MEASUREMENTS AND MODELLING OF SEA LEVEL AND CURRENTS IN SANTOS COASTAL AREA (SAO PAULO STATE, BRAZIL)

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1 – INTRODUCTION

Recent research on hydrodynamic numerical modeling of the coastal area of Santos involve the specification of all the forcing effects - tides, winds and density gradients (including rivers flows); the main objective of this study was to compare modeling results with measurements of sea level and currents in the Bay of Santos, in order to calibrate the numerical model aiming future use in studies of coastal circulation and dispersion of pollutants and sediments.

2 – METODOLOGY

Since March 2007, measurements have been carried out almost continuously in Santos Bay, of currents along the water column, temperature at the sea bottom and sea surface level, through an acoustic current profiler Sontek Argonaut XR instrumented with three acoustic transducers operating at 750 kHz, together with temperature and pressure sensors. Measurements of this ADP (Acoustic Doppler Profiler) are performed in the position 24° 0.757' S 46° 19.579' W, with depth of approximately 11.0 m, at intervals of 30 minutes; current data are obtained in 10 cells of 1.0 m each, from 0.5 m above the bottom up to 0.5 m below the sea surface, in the form of north-south, east-west and vertical components. The equipment is installed in a U-type anchor, using especially designed structures, in a position near Palmas Island, chosen due to safety requirements. In this paper, a measurements processing is presented, for the period from 16:30 GMT January 7 up to 00:30 GMT March 1, 2010. A total of 2513 measurements were obtained, that were submitted to a 3 points running means filter, in order to have a sample interval of 01 hour, resulting 1256 hourly data.

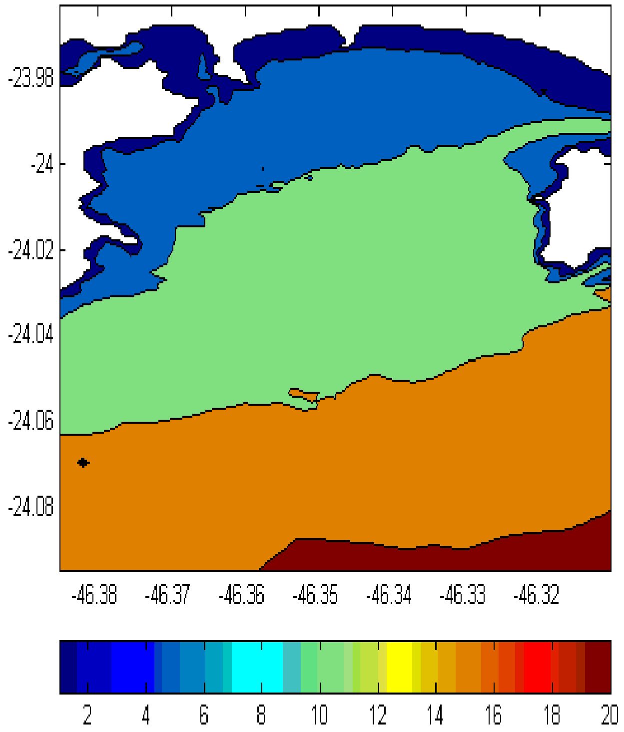
The sea surface level is estimated from sub-surface pressure data through the hydrostatic relation ($p = \rho\ g\ h$, where p is pressure, ρ sea water density, g gravity acceleration and h height of the water column); the velocity components (horizontal and vertical) are estimated through the composition of the Doppler shifts of the acoustic signals emitted and received in the transducers.

The circulation in the coastal area of Santos is estimated from results of hydrodynamic numerical models for the region. These models are based on the Princeton Ocean Model - POM (Blumberg & Mellor, 1987); POM is a three-dimensional nonlinear hydrodynamic model with the complete equations (for sea level, currents, temperature, salinity and density) whose solutions are obtained in sigma coordinate system (which follows the submarine relief), considering mode splitting and second order turbulent closure (Mellor, 1998). The models are processed with: 1) tidal forcing at the open boundaries, specified from the results of the model of the shelf (Harari & Camargo, 1994); 2) mean sea level variations at the boundaries, estimated by filtering sea level observations from coastal stations, and through the numerical model of the shelf (Camargo & Harari, 1994); 3) monthly climatological salinity and temperature fields; and 4) surface winds, provided by the reanalysis of the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP / NCAR) (Kalnay et al., 1996). These hydrodynamic models have been intensively used in simulations of sea level and currents in coastal regions and platforms (Harari & Camargo, 1998, 2003; Camargo & Harari, 2001; Camargo, Harari & França, 2006; Harari et al, 2006).

In this study, besides the shelf grid of Harari & Camargo (1994) and Camargo & Harari (1994) a nested coastal grid was used for the Bay of Santos; this grid has 100 m horizontal spacing and allows detailing the circulation in the bay, with a precise comparison between modeling results and ADP measurements. The bathymetry of the high resolution grid is presented on Figure 1.

3 - ATMOSPHERIC CONDITIONS AND MEAN SEA LEVEL VARIATIONS

For analyzing weather conditions, winds, air temperature and atmospheric pressure at the surface were extracted from the reanalysis of NCEP / NCAR and the synoptic analyses of Centro de Hidrografia da Marinha / Serviço Meteorológico Marinho (CHM / SMM) and Centro de Previsão de Tempo e Estudos Climáticos / Instituto Nacional de Pesquisas Espaciais (CPTEC / INPE). Time series of meteorological variables for the month of February 2010, referred to the grid point of the NCEP / NCAR model closest to Santos, are presented on Figure 2; the climatology of the re-analysis at this point can be found in Harari, França & Camargo (2008); the synoptic map produced by CHM / SMM for 12:00 GMT on February 24, 2010, is on Figure 3.



Fig, 1 - Bathymetry of the high resolution grid (in meters), centered in the Bay of Santos.

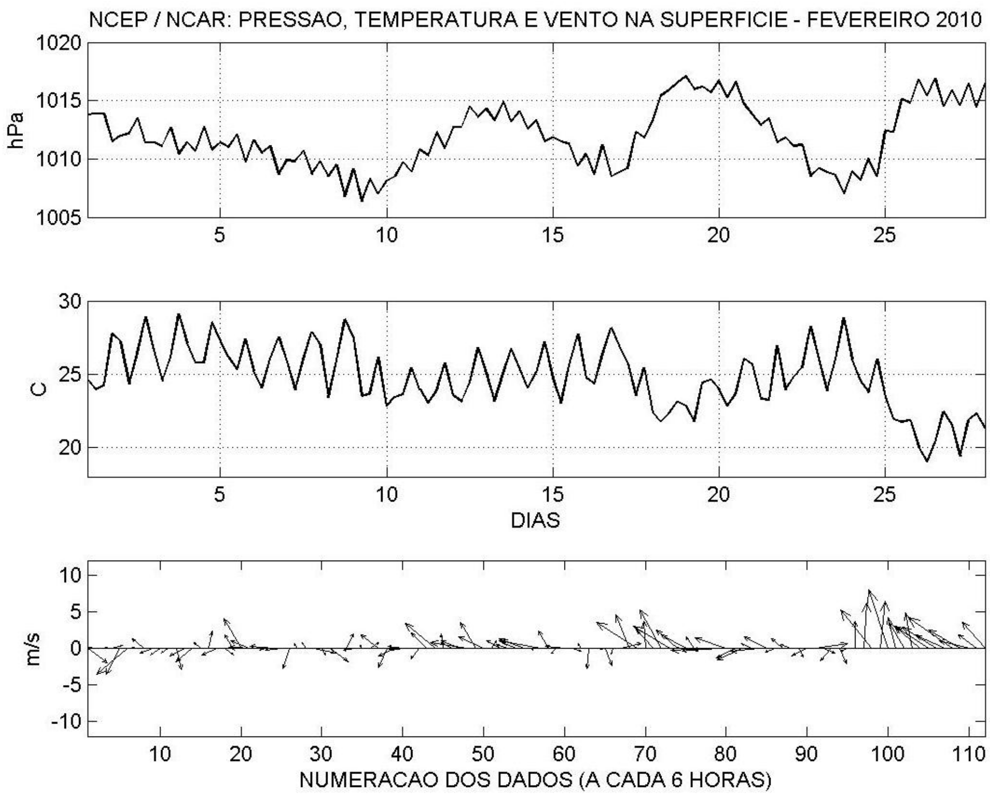


Fig. 2 - Atmospheric pressure, air temperature and winds at the surface, computed by NCEP / NCAR model for the month of February 2010, at 25°S 047.5°W

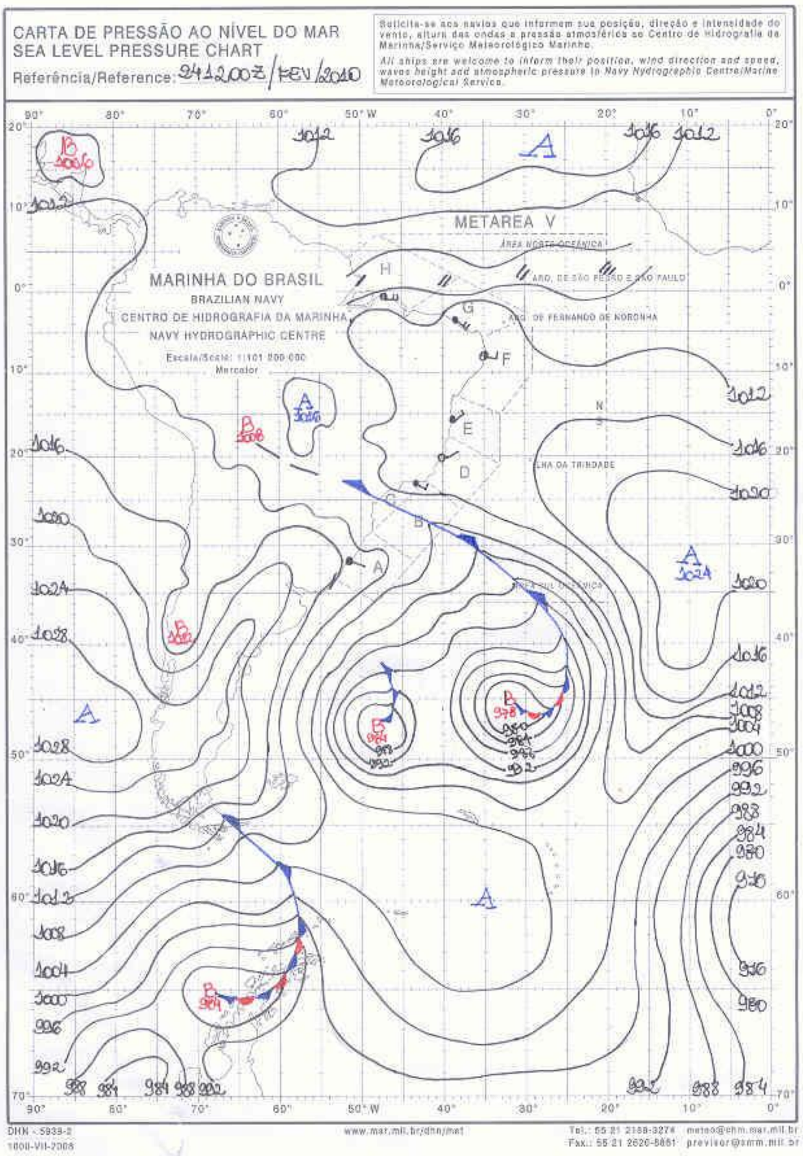


Fig. 3 - Synoptic chart produced by CHM / SMM for 12:00 GMT on February 24, 2010.

In February 2010, only two frontal systems reached the southern coast of Brazil, in the 17^{th} and 25^{th} of the month; these systems have signals in the time series of atmospheric pressure and surface temperature in Santos, mainly in the temperature during the second front, which reached 28.04°C on day 23 and 19.04°C on day 26 (Figure 2). In fact, the weather conditions in February 2010 are typical of summer, with very high temperatures, having monthly average 24.70±2.16°C, minimum of 19.04°C and maximum of 29.14°C. The winds were generally weak, with mean intensity of 2.8±1.7m/s; however, southerly winds were significant on days 17-18 (due to the first frontal system, with intensity of 6.2m/s) and on days 25-27 (second frontal system of the month, much more intense, with the wind magnitude in the region reaching 8.4 m/s, maximum of the month); the position of this second cold front on February 24 can be seen in the synoptic map of Figure 3; on the other hand, in February 2010, there were several periods with light winds from the east, as in days 02, 05, 11-12, 15 and 20, reaching maximum of 5 m/s (Figure 2).

Measurements of sea level in Cananeia (25°S, 47.5°W), in February 2010, are shown on Figure 4, together with values of mean sea level, calculated by applying a running means filter to the hourly observations. In this month, the sea level in Cananeia ranged from -0.95 m to +1.15 m, with standard deviation of 0.39 m, while the mean sea level ranged from -0.33 m to +0.47 m, with a standard deviation of 0.16 m; the mean sea level showed small fluctuations during February 2010, except for the effects of the two frontal systems, which caused elevations of +0.20 m on day 17 (low intensity) and +0.47 m on day 26 (intense frontal system which caused the monthly maximum elevation). Moreover, after the first system, winds from the east blew during 2 to 3 days, that caused a large decrease of mean sea level, reaching -0.33 m on day 20, the corresponding monthly minimum (Figure 4).

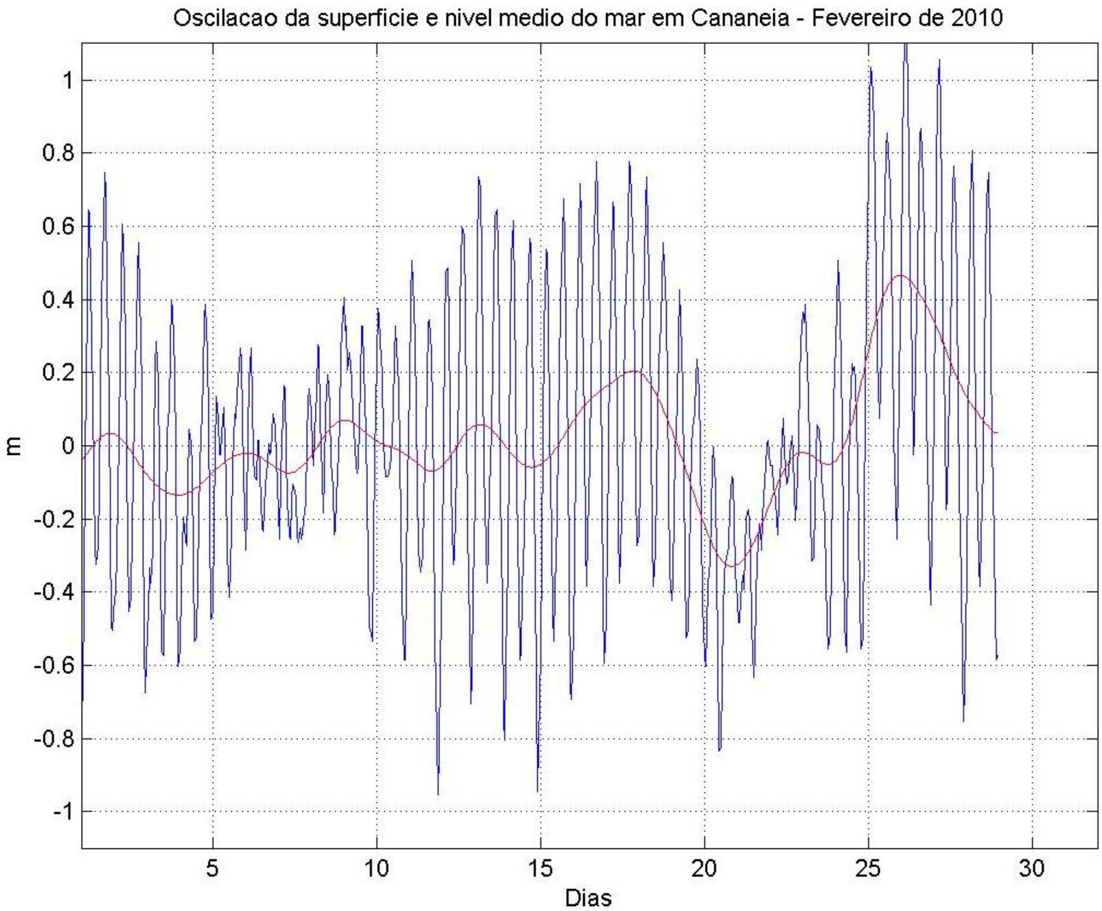


Fig. 4 – Sea surface oscillations and mean sea level at Cananeia, in February 2010.

4 - MEASUREMENTS OF THE ACOUSTIC CURRENT PROFILER

Next, measurements of the acoustic current profiler are presented, as time series of sea level and currents at mid water depth (Figure 5) and compass - roses of currents at the surface, mid - water and near the bottom (Figure 6). The time series of sea level, calculated from the measurements of the pressure sensor, shows the mean sea level oscillations superimposed on tidal variations, which are similar to those observed in Cananeia, especially the elevations on days 17 and 26 February (Figures 4 and 5). Moreover, the predominance of tidal currents on the period of observations is striking, with the particularity of the alignment of the current in the North – South direction, due to orientation of the coastline in the Bay of Santos near the Island of Palmas (Figures 5 and 6).

5 - RESULTS OF HYDRODINAMIC NUMERICAL MODEL

An example of the results of the high resolution model is given, with strong currents in the coastal region, especially off Santos Bay (Figure 7).

Results of the hydrodynamic numerical model, at the point of the ADP measurements, are presented as time series of sea surface level and currents in mid water (Figure 8) and compass - roses of currents at the surface, mid - water and near the bottom (Figure 9), for the same period of currents measurements (January / February 2010).

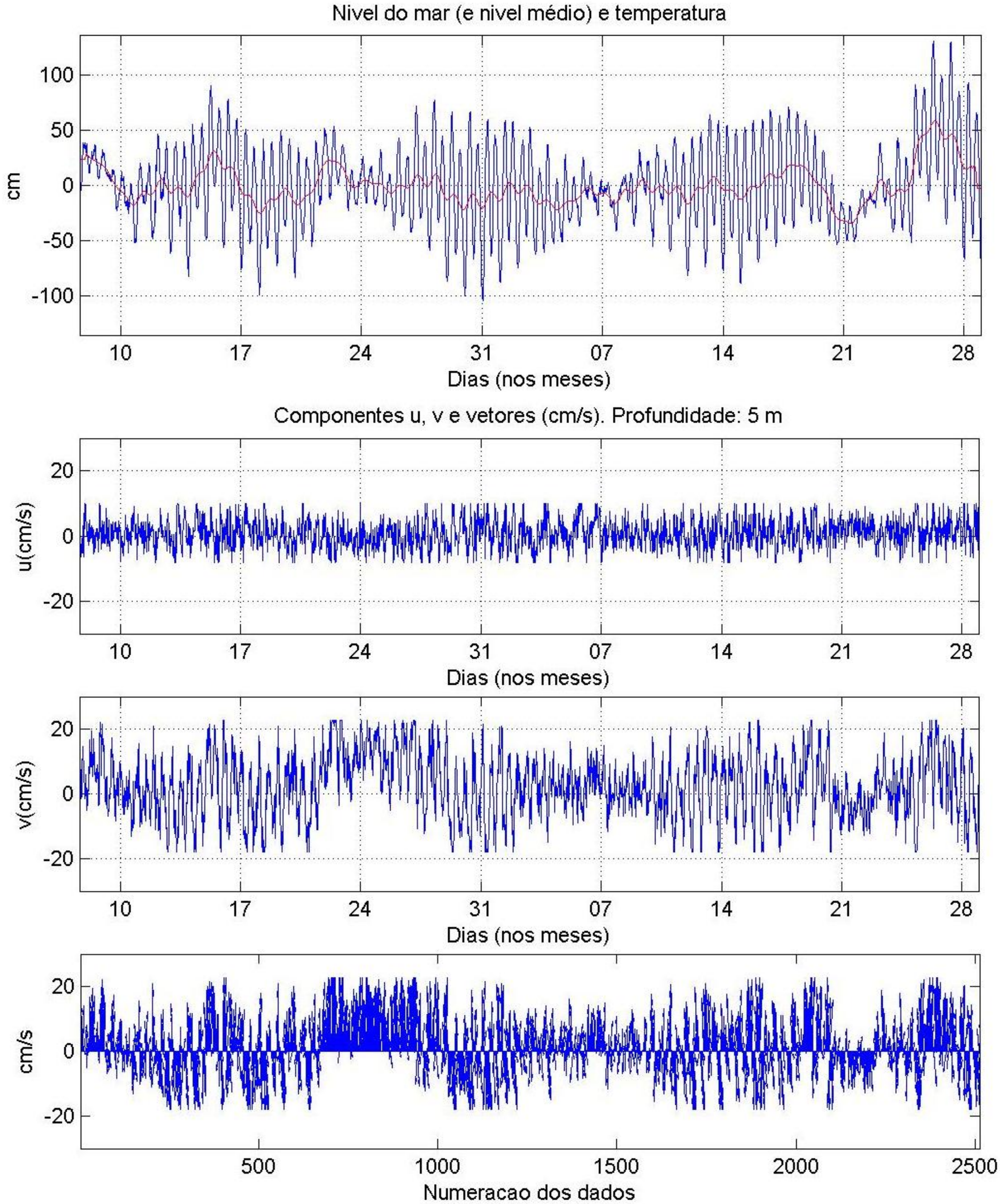


Fig. 5 - Time series of sea surface level (and mean sea level), EW and NS current components and current vectors at mid water, in the period from 16:30 GMT January 7 to 00:30 GMT March 01, 2010 - measured by Sontek Argonaut.

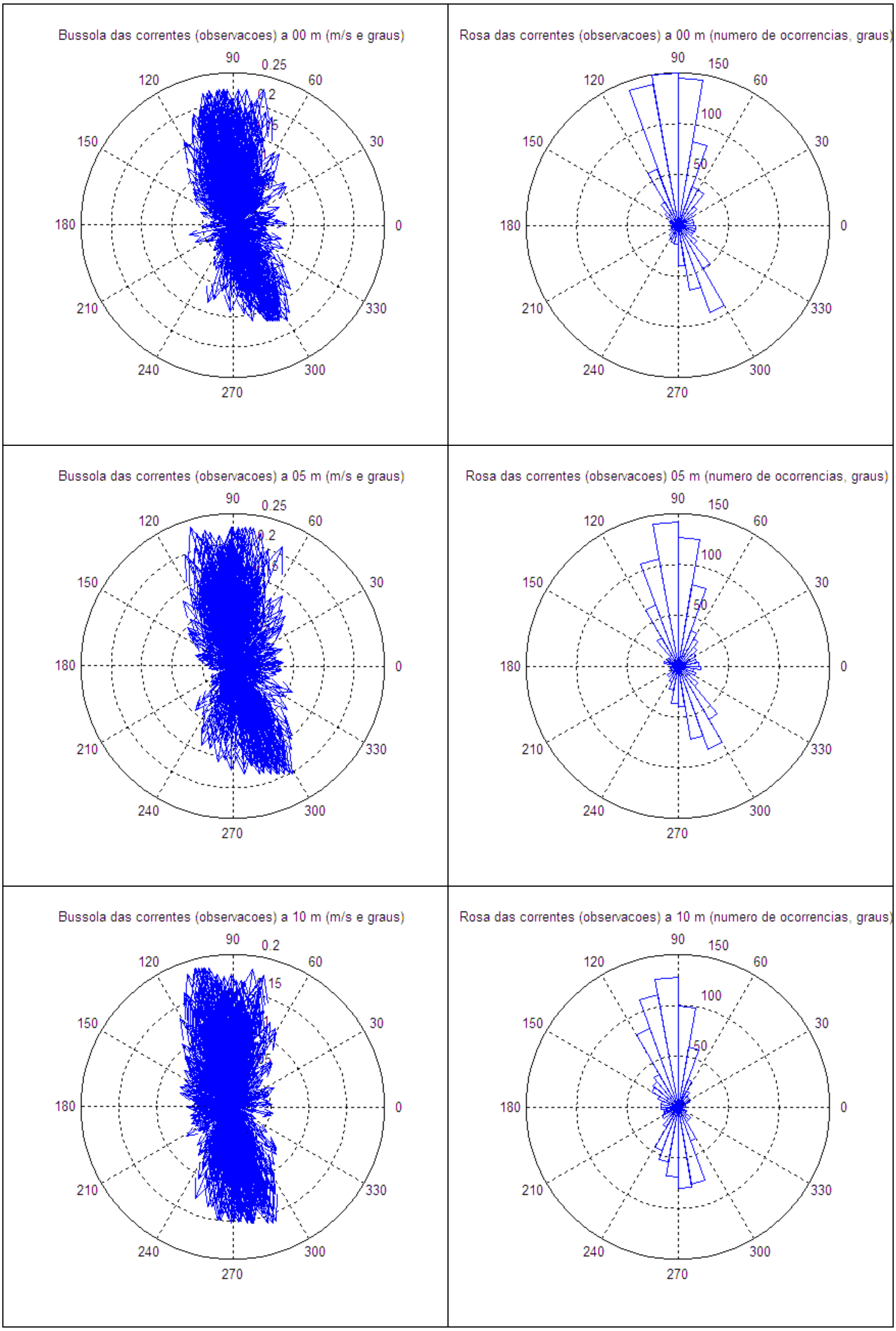


Fig. 6 – Currents compass and roses measured by the Sontek Argonaut in January / February 2010, considering the currents at the surface, 05 m and 10 m depth.

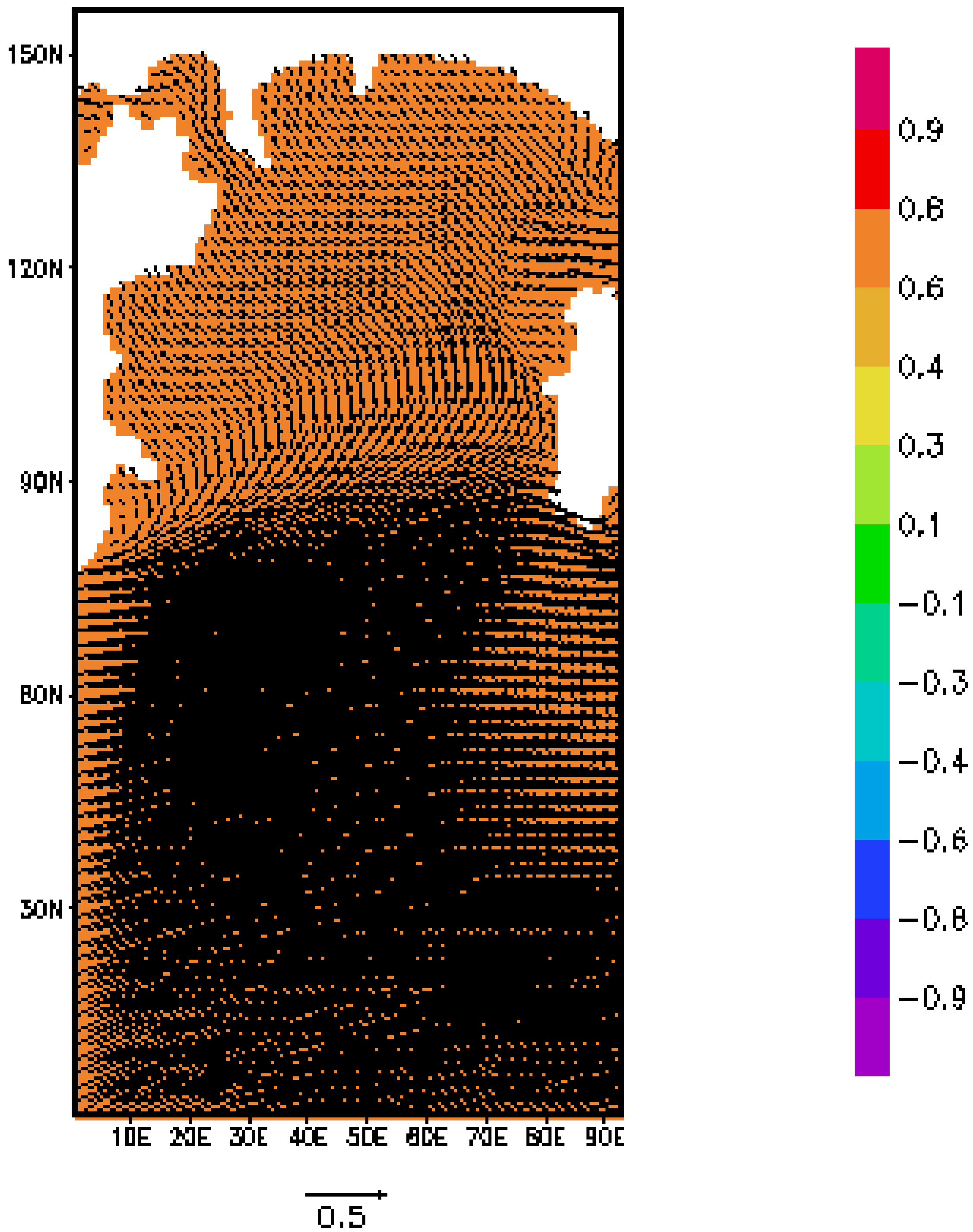


Fig. 7 - Elevation (shaded in m) and surface currents (vectors in m/s) within and off the Bay of Santos, on 03:00 GMT 25 February 2010; plotting a vector every second.

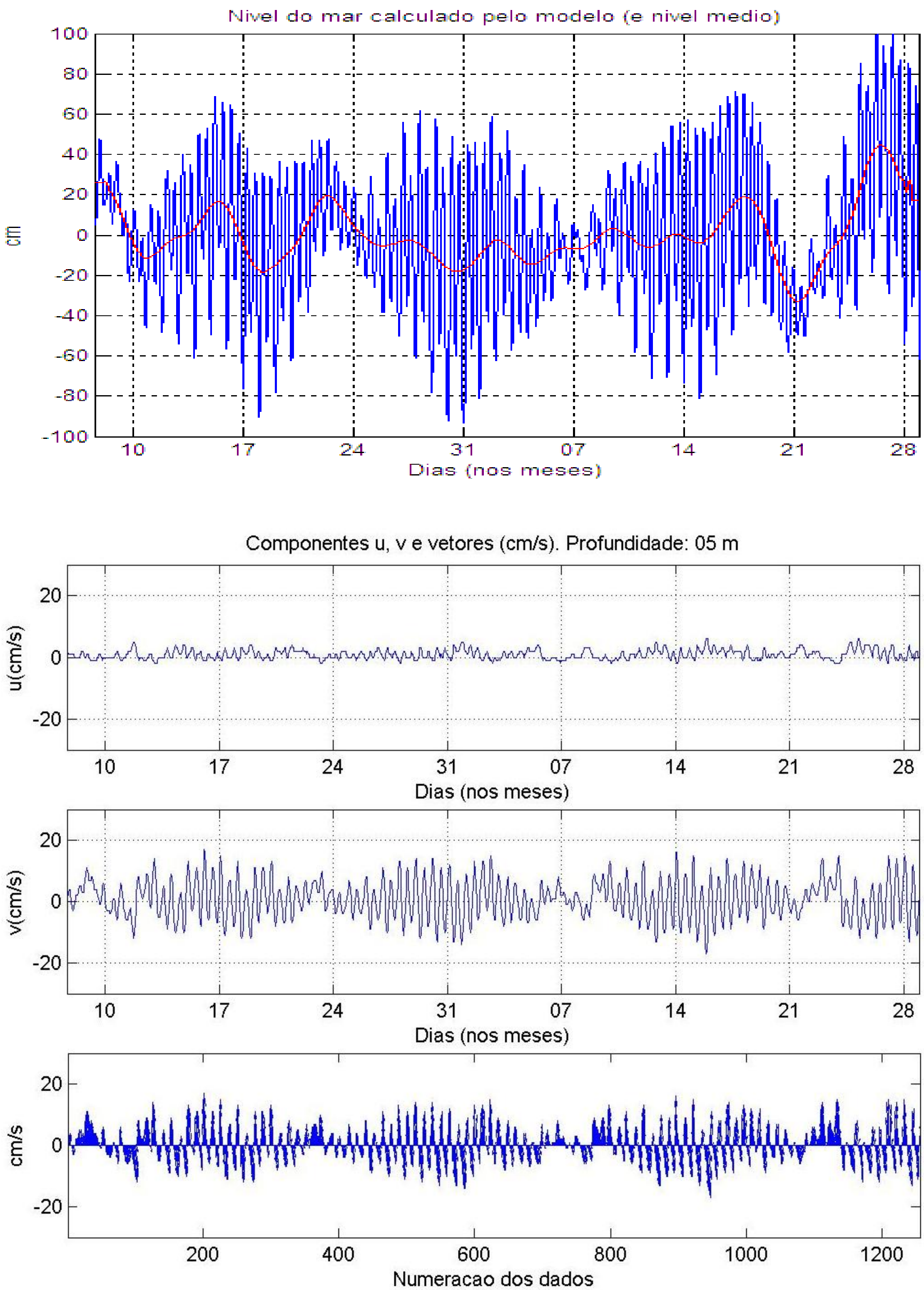


Fig. 8 - Time series of sea surface level (and mean sea level), EW and NS current components and current vectors at mid water in January / February 2010, calculated by the model, in the point of ADP measurements.

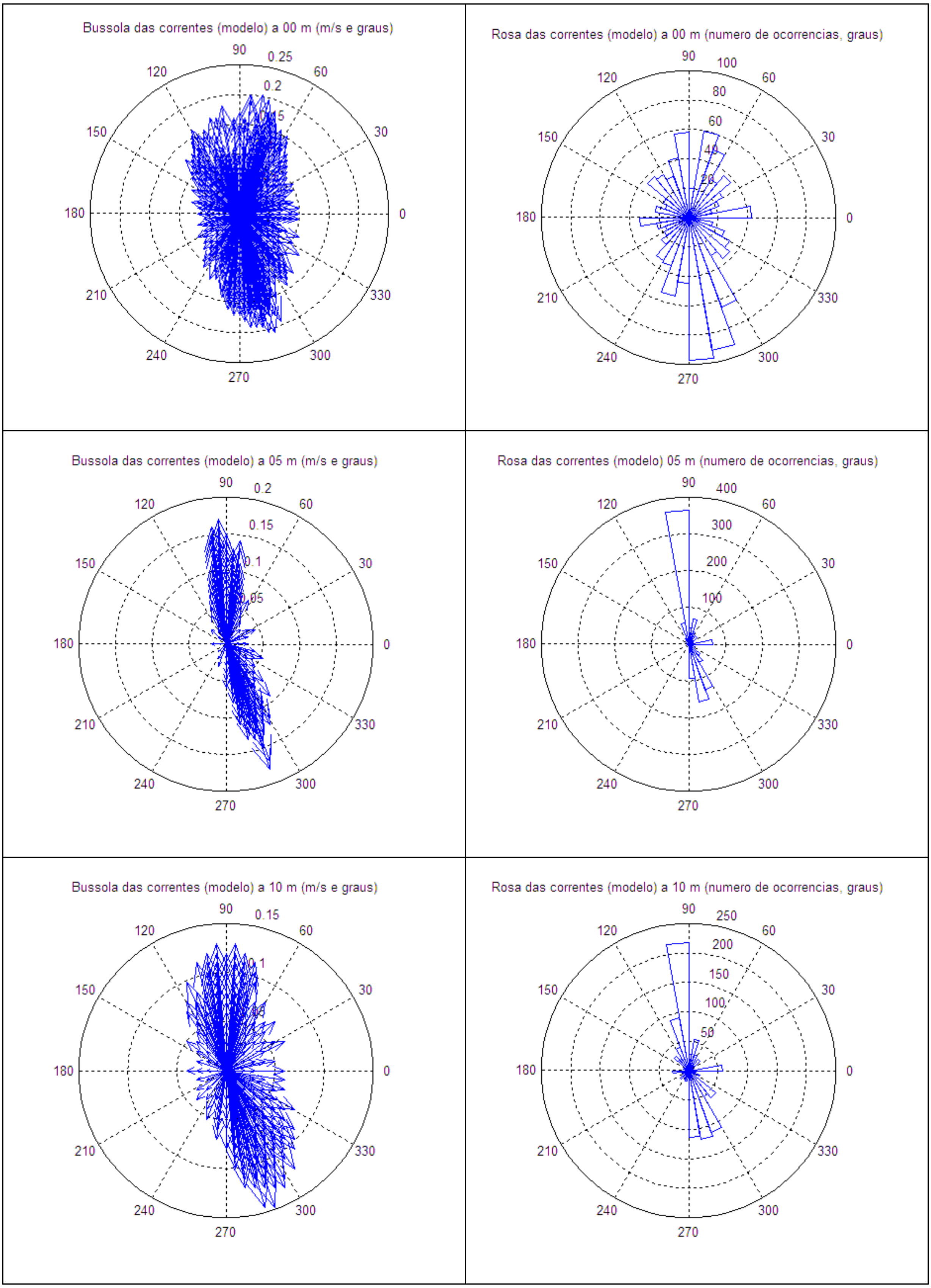


Fig. 9 - Currents compass and roses at the surface, 05 m and 10 m depth, computed by the hydrodynamic numerical model at the point of ADP measurements, in January / February 2010.

6 - COMPARISON OF MODEL RESULTS WITH MEASUREMENTS

The comparison of Figures 5 and 6 with Figures 8 and 9 shows good agreement of model results with measurements (currents and sea level): there is the predominance of tidal currents and the alignment in the North - South direction, due to the orientation of the coastline. The periods of southerly winds (and their influence on coastal circulation) are also noted in the records of elevations and currents in the Bay of Santos and the results of hydrodynamic modeling. The statistical comparison is presented in Table 1, which contains the correlation model x measurements (correl.), mean differences (difmed) and their standard deviations (dpadr), the mean absolute errors (meabs) and Wilmott parameter (skill), which is closer to 1 the better the model fits the observations and closer to zero the greater the discrepancy (Wilmott, 1981); this statistics considers total elevations and current and the respective tidal contributions. The currents statistics considers only the NS component of current, whose amplitude is much larger than the EW component, which is reduced due to the proximity of the continental boundary at the east.

Table 1 - Statistical comparison of measurements and results of the model, considering the elevation and NS current component, at the surface and 5 m and10 m depth (total values and tidal contribution): correlation coefficients and their significance levels (correl., ±), mean differences (difmed) and their standard deviations (dpadr), mean absolute error (meabs) and Wilmott parameters (skill).

	Total					**Tidal contribution**				
	Correl ±	**Difmed (m)**	**Dpadr (m)**	**Meabs (m)**	**Skill**	**Correl ±**	**Difmed (m)**	**Dpadr (m)**	**Meabs (m)**	**Skill**
Elevation	**0,98 0,00**	**0,00**	**0,07**	**0,06**	**0,99**	**0,99 0,00**	**0,00**	**0,06**	**0,04**	**1,00**
	Correl ±	**Difmed (m/s)**	**Dpadr (m/s)**	**Meabs (m/s)**	**Skill**	**Correl**	**Difmed (m/s)**	**Dpadr (m/s)**	**Meabs (m/s)**	**Skill**
NS Comp. sup	**0,54 0,04**	**0,04**	**0,08**	**0,07**	**0,86**	**0,69 0,03**	**0,00**	**0,05**	**0,04**	**0,90**
NS Comp. 05 m	**0,61 0,03**	**0,02**	**0,07**	**0,06**	**0,88**	**0,73 0,03**	**0,00**	**0,05**	**0,04**	**0,91**
NS Comp. 10 m	**0,67 0,03**	**0,01**	**0,06**	**0,05**	**0,89**	**0,78 0,02**	**0,00**	**0,05**	**0,04**	**0,92**

The comparative statistics shows that the model satisfactorily reproduces measurements of ADP, although the profiler is positioned within the Santos Bay, close to the Isle of Palmas, with EW component of current very small; however, the correlation of the more significant current component (NS) reaches 0.67 and the standard deviation of the differences is always less than 0.1 m/s; for the tidal contribution, which is the most frequent dynamic feature, comparative statistical parameters are even better, with correlations reaching 0.78 and standard deviations not exceeding 0.05 m/s (Table 1). One limitation of the model in reproducing the measured currents is found in the calculation of weaker currents in several cases of extreme observed values; these discrepancies are due to the occurrence of strong jets of local winds, which are not present in the global atmospheric model, but produce very intense currents, especially at the surface (in fact, the standard deviations of currents at depth tend to be smaller than at the surface). For the sea level, the correlations are very high, reaching 0.98 and 0.99 for the total and tidal contribution, with standard deviations of about 10% of the amplitudes (Table 1). Wilmott parameters are also high, between 0.86 and 0.89 for the total currents, 0.99 for the total elevation, between 0.90 and 0.92 for tidal currents and 1.00 for tidal elevation (Table 1).

Therefore, we can conclude that as the results of hydrodynamic numerical modeling and measurements of sea level and currents are satisfactorily consistent, the model results can be used in analysis of currents and dispersion in the coastal area. Concluding the study, the numerical model computations of the strongest elevations and currents, on 25 February 2010, are presented on Figure 10, with sea level reaching almost 0.9 m above the mean and the currents reaching 0.2 m/s.

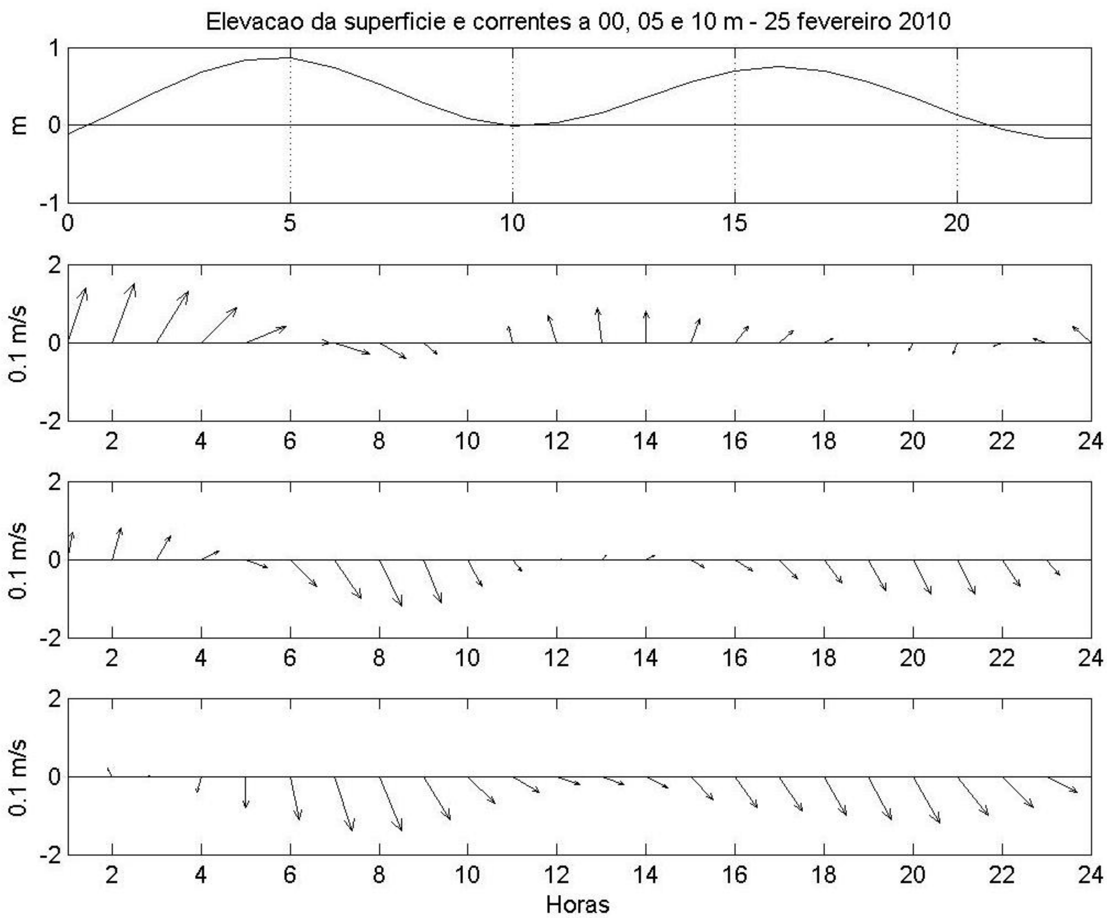


Fig. 10 - Sea surface level and sea currents at the surface (0 m), 5 m and 10 m depth, computed by the hydrodynamic model for the day 25 February, 2010, at the same position of the ADP measurements.

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