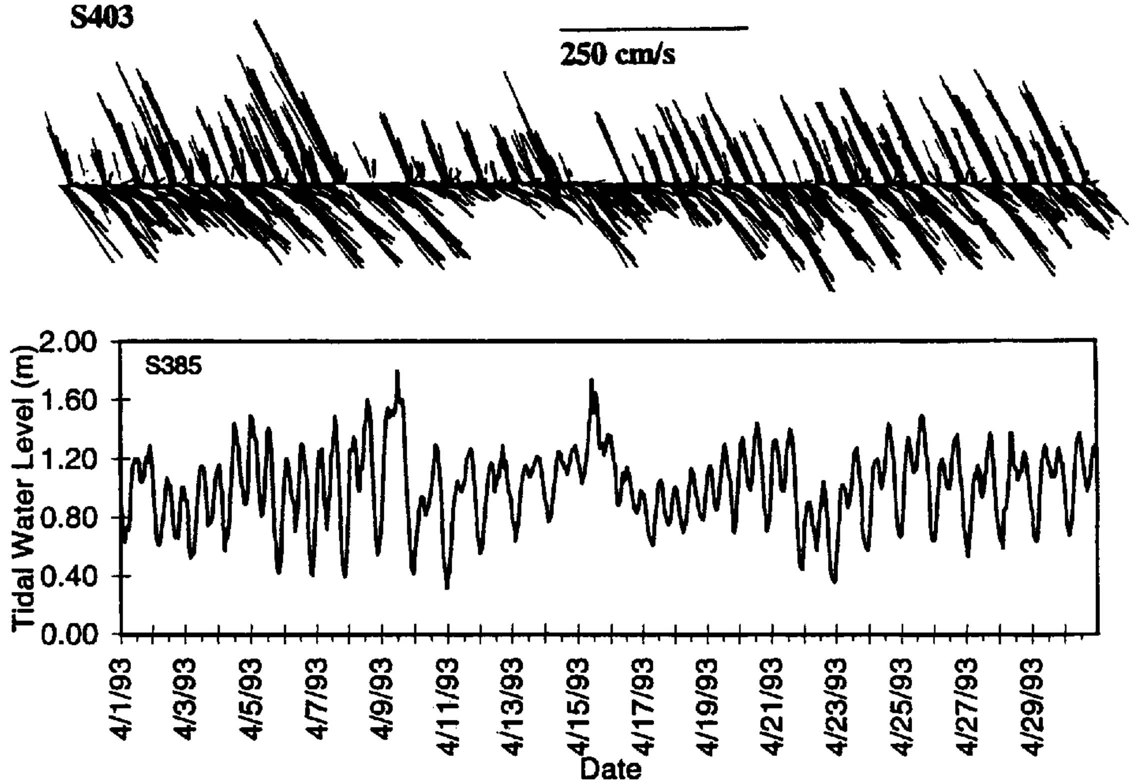

Fig. 2: Tidal heights (bottom) and current velocities (top) at two stations

2.2 Theoretical approach

Tidal harmonic analysis is based on a decomposition of the observed tidal height h(t) and/or tidal current v(t) into the basic tidal modes provided by the periodic variations of the earth-moon-sun gravitational system, i.e.

$$h(t) = h_0 + \sum_{i=1}^{N} a_i \sin(2\pi t / T_i + \delta_i) \qquad (1)$$

where h_0 is the average equilibrium height; a_i the amplitude; T_i the period, i.e. $\omega = 2\pi / T_i$ is the tidal velocity; δ_i the phase or epoch (here the modified epoch for the Apalachicola Bay, relative to 75° W longitude is calculated) of the i^{th}- tidal constituent, and N is the maximum number of astronomical tidal coefficients considered (=35 in the present case). The unknown coefficients a_i and δ_i are then the magnitude and the phase of the Fourier coefficients computed through standard discrete Fourier analysis *(Boon and Kiley, 1978)*.

A similar expression to (1) holds for two orthogonal components vL and v_T of the tidal current v(t). After orthogonal vector summation current ellipsoids are obtained whose shape and inclination provide the essential information for each of the tidal current constituents.

3. Results

The harmonic analysis shows that of the 35 tidal constituents used, as expected, only the three major semidiurnal constituents M_2, S_2, and N_2 and the two diurnal constituents K_1 and O_1 are of importance. Only those are, therefore, primarily considered in the following discussion of the results.

3.1 Tidal variation of water levels

Amplitudes and epochs of the M_2 constituents are plotted in *Fig. 3*. The former show an overall decrease from the east towards the west side of the bay, indicating the effect of friction in the bay, as the open gulf wave propagates from the east through the estuary. A similar tendency was observed for the K_1 diurnal constituents. The epochs illustrate a progression of the tidal waves up the bay, due to their traveltimes. With an epoch difference $\Delta\delta_{M2}$ ~

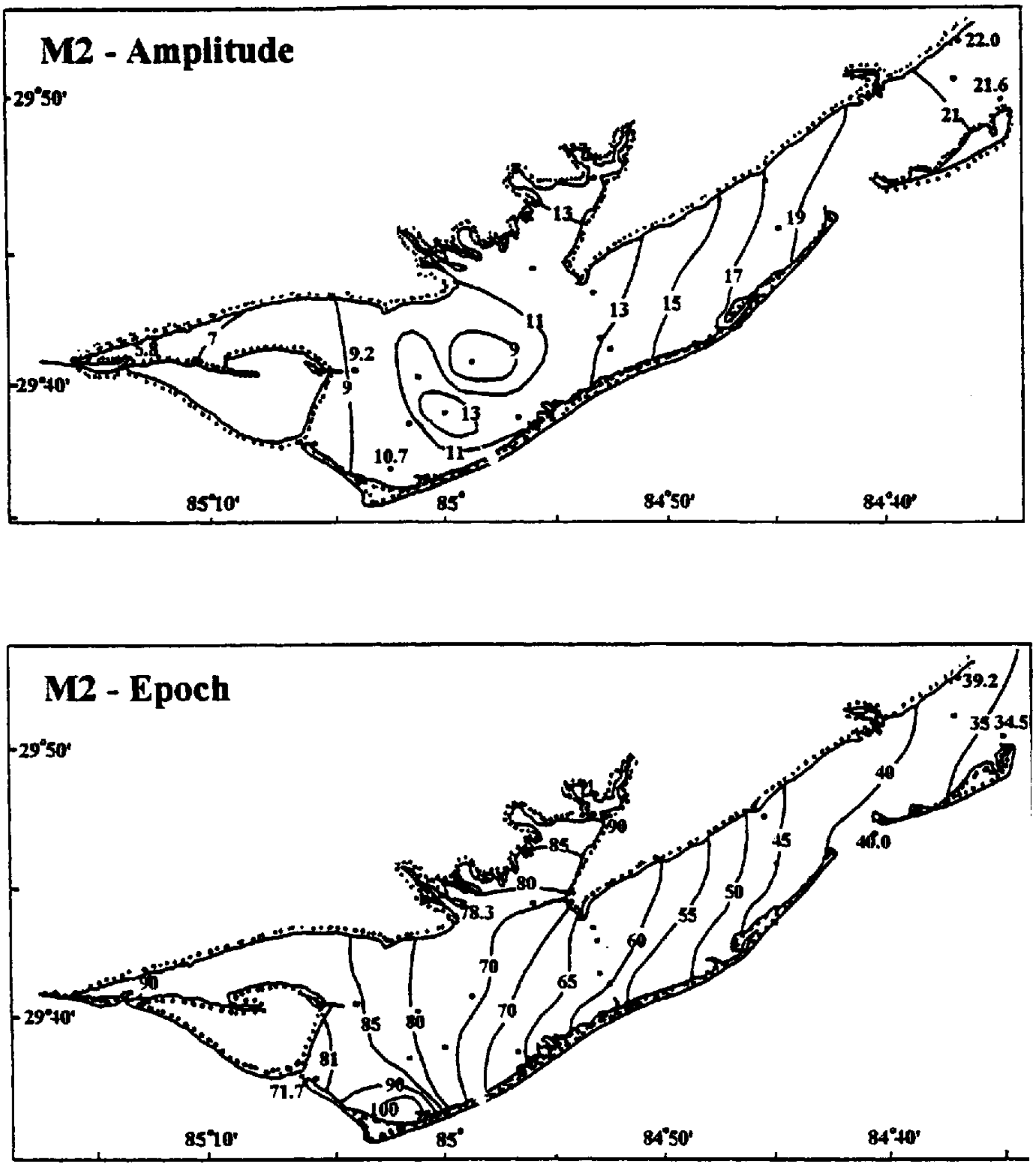

Fig. 3: Amplitudes and epochs of M_2 tidal height constituents

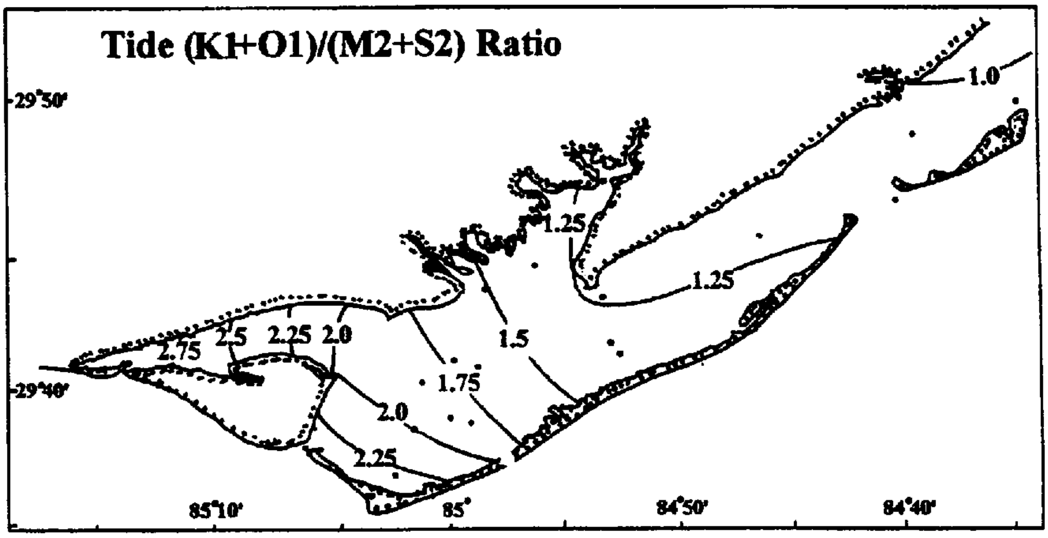

Fig. 4: $(K_1+O_1)/(M_2+S_2)$ *amplitude-ratio for tidal heights*

55° for M_2 from the east to the west, it takes about 1.8 hours for a semidiurnal tide to travel all through the estuary. For the diurnal tide K_1 the difference $\Delta\delta_{K1}$ ~20°, resulting in a travel time of 1.3 hours through the bay. The amplitude ratios $(K_1+O_1)/(M_2+S_2)$ for the tidal heights increase from 1.00 to 2.99 from the east to the west side of the bay *(Fig. 4)*, indicating a mixed tide that changes from a semidiurnal type at the bay entrance in the east to a diurnal one in the west. This agrees with the general principle that a short-period wave attenuates faster than a long-period one.

3.2 Tidal variation of current circulation

The current ellipses are drawn from a several month-long average of the amplitudes of the major tidal constituents M_2, S_2, K_1 and O_1, using the amplitude in the principal direction of the current as the long (major) and the one in the direction perpendicular to it as the short (minor) axis. *Fig. 5* illustrates that the current amplitudes in the principal direction are higher at the entrance section of the bay and lower in its middle and northern landward portion. The rather elongated ellipsoids at the narrow exits of the bay demonstrate the stronger currents (velocities >1 m/s here), in agreement with basic hydraulic principles *(Jones et al., 1994)*. Moreover, the ellipsoids for the semidiurnal constituents are usually larger than the diurnal ones.

The spatial variations of the current epochs of the surface to mid-depth stations *(Fig. 6)* are complicated due to the multiple openings in the bay. A detailed inspection of the results of the harmonic analysis for each of the station considered reveals that the epochal phase-differences between the surface and bottom current stations show only small variations with the water column depth, with earlier epochs closer to the surface and smaller amplitudes closer to the bottom (due to friction). Particle tracking plots show a particularly strong zigzag rotary path for stations close to the bay shorelines, where the waves are reflected, at the exits of the bay, and at the river mouth.

Fig. 7 illustrates that, unlike the $(K_1+O_1)/(M_2+S_2)$- ratio for the tidal heights which exhibit large variations across the bay, this ratio for the current amplitudes is more constant. With values ranging between 0.5 and 1, the tidal currents in the bay are to be considered as mixed and mainly semidiurnal.

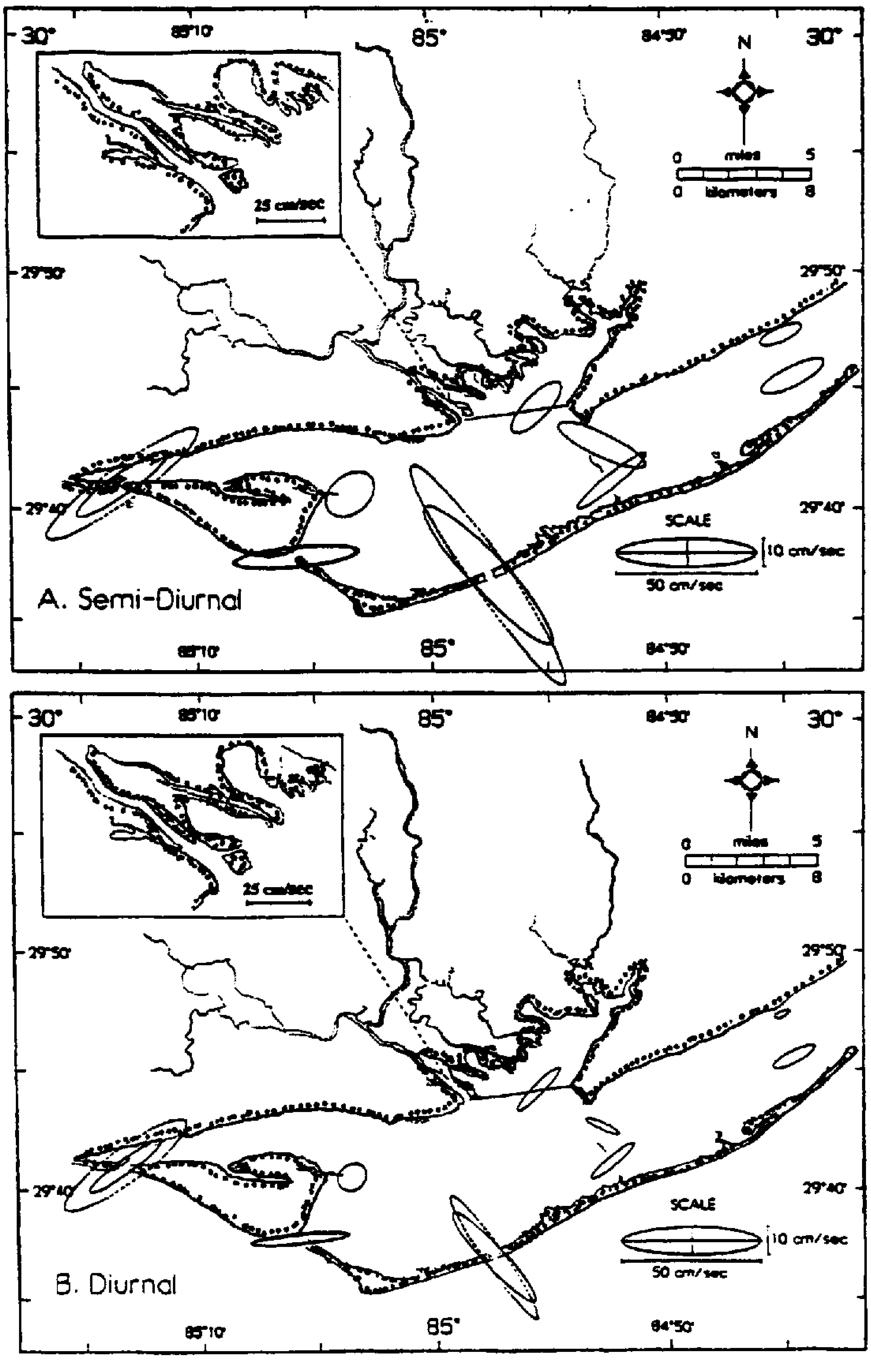

Fig. *5: Semidiurnal (top panel) and diurnal (bottom panel) tidal current ellipses for each current meter. Single ellipses indicate mid-depth, two ellipses surface (solid) and bottom (dashed) meters, respectively.*

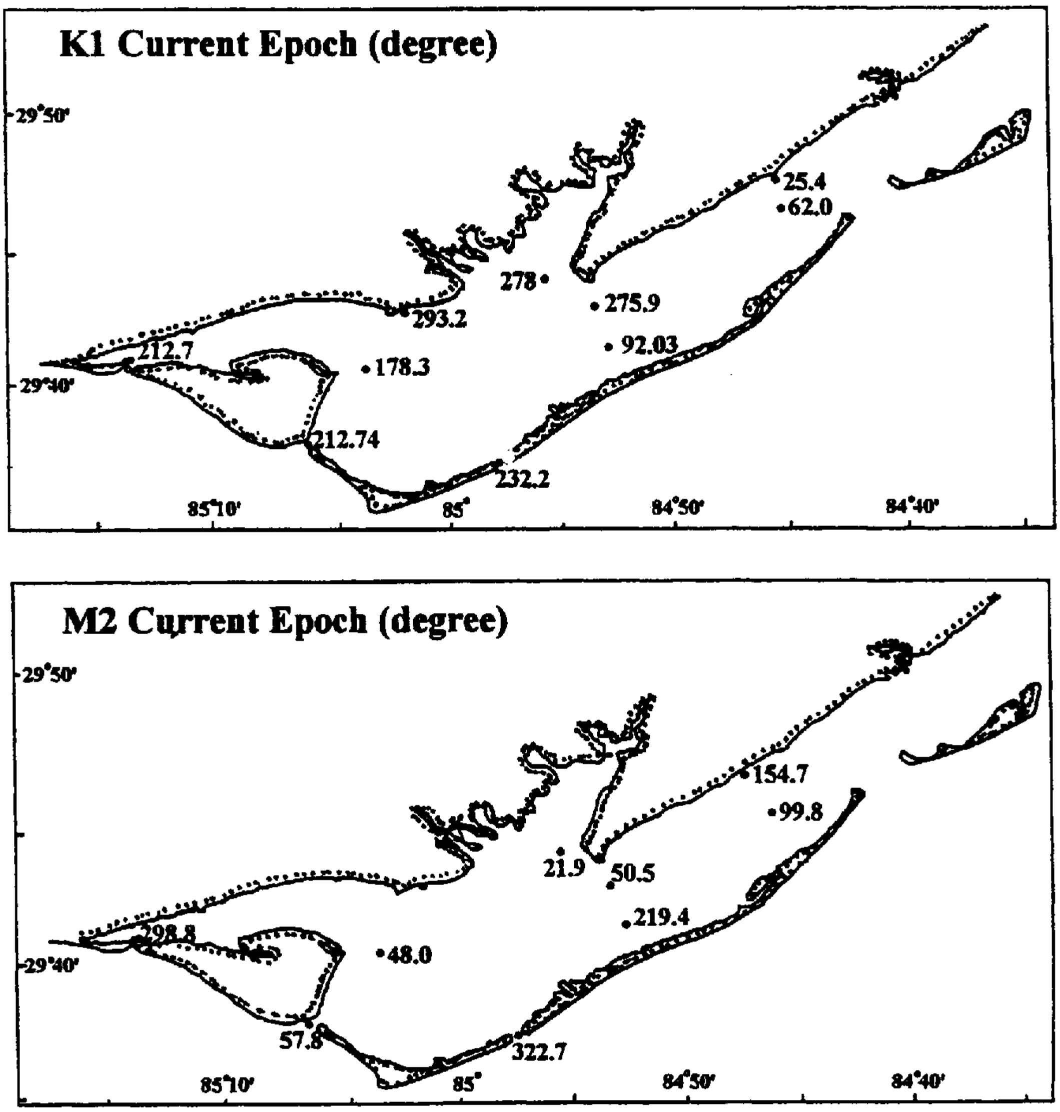

Fig 6: Epochs of tidal current constituents M_2 and K_1

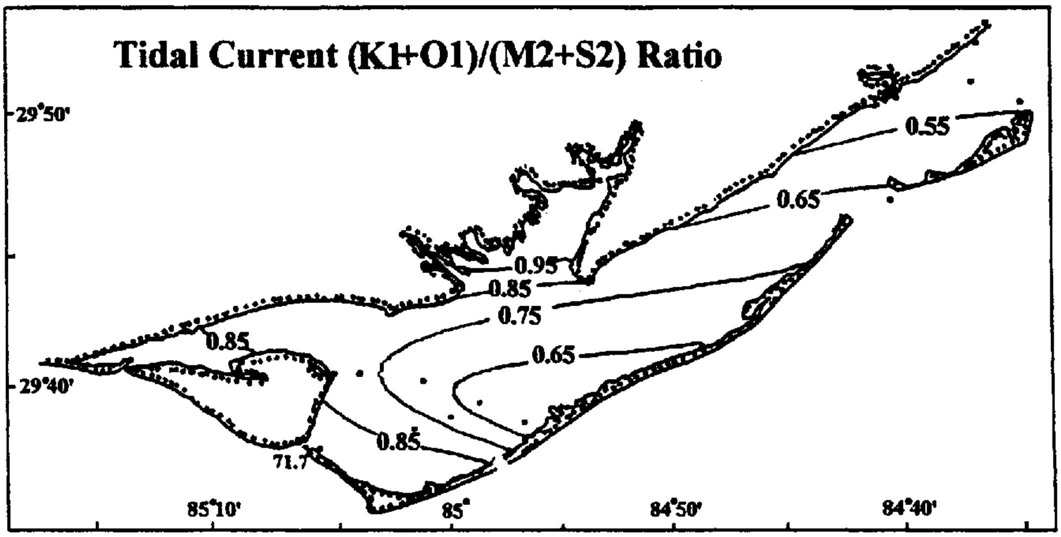

Fig 7: $(K_1 + O_1)/(M_2 + S_2)$ amplitude- ratio for tidal currents

3.3 Non-tidal effects in the currents

3.3.1 General aspects

Tidal currents are only one part of the circulation in the bay. Long-term non-tidal currents are important in estuaries as the primary means of transport for dissolved and suspended matter. Non-tidal currents are driven by winds, river discharge, non-tidal water level variations (winds and storms) in the Gulf and horizontal density gradients in the bay *(Sun and Koch, 1996; Sun et al., 1999)*. Non-tidal circulation effects can be examined by calculating the mean and the residual currents. Permanent currents are induced by driving forces that have a time-invariant component. Permanent currents in the Apalachicola Bay may be density-driven currents and tidally-induced residual currents. A time-series long enough to average out long-period currents is necessary to measure accurately the permanent or mean current since density-driven currents can have seasonal and interannual variability. As already depicted in *Fig.5* through the axes of the current ellipses, the net direction of the current flow at the surface is generally southwest, and mixed northeast/southwest in the bottom of the water column. Such a current direction was also found in one of the modeling studies of *(Jones et al., 1994)* using a shallow water ocean model.

3.3.2 Shelf water level effect

Non-tidal water level fluctuations on the continental shelf are produced in part by both local and distant wind-driven currents. Where the shelf is deeper than the Ekman depth, the long-shore component of the wind can raise and lower coastal water levels by Ekman transport. The average depth of the Apalachicola bay is approximately 5.7m. As the shelf depths get shallower than the Ekman depth, the transport vectors rotate toward the wind direction. In general, the longshore component of the wind will raise or lower coastal water levels. The west Florida coastline and the continental slope have an orientation of about 340 (20^0 west). When the wind blows from the south and southeast, shelf water levels should rise; when the wind blows from the north and northwest, shelf water levels should fall *(Zervas, 1993; Brooks, 1973)*.

3.3.3 Density gradient effect

There are strong vertical and horizontal density gradients in the Apalachicola bay owing to the large amount of freshwater input from the Apalachicola River, as is also shown by the salinity profiles and a cross-correlation study *(Sun and Koch, 1996; Sun et al., 1999)*. Within the main channel, a classic estuarine circulation cell exists, so that in the mean, more saline water from the Gulf flows into the bay near the bottom and less saline water flows out near the surface. The amount of fresh river water input is expected to control the magnitude of the density-driven flow.

3.4 Non-tidal effects of water levels

Using Eq. (1), with the amplitudes and epoch parameters computed from the harmonic analysis, the theoretical tidal water levels/currents are predicted. Subtracting these from the measured water levels/currents results in residuals that, apart from measurement errors, should provide evidence for the named non-tidal effects. Significant residuals were found at all stations and two non-tidal driving forces were apparent: (1) Sub-tidal (periods >24 hours) water level fluctuations on the west Florida continental shelf and (2) head-to-mouth density gradients in the bay due to freshwater input from rivers.

The residual series allows to investigate the response of water levels to short- and long-term meteorological forcing due to thunderstorms and cold fronts. This is shown in Fig.8 for three specific events occurring in April 1993, with the first a storm (on 4/4), the second a wind front (on 4/15), and the third a strong thunderstorm (on 4/26). Whereas the effect of these meteorological events on the water levels is evident, no effect of the discharge rates of the Apalachicola River on the tidal residuals is found during the same period.

Tidal forces cause daily salinity fluctuations as well and are responsible for the mixing of saline and freshwater. As found by *Sun and Koch (1996)* and *Sun et al. (1999)* through a correlation time-seris analysis, a strong positive correlation exists between the tidal water level and the salinity.

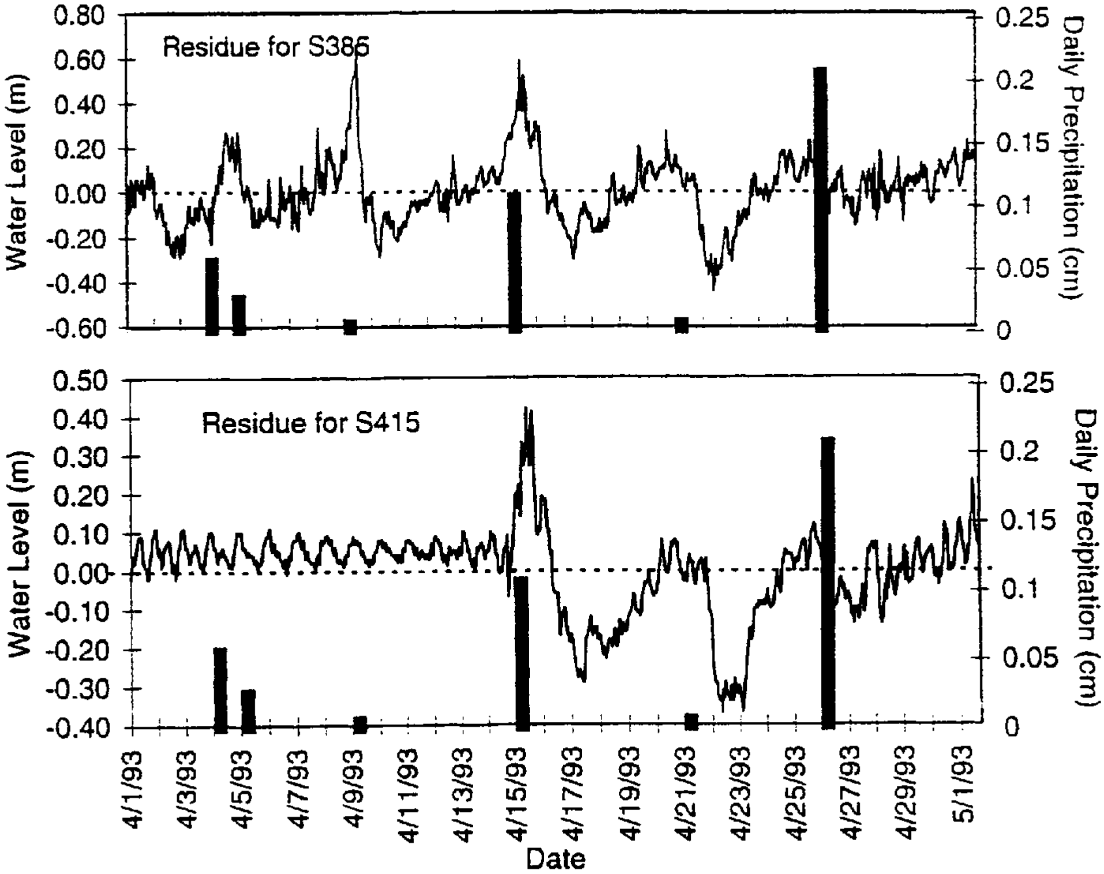

Fig. 8: Residual tidal water levels for three meteorological events.

4. Summary and conclusions

Amplitudes and epochs of tidal water levels and currents for the Apalachicola Bay were computed. The results indicate that tidal heights are of mixed type that changes from a semidiurnal type at the bay entrance in the east to a diurnal one in the west. Tidal currents in the bay, on the other hand, are more of semidiurnal type. Tidal ranges gradually decrease from the east to the west side of the bay, but tidal currents are strongest in the narrow exits of the estuary. The currents exhibit a rotary current pattern, with the tide resembling a progressive wave in the bay. Currents are strongest in the entrance section of the bay and in the narrow barrier island cuts. The non-tidal circulation contributes to the long-term transport of nutrients in and out of the bay. The analysis of the tidal residuals demonstrate that in addition to river recharge, wind and storm events are the main causes for significant non-tidal water level changes. Such meteorological events have a major effect on the ability to predict accurately the tidal currents and water levels using traditional harmonic analysis and prediction techniques.

References

[1] Boon, J. D. and K.P. Kiley, *Harmonic analysis and tidal prediction by the method of least squares,* Special Report No.186, Virginia Institute of Marine Science, Glocester Point, Virginia, 1978.

[2] Brooks, H.,*A Summary of Knowledge of the Eastern Gulf of Mexico,* Florida Institute of Oceanography, St. Petersburg, FL, 1973.

[3] Dean, R. G. and Dalrymple R. A., *Water wave mechanics for engineers and scientists,* Prentice Hall, Inc., Englewood Cliffs, NJ, 1984.

[4] Jones, W.K, Galperin, B., Wu, T.S. and Weisberg, R. H., *Preliminary Circulation Simulations in Apalachicola Bay, FL.* Water Resources Special Report, NW Florida Water Man. District, Havana, FL, 1994.

[5] Johnson, V., Apalachicola Bay: Endangered Estuary, *Florida Water,* 2, 14-20, 1993.

[6] Sun, H., A two-dimensional analytical solution of groundwater response to tidal loading in an estuary, *Water Resour. Res.*,33, 1429-1435, 1997.

[7] Sun, H. and M. Koch, Time series analysis of water quality parameters in an estuary using Box-Jenkins ARIMA models and cross correlation techniques, In: *Computational Methods in Water Resources,* Vol. XI, Alamo, A.A. et al. (eds.) Comp. Mech. Pub., Boston, MA, p. 230-239, 1996.

[8] Sun, H., M. Koch and W. Jones, Application of ARIMA models and Kalman filter techniques to the analysis and forecasting of salinity variations in the Apalachicola Bay, Florida. *J. Hydraul. Engineer.*, In Press, 1999.

[9] USGS, *Water Resources Data Florida, Water Year 1993-1994,* USGS, Tallahassee, FL, 1994.

[10] Zervas, E. Chris (ed.), *Tampa Bay oceanography project: Physical oceanographic synthesis,* NOAA Technical Report NO-SOES-002, 1993.