AN INTEGRATED STUDY OF SEA LEVEL AND HYDRODYNAMICS IN COASTAL REGION OF PARANAGUÁ (PR, BRAZIL) USING IN SITU AND SATELLITE DATA AND NUMERICAL MODELING

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Abstract

This research has the objective of performing an integrated study of sea level and hydrodynamics of the coastal region of Paranaguá (PR, Brazil), by using in situ data, satellite data and the results of a numerical model. The area comprises the Southeastern Brazil, relative to 30°S-20°S 50°W-40°W, with an emphasis on the coastal region of Paranaguá, 26°S-25°S 49°W-48°W.

The analyses considered the following set of data: meteorological data, produced by reanalysis of a global atmospheric model, in situ meteorological measurements in the Ilha do Mel, satellite altimetric data, results of a wave propagation numerical model and also, results of a high-resolution hydrodynamic numerical model.

Time series were submitted to statistical, spectral and tidal analysis. Measurements by satellite altimetry were analyzed for the entire year of 2014. In situ measurements and model results covered only the month of April 2014.

The most important conclusions of present research were relative to the annual, semi-annual and seasonal components, but on a time scale of 1 to 3 days, the net effects of cold fronts prevail; information of in situ satellite measurements and by numerical modeling, have differences clearly indicating the different space and time scales involved in each case; on the other hand, the annual, semi-annual, seasonal scales associated with cold fronts, were both found in the observations by remote sensing and by computer simulations.

I - INTRODUCTION

This research has the objective of performing an integrated study of sea level and hydrodynamics of the coastal region of Paranaguá (PR, Brazil), by using in situ data, satellite data and results of numerical modelling. The area comprises Southeastern Brazil, 30°S-20°S 50°W-40°W, with an emphasis on the coastal region of Paranaguá, 26°S-25°S 49°W-48°W (**Figure 1-1**). The study also includes a comparison of the information obtained through the different kinds of data (direct observations, remote sensing and computer simulations) – for both atmospheric and oceanic environments.

The analyses considered the following set of data:

1) Meteorological data produced by reanalysis of the global atmospheric model from the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP / NCAR);

2) Meteorological measurements in Ilha do Mel (by automatic station of the National Institute of Meteorology - INMET);

3) Satellite altimetric data, corresponding to absolute dynamic topography, significant wave height and wind intensity (AVISO altimetry);

4) Results of numerical model of wave propagation (NWW3);

5) Results of high-resolution hydrodynamic numerical model (Delft3D-FLOW).

Measurements by satellite altimetry were analyzed for the year 2014 and in situ measurements and model results covered the month of April 2014.

II - STUDY AREA AND METEOROLOGICAL - OCEANOGRAPHIC FEATURES

The atmospheric circulation at the sea surface, in Southeastern Brazil, depends on the South Atlantic High Subtropical Pressure Center and its interaction with the region of subpolar low pressure (Moscati et al, 2000; Seluchi & Marengo, 2000). At the boundaries between these two areas, there are strong westerly winds and instabilities; these instabilities have temporal and spatial scales of days and thousands of kilometers.

Under the influence of the Subtropical High in the Brazilian Southeast, moderate surface winds prevail from the East, generally not exceeding 5 m/s, with relatively high pressure of the order of 1025 hPa. Instabilities cause a pattern of atmospheric conditions of the typical evolution of cold frontal systems, with winds rotating from the east quadrant to winds from the North quadrant, then from West, atmospheric pressure decreasing, around 10 hPa, followed by South winds, temperature decrease and atmospheric pressure increase. Next, the South winds turn again to east winds, temperature and pressure increase, returning the influence of the Subtropical High.

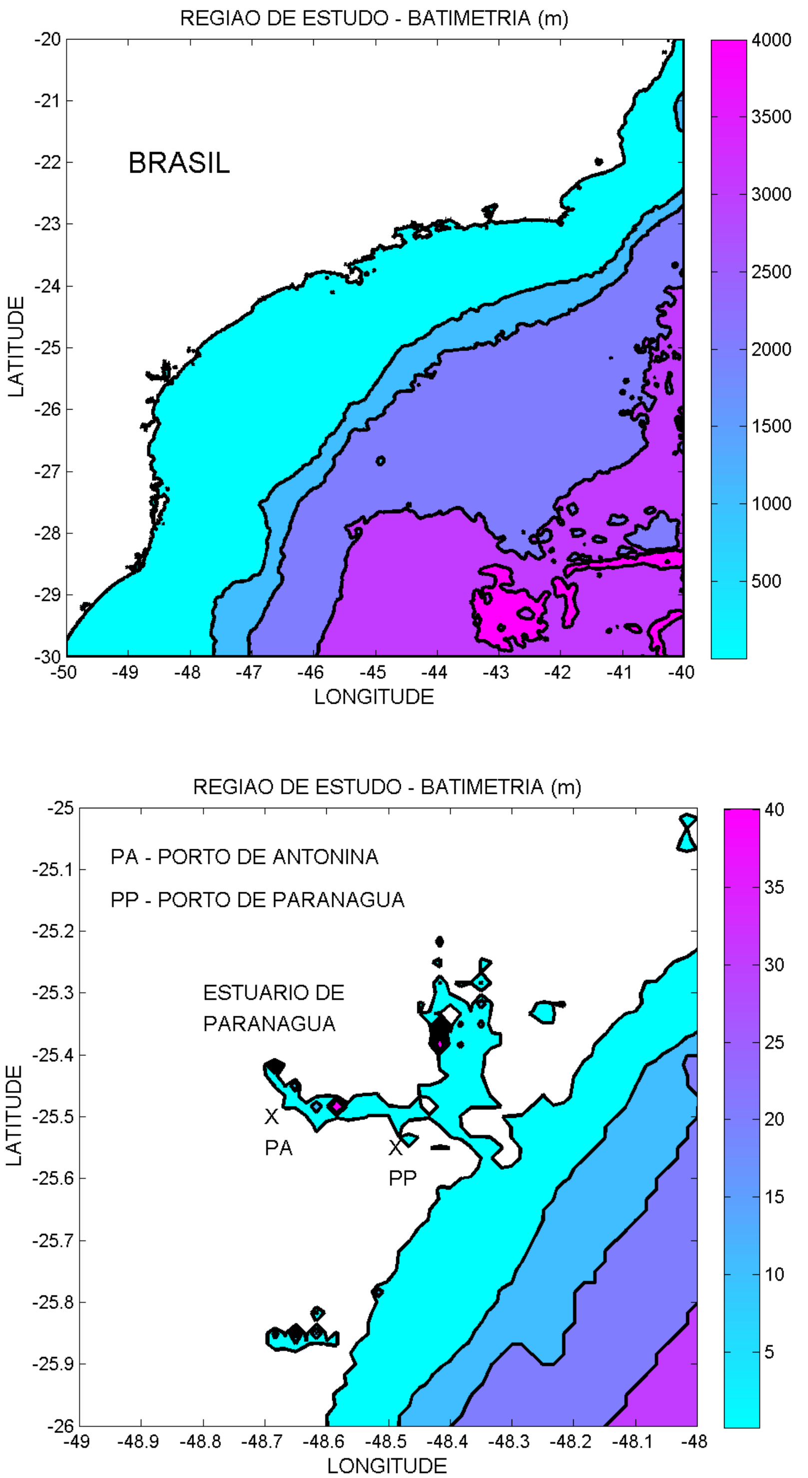

Figure 1-1 - Coastal Region of Paranaguá and location of Antonina and Paranaguá Ports (PA and PP).

The intensity, duration and interval between these events have seasonal and interannual variability. In general, in the Brazilian Southeast coast, the winds from the east quadrant have low intensity (typically less than 5 m/s) and long duration (5-10 days), while the turning to winds from the North and West quadrants occurs rapidly with scale of hours and high intensity (indicating arrivals of frontal systems). The winds from the South quadrant are more intense (around 10 m/s), with duration of 1 to 3 days.

One of the main consequences of the meteorological conditions is the wave fields generated by the winds on the ocean surface. The highest waves observed in the Brazilian Southeast coast are generated in middle and high latitudes from storms originating in the low pressure centers that come from Antarctica, associated with cold fronts (Candella, 1997); these waves have direction ranging between SW and SE, reaching the entire South – Southeast Brazilian coast (Siegle & Asp, 2007). In addition to the waves generated in the middle and high latitudes, waves of significant amplitude come from the East and Northeast, influenced by prevailing winds, associated with the South Atlantic High Pressure Center (Seixas, 1997).

The circulation in the Southeastern Brazilian platform is dominated by tidal and wind forcing, with strong bathymetric influence. Tidal currents are weak and rotating in time with the major axis approximately perpendicular to the coast, while the currents generated by the prevailing winds are persistent and a little stronger, to West - Southwest (parallel to the coast), turning to the East - Northeast (in general more intense) under the influence of frontal systems and waves. However, near the Estuarine Complex of Paranaguá, and within this complex, the hydrodynamics is governed by two main driving forces: river discharges and tides. By continuity, tidal currents are very intense on the entrance channels of this complex (Ribas, 2004).

The tide in the Bay of Paranaguá has an average range of 2.2 m, is predominantly semi-diurnal, with diurnal inequalities, and has a strong asymmetry in elevations and tidal currents. The tide has an amplification and increasing asymmetry towards the inner parts of Paranaguá Bay, characterized by a short period of tidal descending and a long period of tidal ascending (Campbell, 1998; Marone et al, 1995).

III – DATA AND METHODOLOGY

The methodology was based on statistical, spectral and tidal analysis of time series of the direct measurements and time series generated by satellite observations and model results in selected points. The characteristics of the hydrodynamics and sea level in the region of interest were inferred by comparing the parameters of the time series analyses. Maps of the distributions of remote sensing data and model outputs were also used in the analyses. Next, the five sets of data used in the study are described.

III.1 – Results of the global meteorological model

Meteorological data produced by reanalysis of the global atmospheric model from the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP / NCAR) (Kalnay et al., 1996) were used for analyzing the meteorological conditions in the coastal region of Paranaguá, being available at

(http://www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml).

Sea surface data were considered, in April 2014, at intervals of 6 hours, interpolated to a position close to the Estuary of Paranaguá, in 25.5º S 048.0º W, whereas the grid resolution of 2.5° x 2.5°. The series analyzed were surface values of: air temperature, atmospheric pressure at sea level, relative humidity, precipitable water, East-West wind component (EW) and North-South wind component (NS), and the composition of these last two, as the wind intensity - a total of 7 time series, 120 sampling points for each variable.

All series were initially represented in graphical form and then were subjected to statistical analysis to obtain the parameters average, standard deviation, median, minimum, maximum, kurtosis and skewness, for the analyzed month.

III.2 - Measurements in Ilha do Mel

Meteorological measurements were performed, especially wind and gusts, by the National Institute of Meteorology - INMET in Ilha do Mel Island Station on position 25.4945°S 48.3259°W, in the period from 01 to 30 April 2014 through an automatic station

(http://www.inmet.gov.br/portal/css/content/topo_iframe/pdf/Nota_Tecnica-Rede_estacoes_INMET.pdf).

The meteorological measurements were subjected to the same analytical procedures of the meteorological data of the global model of NCEP / NCAR.

III.3 - Satellite altimetry measurements

Absolute dynamic topography, significant wave height and wind intensity data measured by satellite altimetry and provided by AVISO ALTIMETRY were used.

(http://www.aviso.altimetry.fr/en/data.html). These data were obtained in gridded form, in the region 30°S-20°S 50°W-40°W, with spatial resolution of 1° x 1° and daily time resolution. The time series of 30 altimetry daily data at position 26°S 48°W, in April 2014, were analyzed by statistical and spectral methods.

III.4 - Numerical modeling of waves

Wave information in the coastal region of Paranaguá was obtained from the global waves model NWW3 of NOAA / NCEP (Tolman, 1997, 1999), available at

ftp://polar.ncep.noaa.gov/pub/history/waves . The NWW3 model (WaveWatch III) is a model of third generation that solves the equation of spectral density balance for the directional spectrum of waves. The model parameterizations include the growth and decay of waves as function of the wind action, nonlinear resonant interactions, dissipation and friction with the bottom. The wave propagation is considered linear. The governing equations of the NWW3 model include refractive processes and changes in the field of waves due to spatial and temporal variations of depths.

Significant wave heights, peak periods and directions of waves were obtained at intervals of 03 hours, in April 2014, for the region 30°S-20°S 50°W-40°W, with 30' resolution. Data close to the estuarine complex of Paranaguá, in position 26°S 48°W, were analyzed using statistical and spectral methods.

III.5 – Hydrodynamical numerical modeling

The hydrodynamic numerical modeling system Delft3D-FLOW (Deltares, 2012) solves the shallow water equations and transport properties in two dimensions (2D, vertically integrated) or three-dimensions (3D). The system of equations consist of equations of motion (horizontal), the continuity equation, the equation for transport of properties and conservative constituents (including heat and salt), equation of state of seawater and turbulent closing model. The equations are formulated in orthogonal curvilinear coordinates or spherical coordinates; rectangular grids (in Cartesian reference system) are considered as simplified forms of curvilinear grids.

The hydrodynamic model implemented used an inclined sloping grid, with horizontal spacing around 285 m, containing 369 points in the direction parallel to the coast and 415 points in the direction perpendicular to the coast. Its bathymetry is shown in **Figure 3.5-1**, with maximum depths of about 55 meters. Two processing were performed, the first 2D (vertically integrated), for the simulation of tides, and the second 3D for the simulation of the effects of tides, winds and density together (including river flows); in these processing, 6 sigma equidistant vertical levels were considered (sigma between 0 and 1, at intervals of 0.2). Data processing was performed adopting time steps of 1 minute.

The tidal forcing in the open grid contours were specified from interpolations of the harmonic constants of main tidal components, provided by the global model TPXO of Egbert & Erofeeva (2002). Wind data at the surface were obtained from the global model of NCEP / NCAR, interpolated to the center point of the grid and to 1 hour intervals. Finally, elevation values in the contours, due to meteorological effects and density, were obtained from large-scale model processing (Camargo & Harari, 2001; Camargo, Harari & França, 2006), covering the South and Tropical Atlantic, with a nesting grid on the platform, which results are regularly made available on the Internet (www.model.iag.usp.br).

The hydrodynamic module was processed for the month of April 2014, a processing preceded by a meteorological assessment of this month.

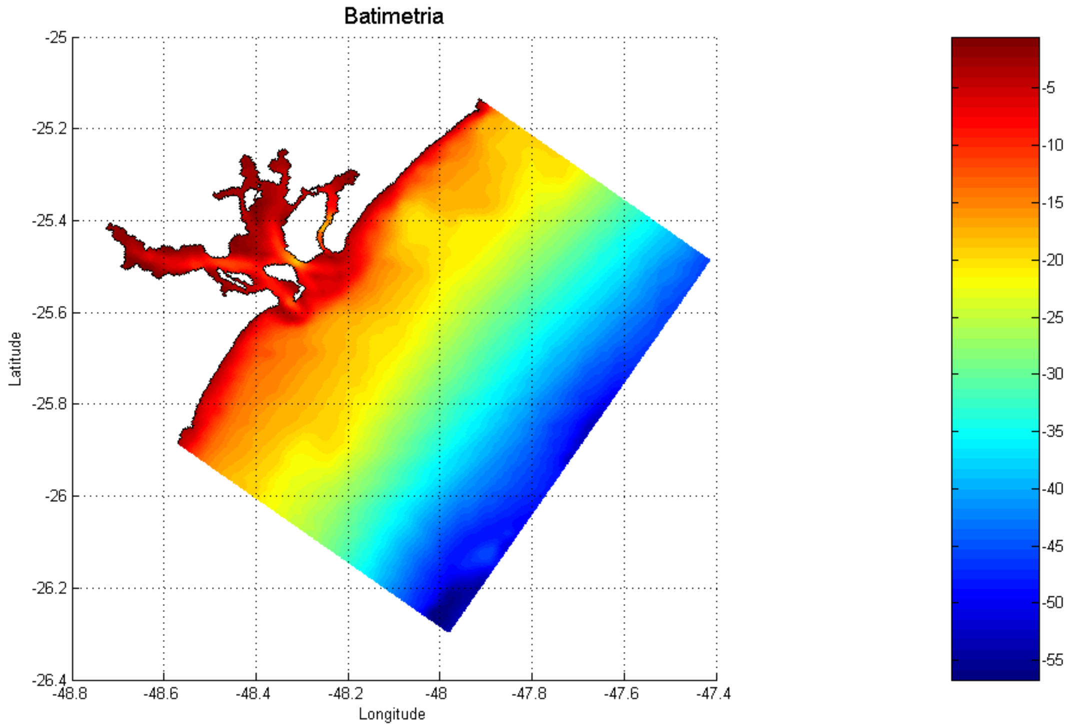

Figure 3.5-1. - Grid bathymetry used in hydrodynamic numerical modeling, with values in meters.

IV - RESULTS OF DATA PROCESSING

IV.1 - Meteorological information from global model

The time series of the meteorological variables for the month of April 2014, on the atmospheric pressure at sea level, air temperature and winds at the surface, calculated by the model of NCEP / NCAR, with interpolation to the coastal area of Paranaguá, are presented in **Figure 4.1-1**. The corresponding angular histogram of winds calculated by the model, for April 2014, is shown in **Figure 4.1-2**. Finalizing the processing of meteorological conditions in April 2014, the results of statistical analyzes of the time series are presented in **Table 4.1-1**.

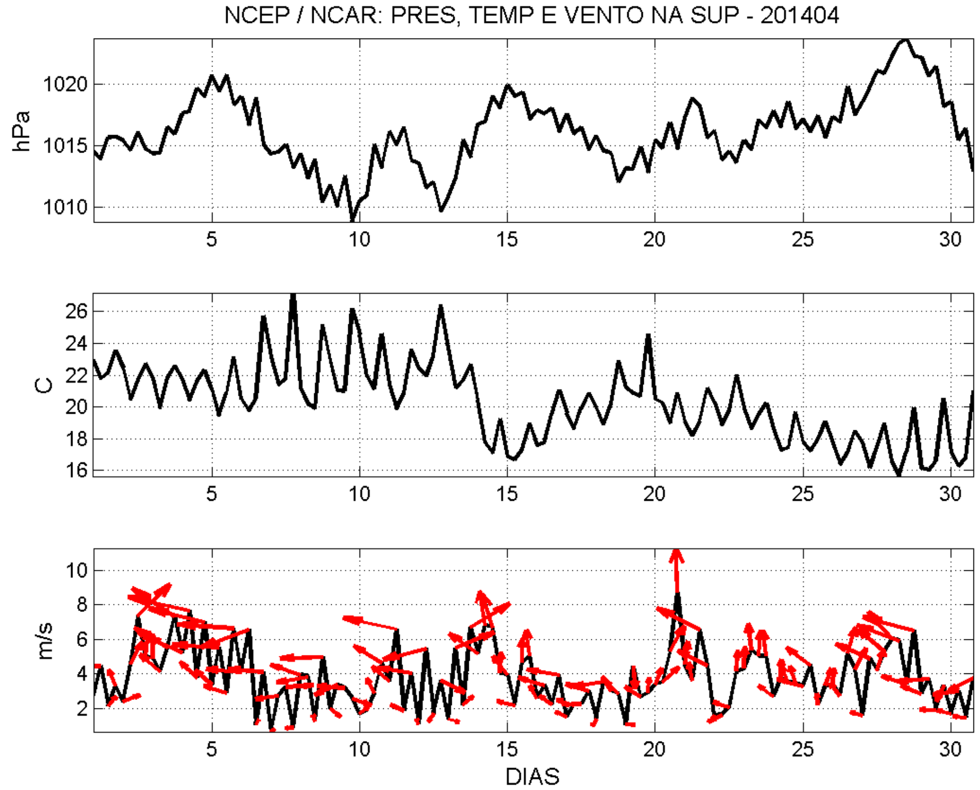

Figure 4.1-1 - Atmospheric pressure, air temperature and wind at the surface (intensities in black and vectors in red), calculated by the model of NCEP / NCAR for the month of April 2014, in the position 25.5º S 048ºW.

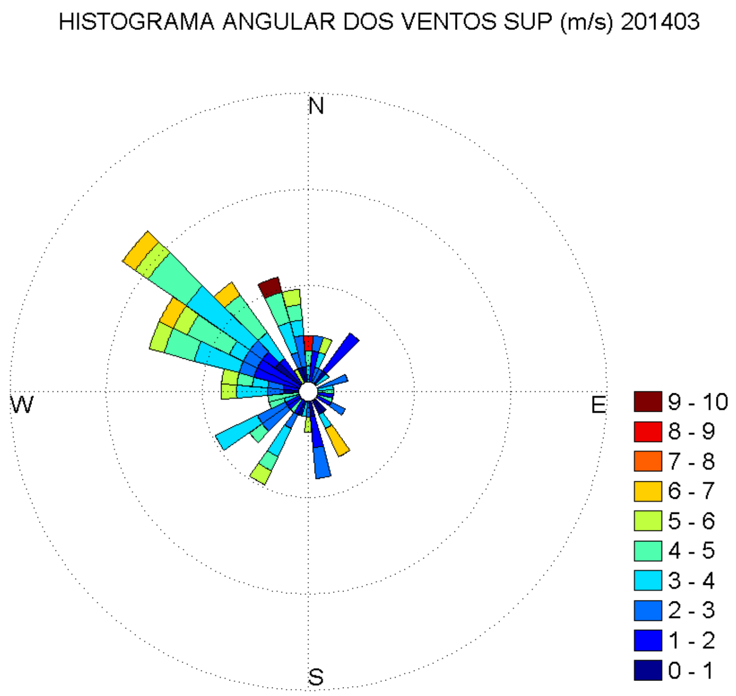

Figure 4.1-2 - Angular histogram of the winds at the surface (m/s), calculated by the model of NCEP / NCAR for the month of April 2014, in the position 25.5ºS 048ºW.

Table 4.1-1 - Basic statistics of NCEP / NCAR data in April 2014, referring to the mean, standard deviation, median, minimum, maximum, kurtosis and skewness, for the variables air temperature, pressure at sea level, relative humidity, precipitable water, EW and NS wind components and wind intensity at the surface.

	Mean	STD	Median	Minimum	Maximum	Kurtosis	Skewness
Air Tmp. (°C)	**20.29**	**2.44**	**20.33**	**15.64**	**27.18**	**2.88**	**0.32**
Pres. (hPa)	**1016.13**	**2.97**	**1016.11**	**1008.82**	**1023.71**	**2.94**	**0.10**
Rel. Hum.(%)	**94.58**	**7.07**	**96.01**	**64.20**	**100.00**	**8.26**	**-2.20**
Prec (kg/m2)	**32.15**	**8.45**	**31.67**	**16.46**	**51.62**	**2.30**	**0.10**
EW (m/s)	**-1.44**	**2.34**	**-1.21**	**-7.18**	**4.61**	**2.96**	**-0.06**
NS (m/s)	**2.01**	**2.37**	**2.14**	**-4.44**	**8.75**	**2.98**	**-0.17**
Wind (m/s)	**3.77**	**1.69**	**3.55**	**0.64**	**8.75**	**2.76**	**0.46**

IV.2 - Meteorological measurements in Ilha do Mel

Measurements in Ilha do Mel Island, during the month of April 2014, are presented as time series of pressure, temperature and wind speed (**Figure 4.2-1**) and the angular histograms of winds and gusts (**Figures 4.2-2 and 4.2-3**). **Tables 4.2-1 and 4.2-2** contain the results of the statistical treatment of the meteorological time series, relative to the sampling period.

Note that, for the wind and gusts directions in Ilha do Mel, the convention of meteorological instruments was adopted, i.e., the direction from which the wind is coming from, originating in the North and positive clockwise (thus 0° direction corresponds to North wind, 90° direction to East wind, etc ...).

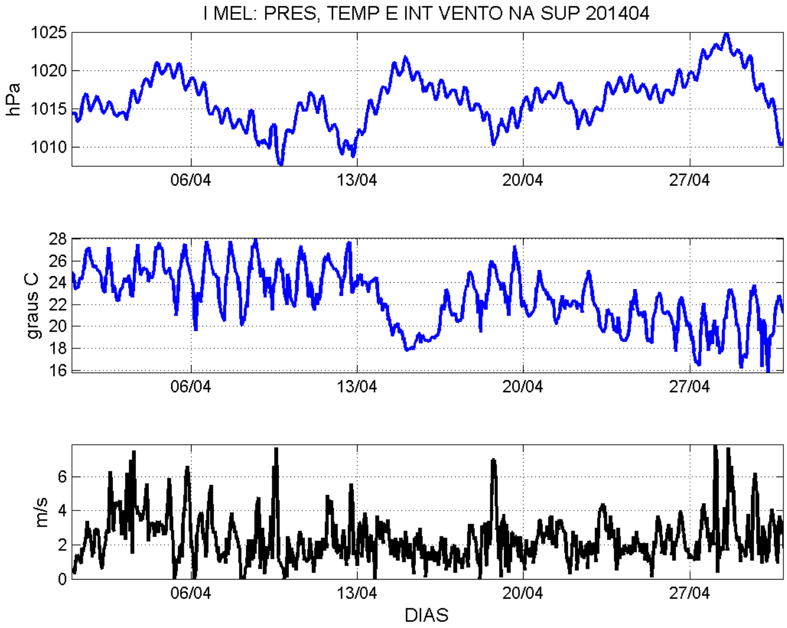

Figure 4.2-1 – Time series of pressure, temperature and wind speed measured at Ilha do Mel, in April 2014.

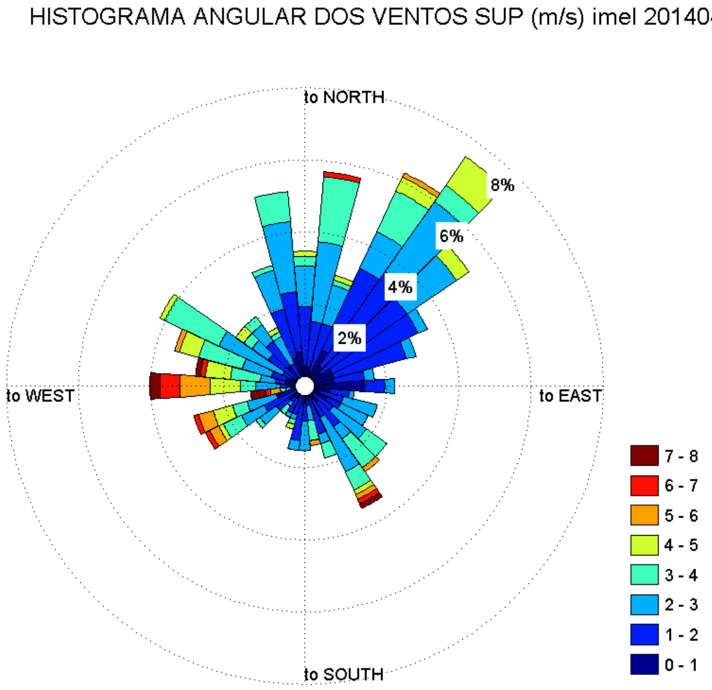

Figure 4.2-2 - Angular histogram of winds at the surface (m/s), according to measurements at Ilha do Mel, in April 2014.

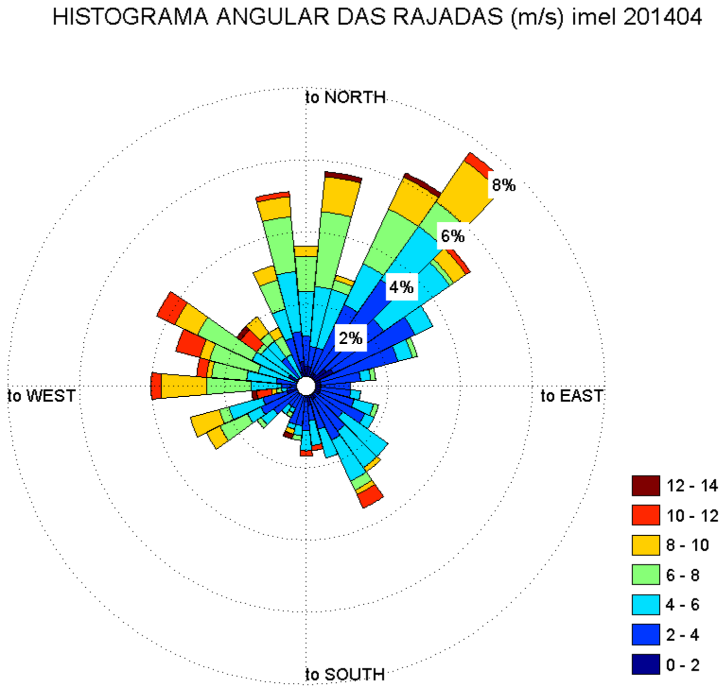

Figure 4.2-3 - Angular histogram of bursts at the surface (m/s), according to measurements at Ilha do Mel, in April 2014.

Table 4.2-1 - Basic statistics of the pressure, temperature, humidity, dew point, incident radiation and rainfall data in Ilha do Mel, in April 2014, related to the mean, standard deviation, median, minimum, maximum, kurtosis and skewness.

(m/s)	Mean	STD	Median	Minimum	Maximum	Kurtosis	Skewness
Pres (hPa)	1016.16	3.24	1016.20	1007.50	1025.00	2.85	0.01
Temp (°C)	22.55	2.57	22.60	15.80	28.10	2.35	-0.16
Humid (%)	83.71	8.47	85.00	52.00	95.00	3.11	-0.75
Dew p. (°C)	19.55	2.34	20.30	12.90	23.90	2.22	-0.52
Rad (kJ/m2)	503.60	804.81	3.83	-3.54	3218.00	4.70	1.65
Prec (mm)	0.36	1.69	0.00	0.00	22.40	74.90	7.67

Table 4.2-2 - Basic statistics of wind and bursts data in Ilha do Mel, in April 2014, related to the mean, standard deviation, median, minimum, maximum, kurtosis and skewness for the EW component, NS component and intensity.

(m/s)	Mean	STD	Median	Minimum	Maximum	Kurtosis	Skewness
WIND EW	-0.21	2.01	0.29	-7.82	3.69	4.32	-1.17
WIND NS	0.49	1.70	0.72	-6.86	6.11	3.40	-0.44
WIND INT	2.32	1.35	2.10	0.00	7.90	4.91	1.16
BURST EW	-0.35	3.93	0.75	-11.85	8.83	2.85	-0.73
BURST NS	1.56	3.74	1.89	-11.54	12.13	2.79	-0.19
BURST INT	5.10	2.43	4.50	0.70	12.50	2.99	0.76

IV.3 - Information obtained from satellite altimetry

The time series of absolute dynamic topography produced by satellite altimetry, at point 25.625°S 48.375°W, during the year of 2014, is shown in **Figure 4.3-1**, with its Fourier series in **Figure 4.3-2**. From the dynamic topography data were calculated geostrophic currents. **Figure 4.3-3** provides the annual mean geostrophic currents in the region 20°S-30°S 50°W-40°W and **Figure 4.3-4** provides the currents for the day 112, corresponding to April 22, when occurred the highest dynamic topography elevation of the entire year of 2014.

The information of most interest in the significant wave height measured by satellite altimetry is given in **Figures 4.3-5 to 4.3-7**, with distributions of the means and their standard deviations in the area 20°S-30°S 50°W-40°W, and the distribution of heights in the Julian day 112 (on 22 April).

Following the presentation of the results of greatest interest in the processing of altimetry data, **Figure 4.3-8** contains the wind speed histogram at position 26°S 48°W, for the year 2014.

Finalizing the information obtained from satellite altimetry, **Table 4.3-1** contains the results of the statistical analysis of time series data at the point 26°S 48°W, for the year 2014.

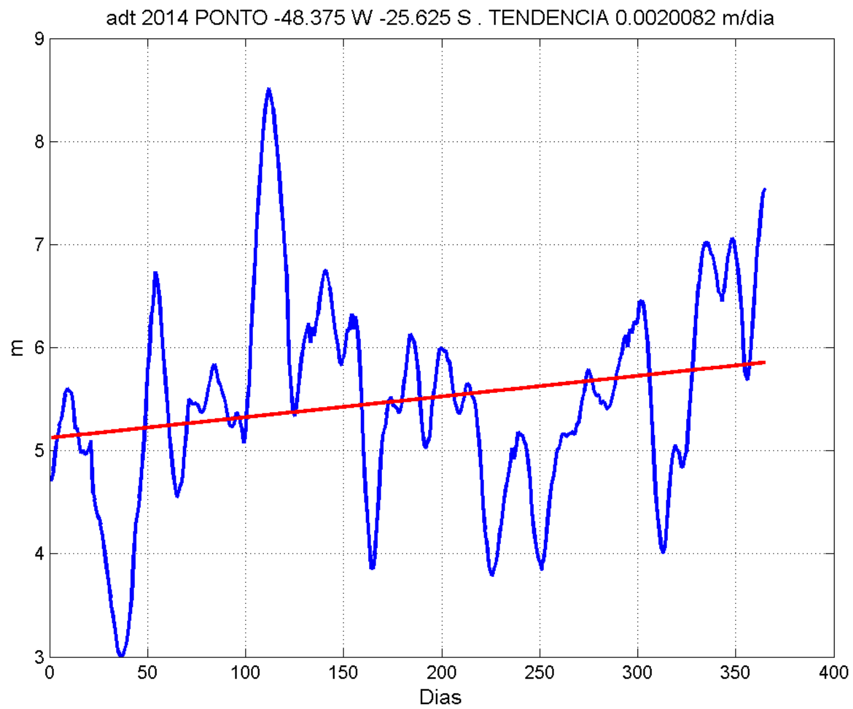

Figure 4.3-1 - Time series of absolute dynamic topography produced by satellite altimetry, at point 25.625°S 48.375°W, during the year 2014.

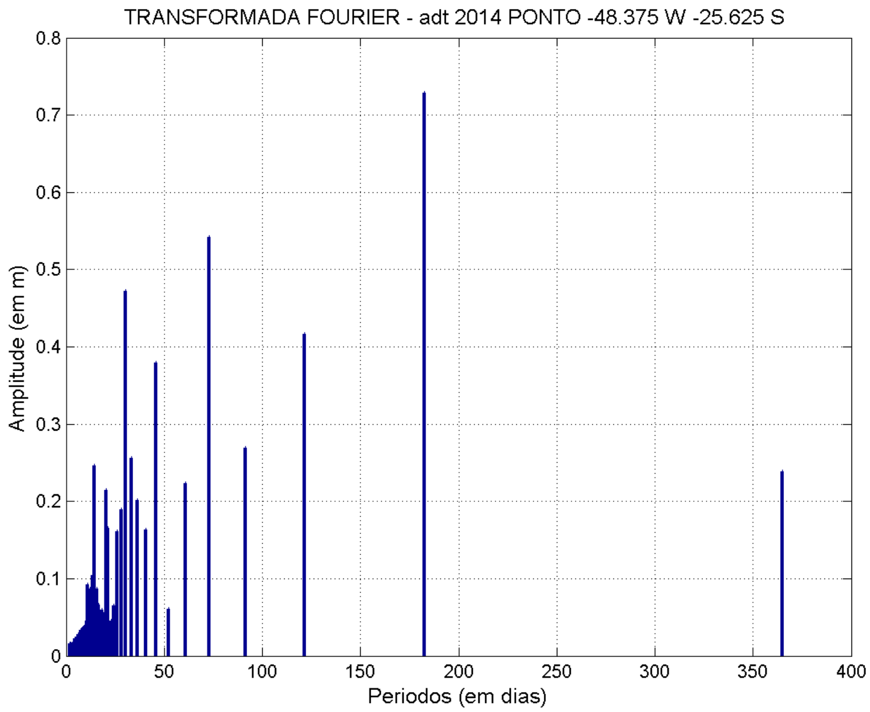

Figure 4.3-2 - Fourier Transform of time series of absolute dynamic topography produced by satellite altimetry, at point 25.625°S 48.375°W, during the year 2014.

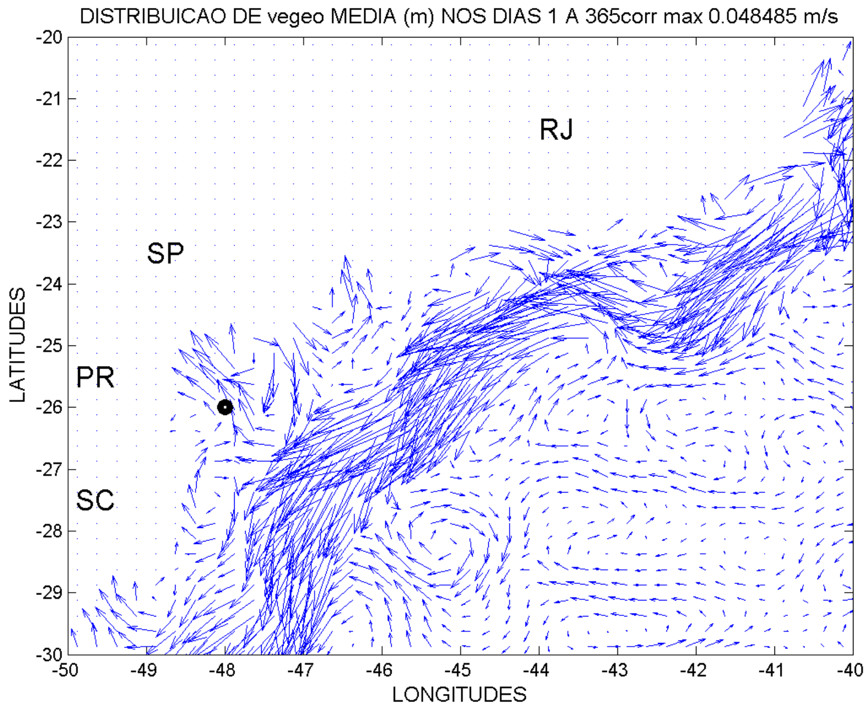

Figure 4.3-3 – Annual mean geostrophic currents in the region 20°S-30°S 50°W-40°W, in 2014 (black dot marks the position 26°S 48°W, at the entrance of the Estuary of Paranaguá).

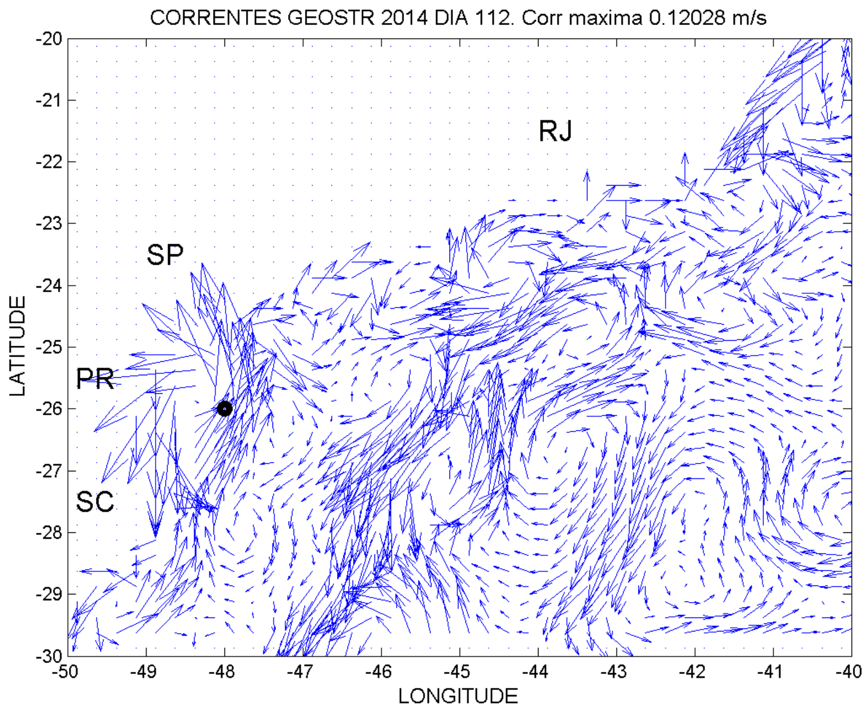

Figure 4.3-4 - Geostrophic currents at 20°S-30°S 50°W-40°W region, for the day 112, corresponding to the day April 22, 2014 (black dot marks the position 26°S 48°W, at the entrance of the Estuary of Paranaguá).

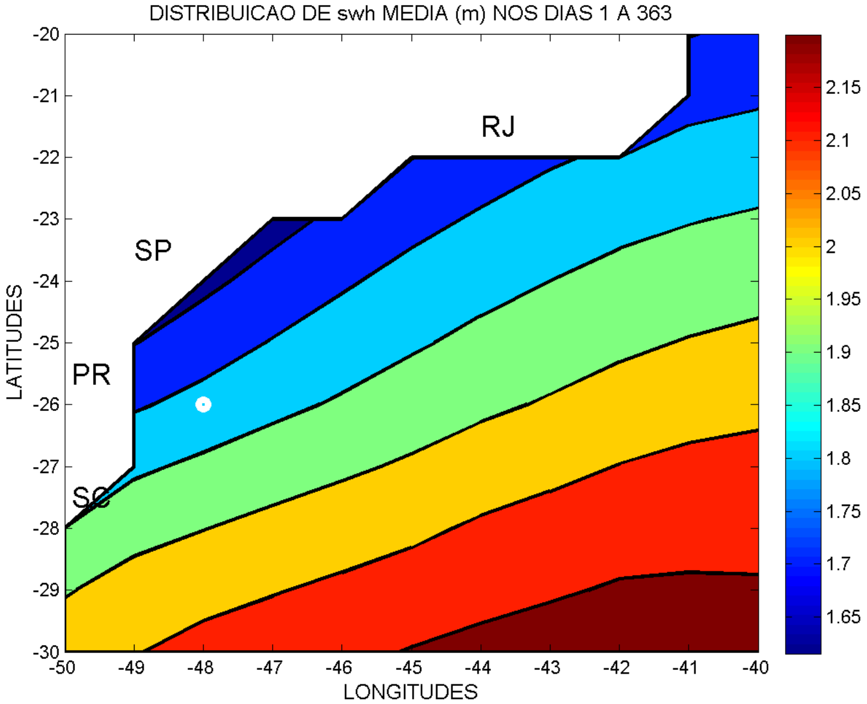

Figure 4.3-5 – Distribution of annual means of the significant wave height measured by altimetry, in the region 20°S-30°S 50°W-40°W, in 2014 (white dot marks the position 26°S 48°W, at the entrance of the Estuary of Paranaguá).

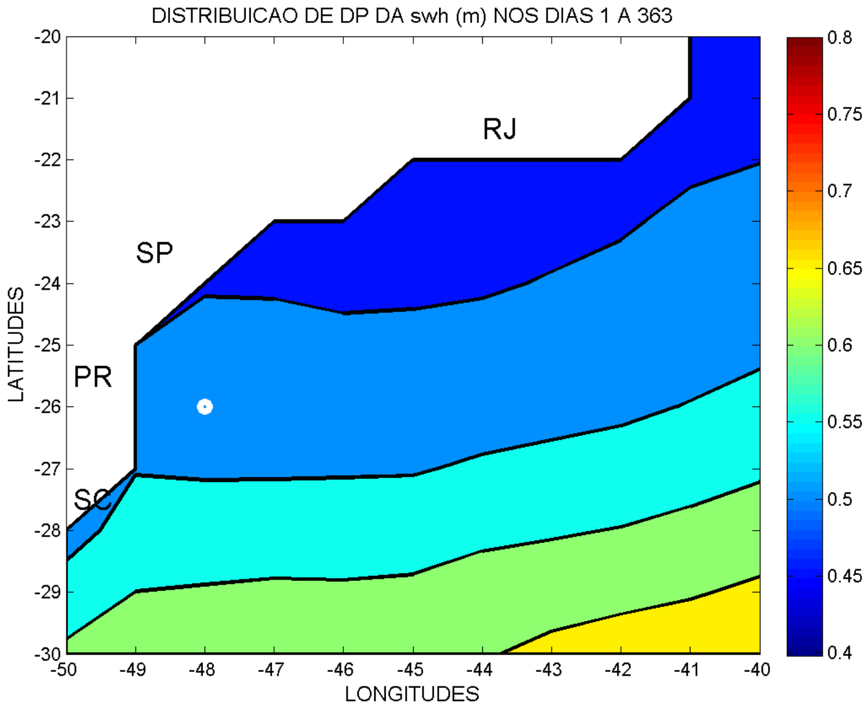

Figure 4.3-6 – Distribution of standard deviations from the mean of the significant wave height measured by altimetry, in the region 20°S-30°S 50°W-40°W, in 2014 (white dot marks the position 26°S 48°W, at Paranaguá Estuary entrance).

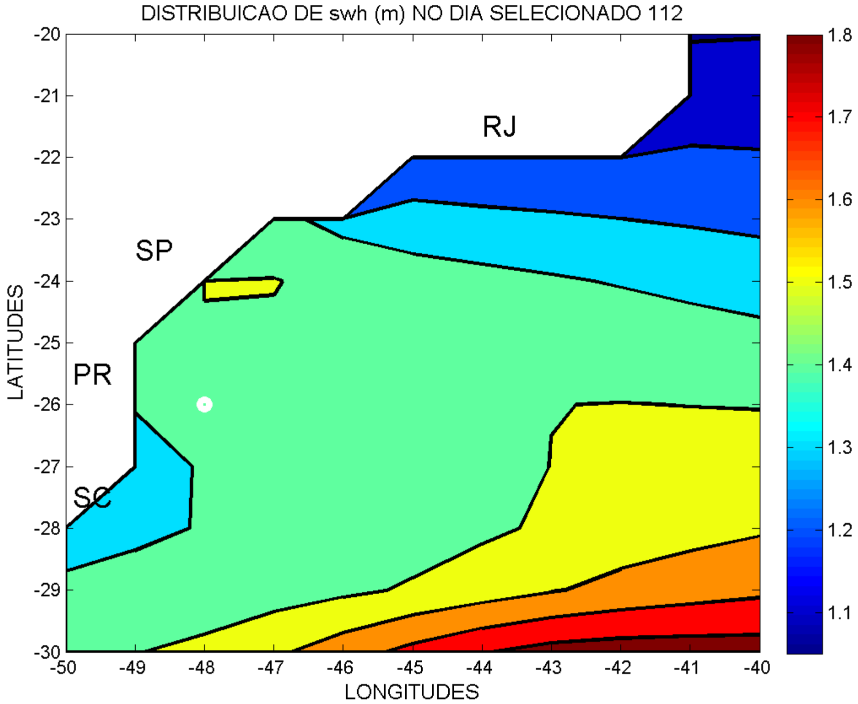

Figure 4.3-7 – Distribution of significant wave heights measured by altimetry, in the region 20°S-30°S 50°W-40°W, on 22 April 2014 (white dot marks the position 26°S 48°W, at the entrance of the Estuary of Paranaguá).

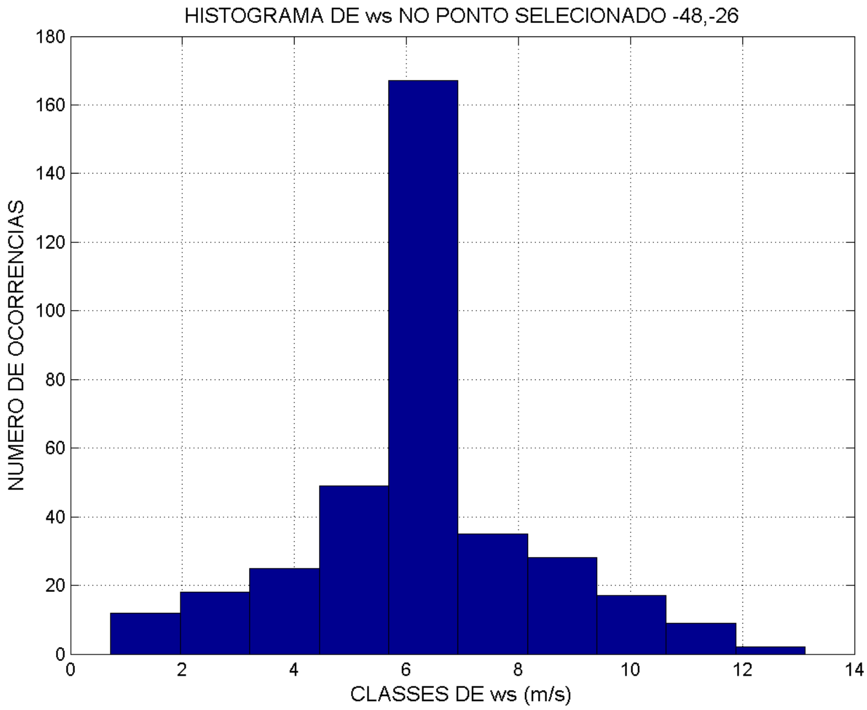

Figure 4.3-8 - Histogram of wind intensity at the surface measured by altimetry, at position 26°S 48°W, during the year 2014.

Table 4.3-1 - Basic statistics of dynamic topography, significant wave height, wind speed, EW component of geostrophic current, NS component of geostrophic current and intensity of geostrophic current, provided by satellite altimetry, at position 26°S 48°W in 2014, referring to the mean, standard deviation, median, minimum, maximum, kurtosis and skewness.

	Mean	STD	Median	Minimum	Maximum	Kurtosis	Skewness
Dyn. Top. (m)	5.49	1.00	5.46	3.01	8.52	3.54	0.19
Wave heigh (m)	1.84	0.51	1.78	0.92	3.92	4.49	0.99
Wind int. (m/s)	6.31	2.01	6.46	0.72	13.12	4.00	0.00
EW geos (m/s)	-0.01	0.02	-0.01	-0.04	0.04	2.65	0.54
NS geos (m/s)	0.01	0.02	0.01	-0.06	0.08	4.19	0.01
Int. geos (m/s)	0.03	0.02	0.02	0.03	0.08	4.30	1.08

IV.4 – Results of numerical modeling of waves

The time series of significant wave height, period and direction, calculated by NWW3 model at position 26°S 48°W, in April 2014, are shown in **Figures 4.4-1 to 4.4-3**. The angular histogram of significant wave heights by directions is in **Figure 4.4-4** and **Figure 4.4-5** contains the distribution of maximum monthly values of the significant wave heights produced by NWW3 model for the region 20°S-30°S 50°W-40°W, in April 2014. Finishing the presentation of results of the wave propagation model, **Table 4.4-1** contains the basic statistics of the significant height of the waves, period and direction, provided by the NWW3 waves propagation model, at position 26°S 48°W, in April 2014.

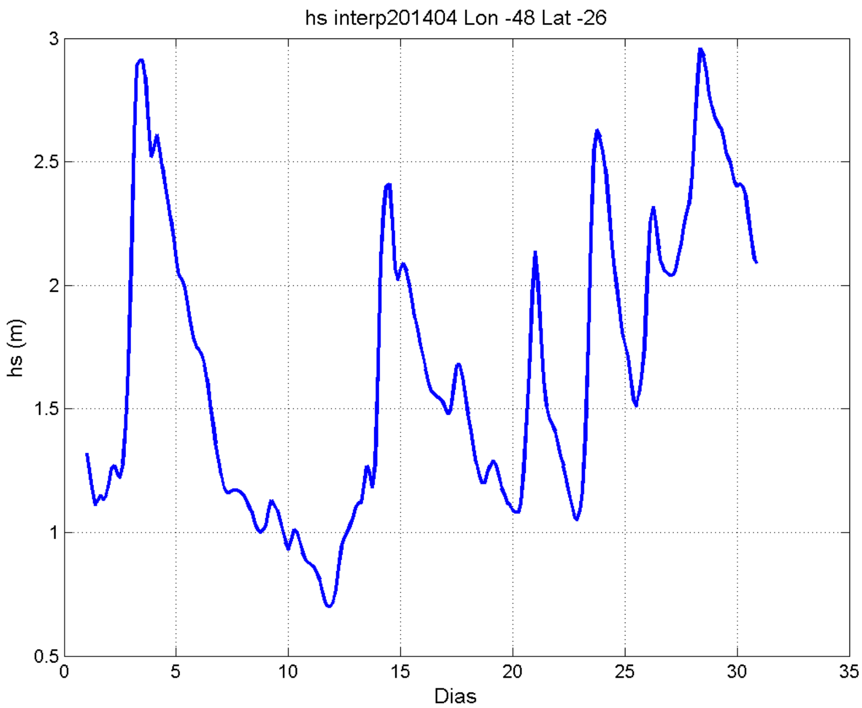

Figure 4.4-1 - Time series of significant wave heights produced by NWW3 wave model, at the point 26°S 48°W, in April 2014.

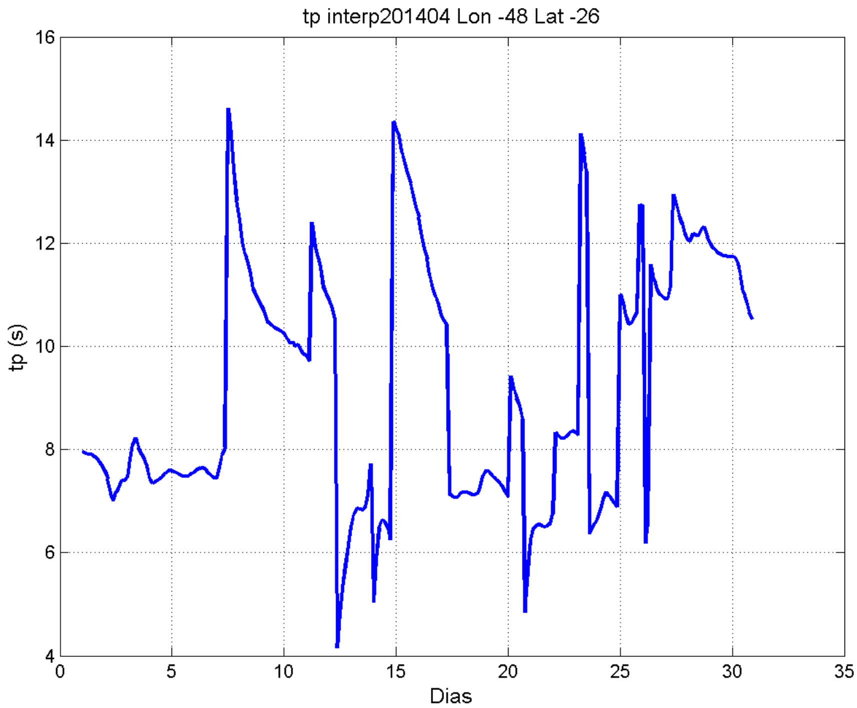

Figure 4.4-2 - Time series of peak wave period, produced by the NWW3 wave model, at the point 26°S 48°W, in April 2014.

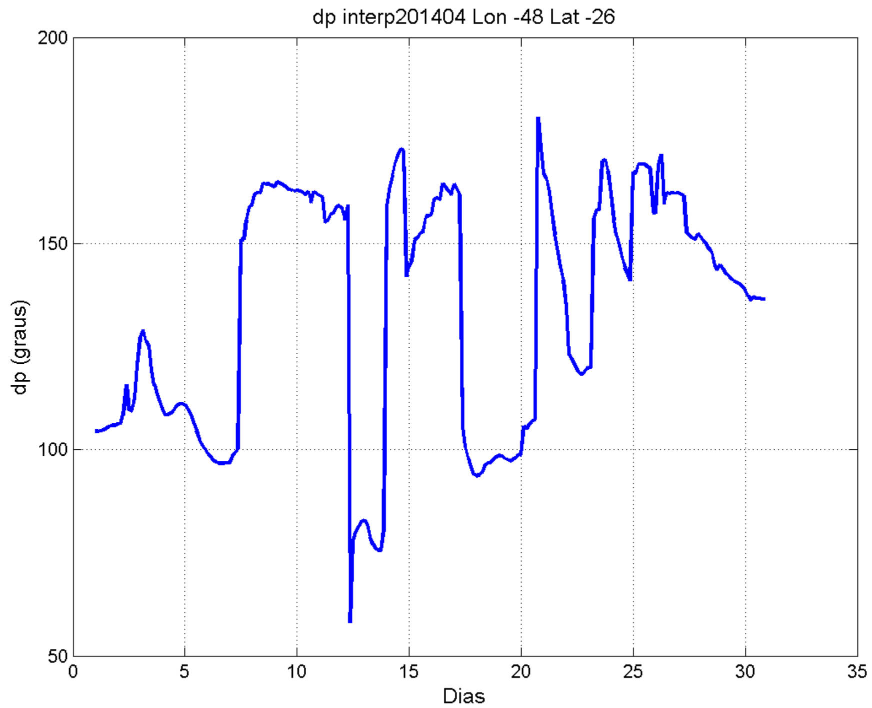

Figure 4.4-3 - Time series of wave direction, produced by the NWW3 wave model, at the point 26°S 48°W, in April 2014.

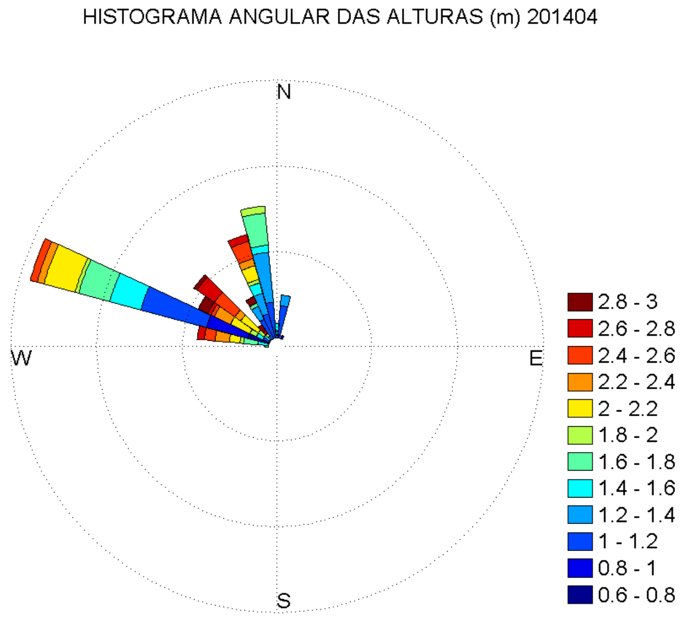

Figure 4.4-4 - Angular histogram of the significant height of the waves by the direction, produced by the NWW3 wave model, at the point 26°S 48°W, in April 2014.

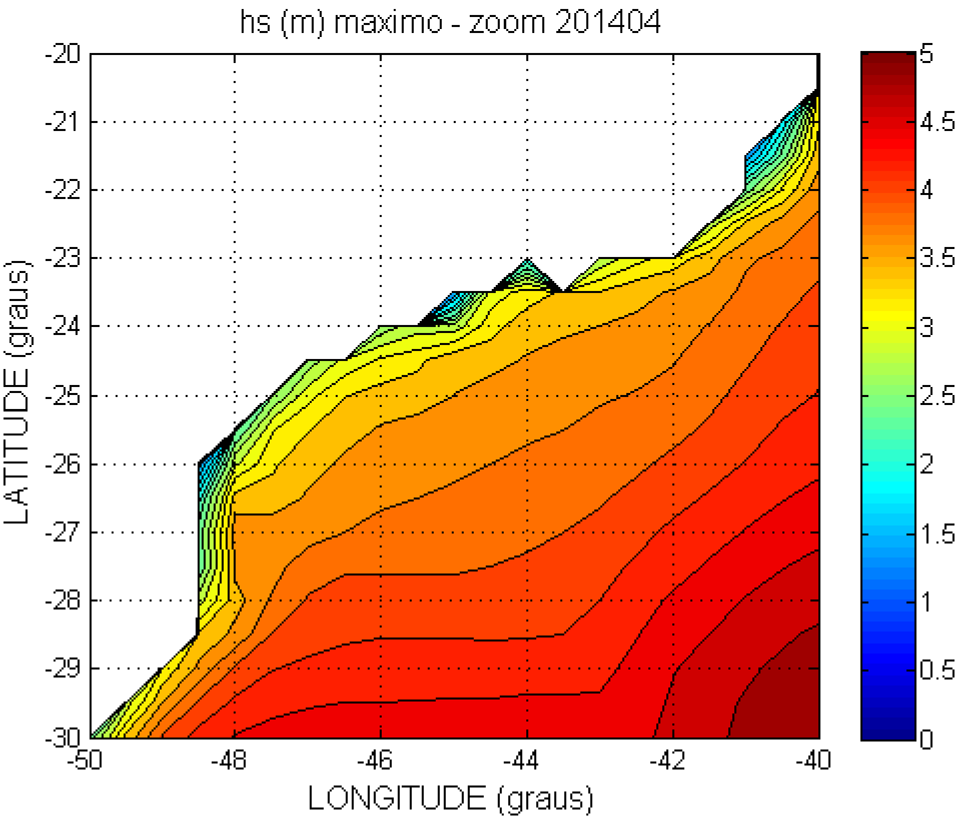

Figure 4.4-5 - Distribution of maximum monthly values of significant wave heights, produced by the NWW3 wave model for the region 20°S-30°S 50°W-40°W, in April 2014.

Table 4.4-1 - Basic statistics of significant height of waves, period and direction, provided by NWW3 wave propagation model, at position 26°S 48°W, in April 2014, referring to the mean, standard deviation , median, minimum, maximum, kurtosis and skewness.

	Mean	STD	Median	Minimum	Maximum	Kurtosis	Skewness
Height (m)	**1.66**	**0.59**	**1.56**	**0.70**	**2.96**	**2.02**	**0.42**
Period (s)	**9.21**	**2.38**	**8.25**	**4.15**	**14.62**	**1.91**	**0.33**
Direct. (°)	**133.89**	**29.06**	**142.57**	**58.16**	**180.74**	**1.77**	**-0.39**

IV.5 - Results of hydrodynamial numerical modeling

For the analysis of results of hydrodynamic modeling were considered a coastal point just outside the estuary and two control points in the South and North entrances of Paranaguá Estuarine Complex; the positions of these points are shown in **Figure 4.5-1 and Table 4.5-1** along with the positions of Paranaguá and Antonina Ports.

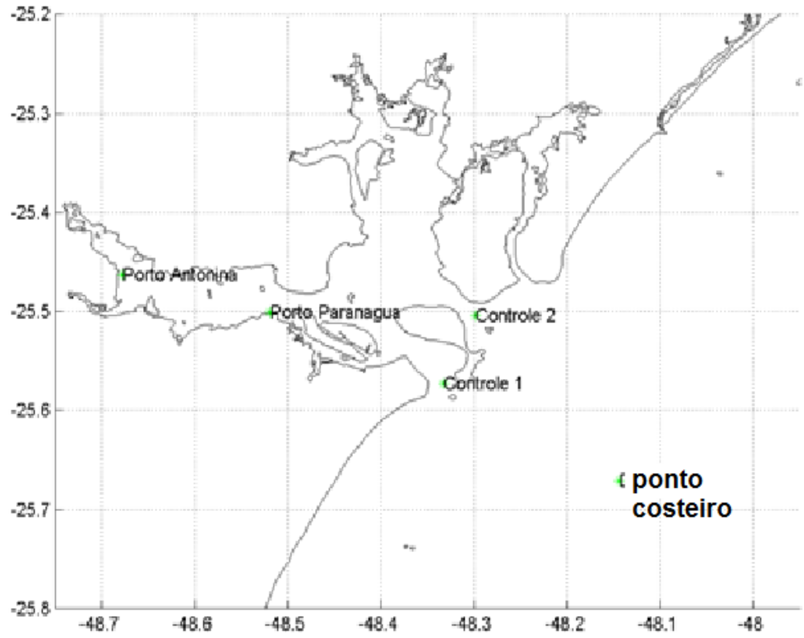

Figure 4.5-1 - Location of the coastal and control (01 and 02) points and Paranaguá and Antonina Ports.

Table 4.5-1 - Location of the coastal and control (01 and 02) points and Paranaguá and Antonina Ports.

	UTM - zone 22J		Decimal degrees	
	X	Y	Longitude	Latitude
Antonina Port	733910	7181800	-48.6736	-25.4624
Paranaguá Port	749720	7177300	-48.5157	-25.5005
Coastal Point	786655	7157609	-48.1443	-25.6715
Control 01	768370	7169000	-48.3286	-25.5722
Control 02	772000	7176500	-48.2940	-25.5040

The time series generated by the model in the processing of tides, for the Port of Paranaguá, was compared with harmonic prediction tide in this port, as shown in **Figure 4.5-2**. The comparative statistical analysis of these two series indicates correlation of 0.97 ± 0.00 and the series of differences has the following statistical parameters: mean 0.00 m; STD 0.11 m; and average of the absolute values 0.09 m. The Wilmott (1981) parameter for these two series (skill) is equal to 0.99.

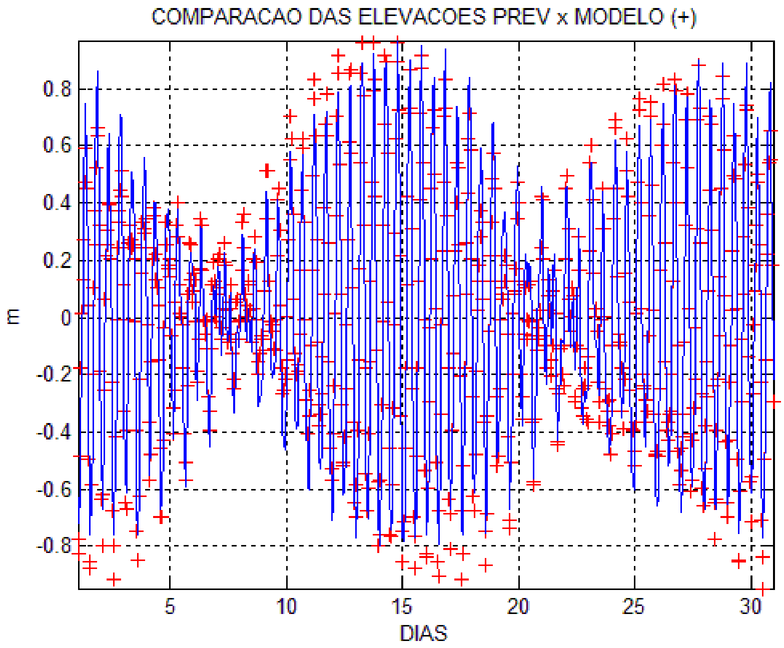

Figure 4.5-2 - Comparison of the model sea level results produced by the tide processing (red, +) with harmonic prediction (blue, solid line), for the Port of Paranaguá, in April 2014.

The model outputs for tide, wind and density forcing are shown in: **Figures 4.5-3 to 4.5-5**, comprising maps with currents in maximum ebb and flood conditions, in April 2014; in **Figures 4.5-6 to 4.5-8**, with time series of sea level and currents in the coastal and control points; in **Figures 4.5-9 to 4.5-11**, with angular histograms of surface currents in the same points; and **Figure 4.5-12** shows the time series of elevation of the mean sea level due to the wind and density gradients in the coastal point (excluding therefore the effects of tides from the total circulation).

The basic statistics of the surface elevation, EW and NS currents components and intensity of the currents at the surface, for the points of interest, is given in **Table 4.5-2**, containing the mean values, the standard deviation, median, minimum, maximum, kurtosis and skewness.

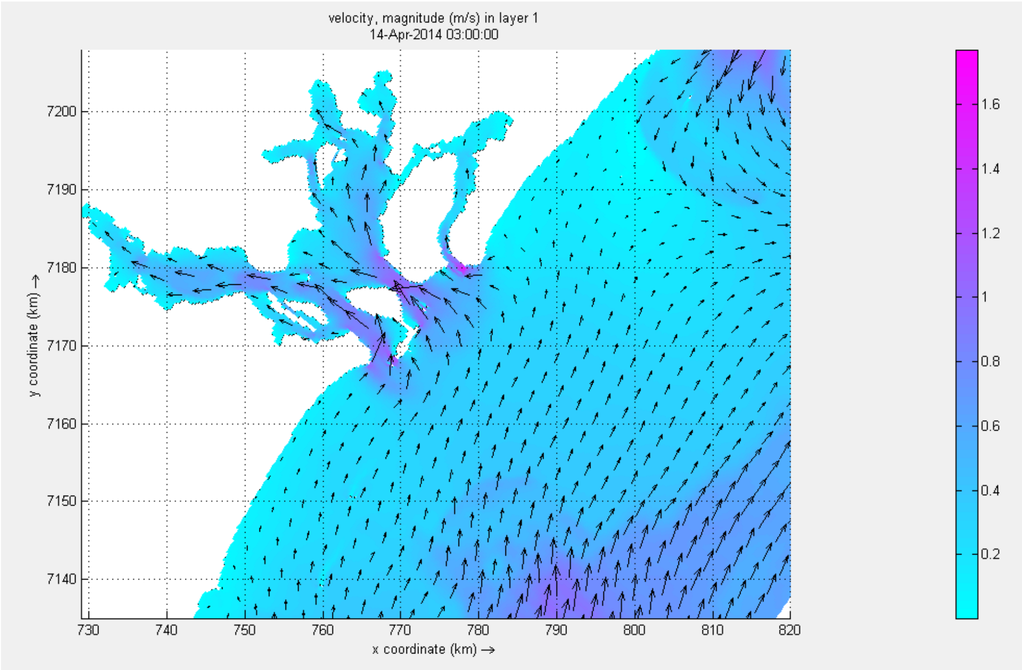

Figure 4.5-3 - Currents at the surface calculated by the model forced by the action of tides, winds and density (m/s), on condition of intense SW currents with frontal influence (at 3:00 GMT on April 14, 2014).

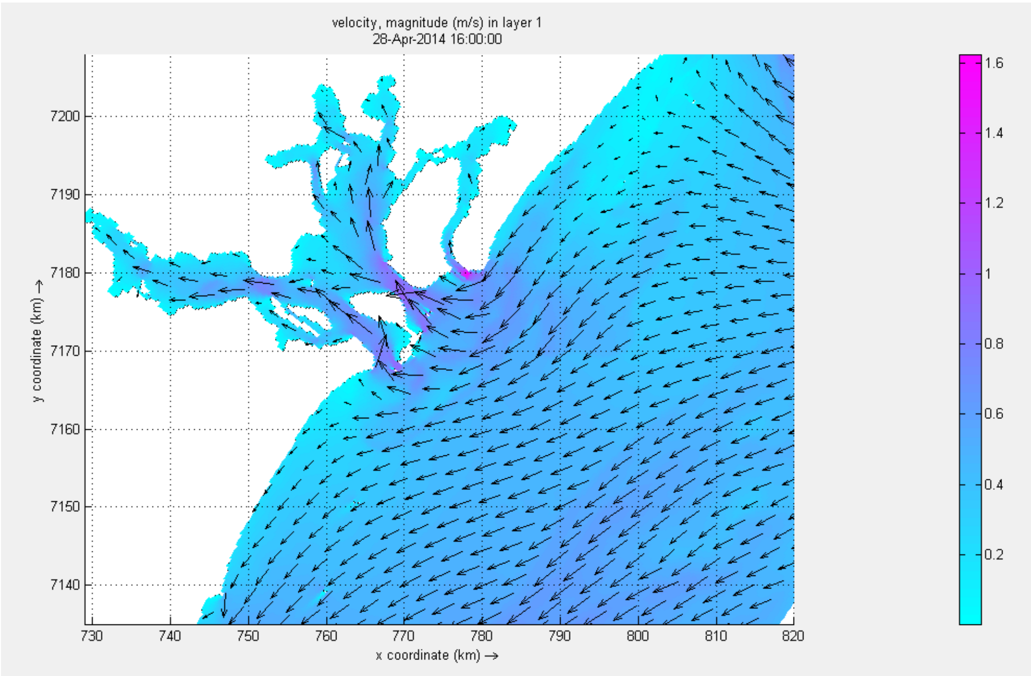

Figure 4.5-4 - Currents at the surface calculated by the model forced by the action of tides, winds and density (m/s), on condition of maximum flood without frontal influence (at 16:00 GMT on April 28, 2014).

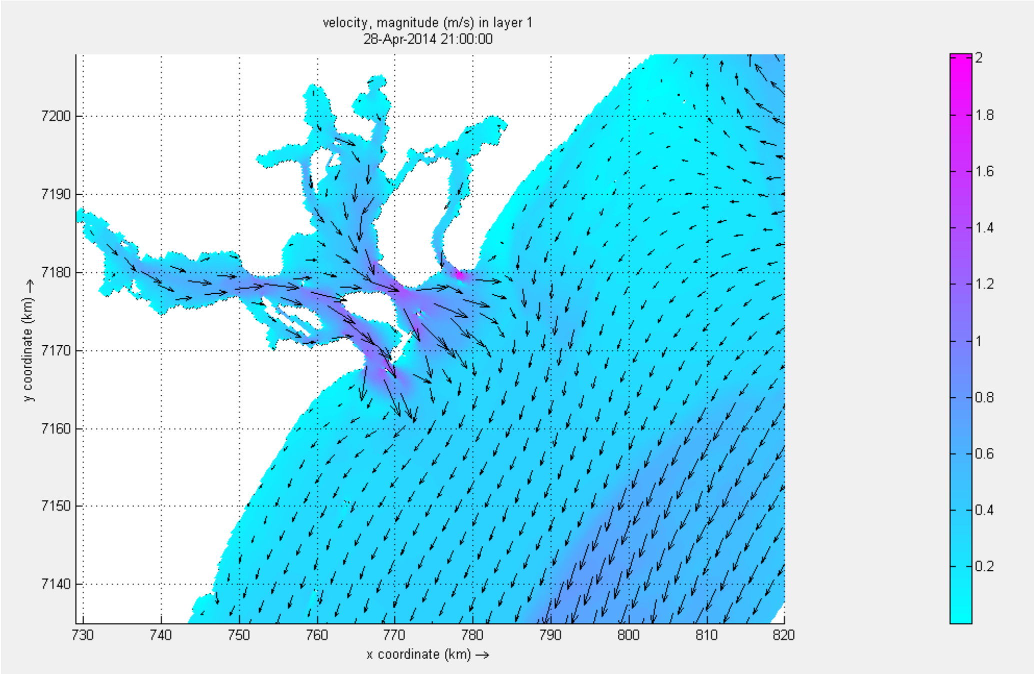

Figure 4.5-5 – Currents at the surface calculated by the model forced by the action of tides, winds and density (m/s), on condition of maximum ebb without frontal influence (21h00 GMT on April 28, 2014).

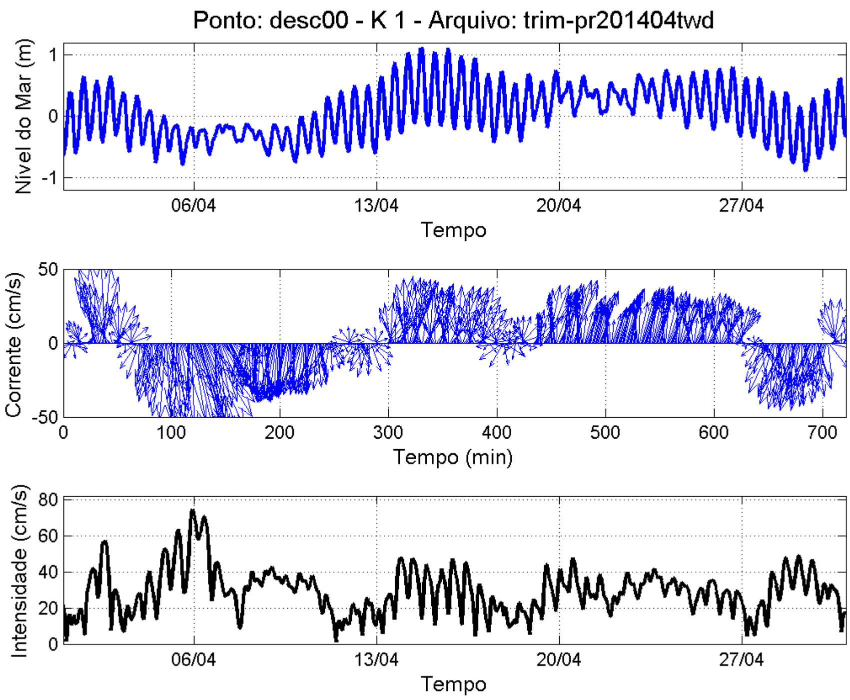

Figure 4.5-6 – Time series of sea level, vectors of currents and intensity of currents at the surface, in April 2014, calculated by the hydrodynamic numerical model forced by tides, winds and density, in the coastal point.

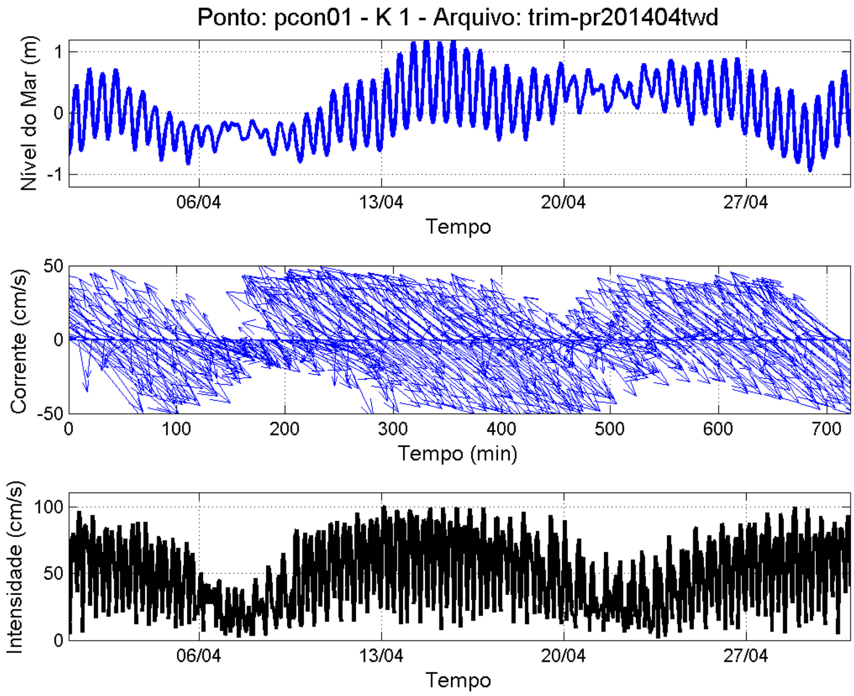

Figure 4.5-7 - Time series of sea level, vectors of currents and intensity of currents at the surface, in April 2014, calculated by the hydrodynamic numerical model forced by tides, winds and density, in the Control Point 01.

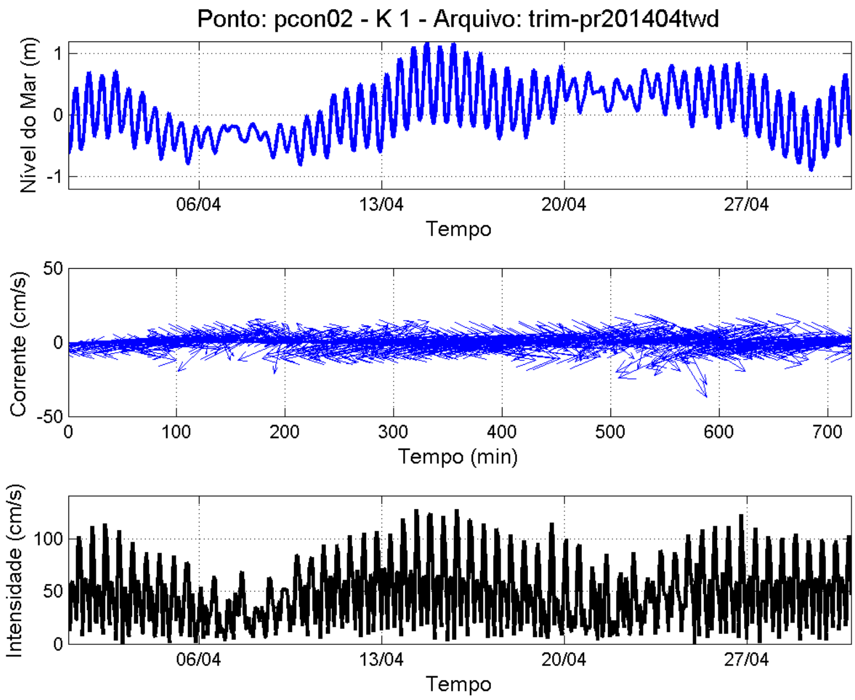

Figure 4.5-8 - Time series of sea level, vectors of currents and intensity of currents at the surface, in April 2014, calculated by the hydrodynamic numerical model forced by tides, winds and density, in the Control Point 02.

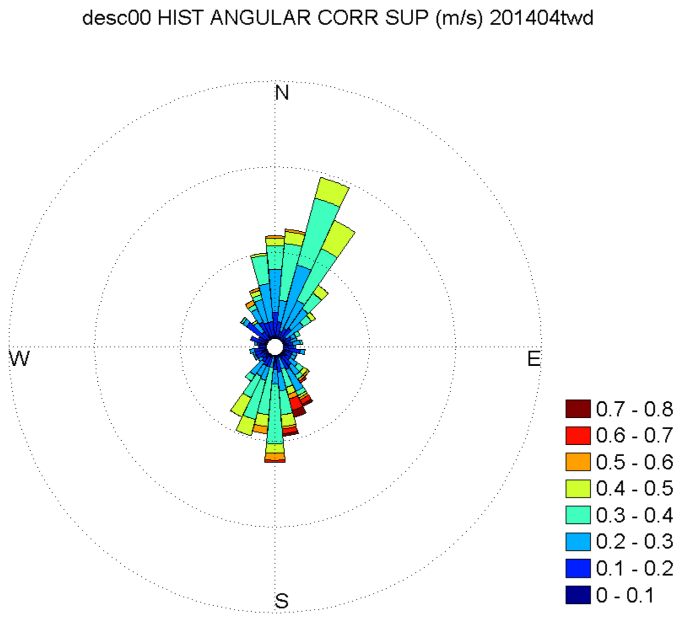

Figure 4.5-9 - Angular histogram (m/s) of the currents at the surface, according to model calculations for April 2014, in the coastal point.

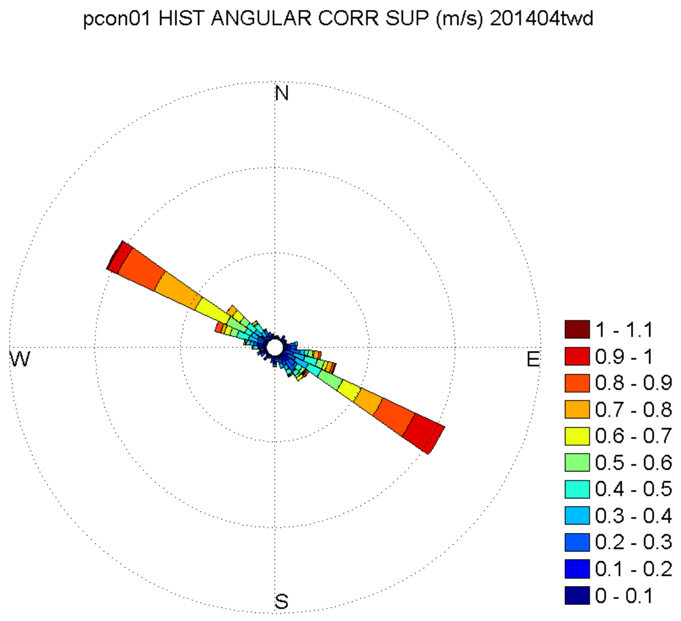

Figure 4.5-10 - Angular histogram (m/s) of the currents at the surface, according to model calculations for April 2014, in the Control Point 01.

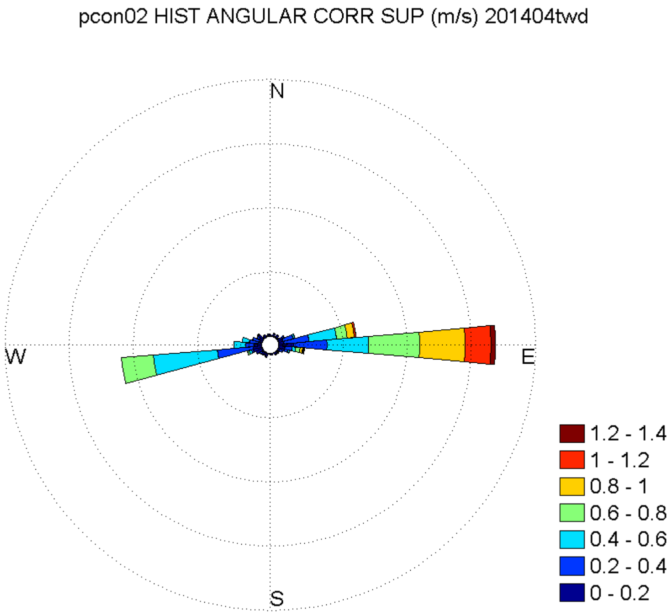

Figure 4.5-11 - Angular histogram (m/s) of the currents at the surface, according to model calculations for April 2014, in the Control Point 02.

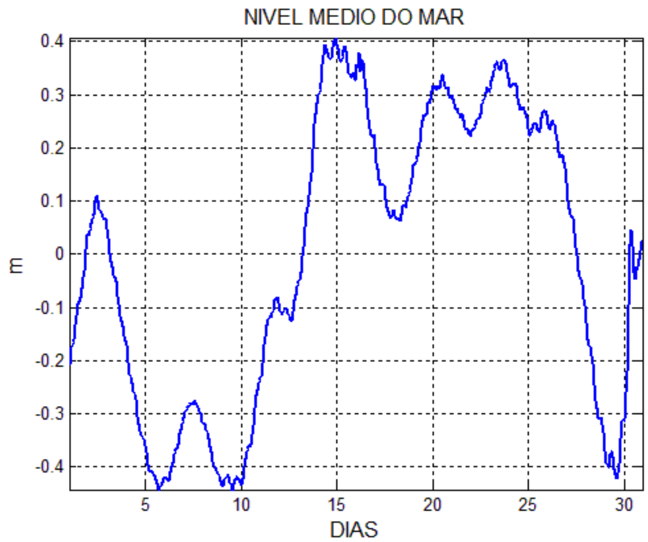

Figure 4.5-12 - Time series of mean sea level, computed by differences in surface elevation between model processing with tide and with all forcing, in April 2014, in the coastal point.

Table 4.5-2 - Basic Statistics of circulation due to tides, winds and density, calculated by hydrodynamic numerical model for the month of April 2014, with mean values, standard deviation, median, minimum, maximum, kurtosis and skewness for elevation, EW and NS components of currents and intensity of currents (at the surface), for the coastal point, Control Points 01 and 02 and the Paranaguá and Antonina Ports.

		Mean	STD	Median	Minimum	Maximum	Kurtosis	Skewness
Coastal point	Elev(m)	0,04	0,42	0,00	-0,89	1,11	2,26	0,19
	Ew(m/s)	0,03	0,13	0,04	-0,30	0,42	2,47	0,04
	Ns(m/s)	0,01	0,28	0,08	-0,71	0,56	1,97	-0,38
	In (m/s)	0,29	0,12	0,29	0,01	0,74	3,85	0,57
PC1	Elev(m)	0,05	0,46	0,01	-0,95	1,25	2,28	0,23
	Ew(m/s)	-0,00	0,47	0,02	-0,89	0,89	1,91	0,03
	Ns(m/s)	-0,01	0,28	-0,02	-0,57	0,52	1,91	-0,01
	In (m/s)	0,48	0,27	0,45	0,02	1,01	1,79	0,15
PC2	Elev(m)	0,05	0,44	0,03	-0,90	1,20	2,25	0,20
	Ew(m/s)	0,17	0,51	0,19	-0,72	1,28	1,95	0,11
	Ns(m/s)	-0,00	0,07	0,00	-0,37	0,15	3,91	-0,53
	In (m/s)	0,46	0,29	0,43	0,00	1,28	2,69	0,57
Para-naguá Port	Elev(m)	0,08	0,54	0,04	-1,09	1,48	2,29	0,24
	Ew(m/s)	0,08	0,27	0,07	-0,48	0,79	2,24	0,14
	Ns(m/s)	0,05	0,29	0,07	-0,67	0,61	2,08	-0,10
	In (m/s)	0,34	0,21	0,31	0,00	1,00	2,27	0,49
Anto-nina Port	Elev(m)	0,11	0,59	0,06	-1,18	1,61	2,23	0,21
	Ew(m/s)	0,01	0,17	0,00	-0,38	0,45	2,10	0,10
	Ns(m/s)	-0,01	0,05	0,00	-0,17	0,15	3,06	-0,18
	In (m/s)	0,15	0,09	0,15	0,00	0,47	2,66	0,47

V – DISCUSSION AND FINAL CONSIDERATIONS

An important point of this research was that, although considering data from different sources (direct measurements, remote sensing and models outputs), one objective was to extract as much information as possible from each data set and analysis, and not necessarily compare the respective extracted information. This is due to the well-known fact that these data sets have different spatial and temporal scales, generating then different observations of the same phenomena.

The period analyzed in this study April 2014 - corresponds to a month of autumn, in which three frontal systems passed through Paranaguá, on days 13, 20 and 24. Seasonal conditions and these frontal systems caused oscillations of meteorological parameters along the month, with temperature extremes between 15.64°C and 27.18°C and atmospheric pressure between 1008.82 hPa and 1023.71 hPa (**Figure 4.1-1 and Table 4.1-1**). Particularly notable are the temperature decrease between days 13 and 15 and between days 20 and 25, as well as the winds with strong components of South calculated by the model of NCEP / NCAR for these days. In the analyzed month, winds were predominantly east, with the average EW component of -1.44 ± 2.34 m/s, the average component NS of 2.01 ± 2.37 m/s and average wind speed of 3 77 ± 1.69 m/s (**Figure 4.1-2 and Table 4.1-1**).

The influence of frontal systems in the meteorological conditions in April in Paranaguá is also noted in the meteorological records of Ilha do Mel, which presented pressure, temperature and wind intensity fluctuations similar to those calculated by the model of NCEP / NCAR: during the month, the pressure varied between 1007.50 hPa and 1025.00 hPa, while the temperature was between 15.80°C and 28.10°C (**Table 4.2-1 and Figure 4.2-1**). In April 2014, the wind speed in Paranaguá ranged between 0 and 7.90 m/s and the intensity of bursts between 0.70 m/s and 12.50 m/s; there is a predominance of East winds and gusts, but with a large number of South and Southwest events, and also from the Northeast, due to the turning of the winds caused by the propagation of cold fronts (**Figure 4.2-2 and Table 4.2-2**).

Measurements of dynamic topography by altimetry during the year 2014 have shown that, close to the estuarine complex of Paranaguá, the maximum annual level was in the Julian day 122 (on April 22), reaching 8.52 m (**Figure 4.3-1 and Table 4.3-1**), as a result of the above mentioned cold fronts that propagated through Paranaguá. On the other hand, the Fourier analysis of the time series of dynamic height at point 26°S 48°W indicates that the maximum amplitude corresponds to the semi-annual period (182.5 days) with 0.73 m, followed by bimonthly (73.0 days) with 0.54 m, the monthly (30.4 days) with 0.47 m and four months (121.7 days) with 0.42 m (**Figure 4.3-2**). **Figure 4.3-3** shows the annual mean geostrophic current calculated by satellite altimetry, which clearly indicates the importance of the Brazil Current in the ocean dynamics of Southeastern Brazil. Returning the analysis to April 22, **Figure 4.3-4** shows the distribution of geostrophic speeds in that day, in which is notorious the presence of the Brazil Current in the shelf break flowing to Southwest, but with eddies associated with variations in atmospheric pressure, as well as strong currents from the South with counterclockwise rotation in the region of Paranaguá, due to frontal influence.

The sea state conditions, measured by satellite altimetry in the area 20°S-30°S 50°W-40°W, show annual mean significant wave heights in 2014 (and their standard deviations) decreasing from South to North and towards the coast, which also occurs in the distribution of heights on 22 April (**Figures 4.3-5 to 4.3-7**). In particular, for the point in front of the Estuary of Paranaguá, the significant wave height waves measured by altimetry had annual mean of 1.84 ± 0.51 m, with a minimum of 0.92 m and maximum of 3.92 m (**Table 4.3-1**).

As the wind speed at the surface measured by altimetry, for the point 26°S 48°W in 2014, the histogram is provided in **Figure 4.3-8**, and the basic statistics indicates annual mean of 6.31 ± 2.01 m/s, with an annual minimum of 0.72 m/s and annual maximum of 13.12 m/s (**Table 4.3-1**).

The time series of the results of NWW3 wave propagation model for the point 26°S 48°W, in April 2014, clearly shows the effects of cold fronts in generating waves with greater heights (including a front of the previous month) usually with longer periods, coming from South (**Figures 4.4-1 to 4.4-3**), despite the predominance of waves coming from the East in good meteorological conditions (**Figure 4.4-4**). The distribution of maximum heights calculated by NWW3 model for the month of April 2014, in the area 20°S-30°S 50°W-40°W, also shows values that decrease from south to north and towards the coast (**Figure 4.4-5**), as in the case of annual mean heights calculated by altimetry (**Figure**

4.3-5); however, the results of NWW3 model differ from altimetry values, mainly because the model outputs are every 3 hours (in one month), while in the case of altimetry they are daily mean values (in a year). As for the basic statistics of the results of NWW3, the point 26°S 48°W, in April 2014, has an average wave height of 1.66 ± 0.59 m and maximum of 2.96 m, and the mean period of the wave is 9.21 ± 2.38, with maximum of 14.62 s (**Table 4.4-1**).

The implemented modeling represented the main hydrodynamic characteristics of estuarine platform and the complex of Paranaguá, especially the importance of the tidal motion and the exceptional increase of the tidal currents in the entry channels of the estuary, as shown in the papers of Camargo (1998), Marone et al (1995), Noernberg (2001) and Ribas (2004).

The comparison between the time series of sea level generated by tidal prediction and the model processing forced only by tides, for the Port of Paranaguá (**Figure 4.5-2**), had linear correlation of 0.97 and skill of 0.99.

The model processing with tidal, wind and density forcing reproduces the very large currents in the estuarine complex entries, in the North Channel and the Galheta Channel, due to tidal influence, with currents that are aligned with the geographical orientation of the channels, with maximum intensities of 1.01 m/s and 1.28 m/s, respectively; on the other hand, in the coastal point, the maximum calculated flow reached 0.74 m/s (**Figures 4.5-3 to 4.5-12 and Table 4.5-2**).

The time series of mean sea level in the coastal point, in April 2014, calculated by the difference in surface elevation between model processing with tide and with all forcing, shows many oscillations between +0.40 m -0.42 m (**Figure 4.5-12**). The large increase in the mean sea level between 14 and 25 April is associated with cold fronts intrusions in the region of Paranaguá, which is also notable in time series of the model results exposed in **Figures 4.5-6 to 4.5-8** and altimetric measurements of dynamic topography (**Figure 4.3-1**).

It is important to note that the currents in the coastal monitoring point are much smaller than in the access channels to the estuary, despite the relatively small distance between them, about 35 km from the coastal point to Galheta Channel (see **Figures 4.5-4 to 4.5-11**).

VI - SUMMARY

Qualitatively, the most important points of this research were:

1) Annual, semi-annual and seasonal variability are important, but, on a time scale of 1 to 3 days, the effects of cold fronts prevail.

2) The comparison of information given by in situ data, by satellite measurements and through high-resolution modeling shows that, besides not being strictly coincident, there are differences that clearly indicate the spatial and time scales involved.

3) On the other hand, annual, semi-annual, seasonal and associated with cold fronts variability are found in the satellite information, as well as, in situ measurements, and in the results of spatial and temporal high-resolution modeling.

The above qualitative conclusions are quite general and confirm results obtained by other research, such as Mesquita (1983), who studied the circulation in the continental shelf, and modelers such as Harari (1984) and Camargo & Harari (1994), who have simulated the storm surges in the coastal region.

However, this research allowed a very useful quantification of the hydrodynamic and sea level variations on the coast of Paranaguá, by using several different sets of data, involving modern technologies and operational Oceanography, such as satellite altimetry and real time numerical modelling. These techniques, together with in situ data, are very useful for many routine activities, such as navigation security, coastal engineering, industrial fishing, pollution control, among others.

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