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# CRUSTAL SINKING AND THE SEA LEVEL AT CANANÉIA, SP, BRAZIL

Cristiano de Salles Almeida[1], André Ribeiro Lopes da Silva[2], Mauro Sznelwar[2] and Afrânio Rubens de Mesquita[2]

**ABSTRACT.** In this study, of tidal data of Cananéia, Brazil (Lat: 25°01,0' S and Long: 47°55,5' W), the following components were identified: 1) astronomical, defined by the tide generating potential; 2) nonlinear tidal dissipative components; 3) radiational, defined by the Sun light on the oceans; and 4) the polar geophysical component. The residual components of the sea level, resulting from filtering the above variables, are called "meteorological tides" (MT). This tidal data, after filtering its values, that include the decadal and intradecadal components, leads to the Long Term (LT) sea level values. Other measurements related to the LT sea level indicated the occurrence of: 5) the variation, due to the sinking of the crust; and 6) a constant rise in the LT sea level. Besides, the LT sea level trend also has components due to: 7) the eustatic variation; 8) the halosteric variation; and 9) the steric variation. The LT sea level trend component in Cananéia is estimated as: $a_1$ = 5.66 mm/year. While the vertical trend values of GPS is $a_2 = -3.8 \pm 01.1$ mm/year, indicating that the sea level rise in Cananéia is mostly due to the sinking of the crust in the region. The real value of the sea level variation corresponds to the difference between $a_1$ and $a_2$, which is an increase of $a_3$ = 1.8 mm/year. This trend value is the sum of the eustatic, halosteric and steric components and all of them seem to be consequences of the global warming.

**Keywords**: mean sea level, crustal variation, eustatic variation, steric variation, halosteric variation.

**RESUMO.** Nesta análise do nível do mar de Cananéia, Brasil (Lat: 25°01,0' S e Long: 47°55,5' W), foram identificadas as seguintes componentes: 1) astronômicas, definidas no potencial gerador de marés; 2) dissipativas da energia das marés; 3) radiacionais da radiação solar; e 4) a componente geofísica da maré polar. As componentes residuais, resultantes da filtragem das variáveis acima, dos registros de nível do mar, são conhecidas como "maré meteorológica" (MM). Essa maré dá origem, filtrando-se os valores da MM, que incluem as componentes decadais e intradecadais, à determinação da variação de longo termo (LT) do nível do mar. Além dessas componentes periódicas, foi determinada, através de medições de GPS, a ocorrência 5) da variação, devido ao afundamento da crosta; e 6) de um constante aumento do nível do mar de LT. Esse aumento, por sua vez, tem também componentes: 7) devido à variação eustática; 8) devido à variação halostérica; e 9) devido à variação estérica. O valor da tendência de LT do nível do mar em Cananéia, que engloba as três componentes acima, é de $a_1$ = 5,66 mm/ano. A tendência dos valores verticais de GPS é de $a_2 = -3{,}8 \pm 01{,}1$ mm/ano, indicando que o aumento do nível médio relativo do mar de Cananéia é devido, em grande parte, ao afundamento da crosta na região. O valor real da variação do nível do mar corresponde à diferença entre $a_1$ e $a_2$ que é igual a $a_3$ = 1,8 mm/ano, valor esse que corresponde à soma das componentes eustática, halostérica e estérica, parecendo serem todas elas decorrentes do aquecimento global.

**Palavras-chave**: nível médio do mar, variação da crosta, variação eustática, variação estérica, variação halostérica.

[1]Universidade de São Paulo, Instituto Oceanográfico, Praça do Oceanográfico, 191, Cidade Universitária, Butantã, Laboratório de Ecotoxicologia Marinha e Microfitobentos, sala 141A/B. 05508-120 São Paulo, SP, Brazil. Phone: +55(11) 3091-6572 – E-mail: almeidacs@usp.br

[2]Universidade de São Paulo, Instituto Oceanográfico, Praça do Oceanográfico, 191, Cidade Universitária, Butantã, Laboratório de Marés e Processos Temporais Oceânicos, sala 204A. 05508-120 São Paulo, SP, Brazil. Phone: +55(11) 3091-6648 – E-mails: andrermare@gmail.com; sznelwar@uol.com.br; ardmesqu@usp.br

## INTRODUCTION

The oceans constitute a water lamina with an average depth of 4 km along the Earth radius, which is around 6400 km, becoming then a thin lamina in relation to the Earth radius. Nevertheless, this lamina is responsible for the climate regulation. Among other more important phenomena under the influence of the complex relations between oceans and climate, there are the variations of the relative mean sea level (Mesquita, 2009).

The expansion of the oceans is one of the most feared effects of the global warming. However, despite proving that the seawater level is rising in many regions, including the Brazilian coast, the predictions about the variations of the relative mean sea level in a worldwide scale are one of the biggest controversies of contemporary science (Mesquita, 2009).

To establish the variations of decadal (10 years) and intradecadal (from 2 to 7 years) periods, it is required to have spectral analyses, similar to the ones recently made from global data of the ocean temperature by Munk (2002). For this, in the southeast region of Brazil, the acquirement of annual measurements of temperature and salinity (in a sistematic way, that is, in time series) is necessary, in order to obtain a perspective of the oceanic variation in decadal and intradecadal scales, as well as a perspective of the LT eustatic, halosteric and steric components of the relative mean sea level of Cananéia.

The data series collected (up to 2012) in the Brazilian coast comprise relatively short measurement periods. In general, less than 60 years. Although being difficult to get an accurate estimate of the average global rise of sea level, the recent analyses based on longer series, like the Brest record, in France, over 120 years, and the analysis in San Francisco, USA, over 110 years, considered more stable and reliable, predict a relative mean sea level rise of 1.8 mm/year, that is, 18 mm/century (Mesquita et al., 2013).

Also, it is required to consider that, besides being different from those estimatives in many places, the sea level variation is also relentlessly negative. That is to say, in many other oceanic regions, a clear sea level sinking is occurring, demonstrating the enigma exposed by Munk (2002) and after by Mesquita et al. (2013).

The Munk (2002) estimative, based on global oceanic data of temperature between 1960 and 2000, indicated that decadal and intradecadal variations in the global values of seawater temperature took place in this period. Also, it occurred an increase close to $2 \times 10^{23}$ joules of the heat content stored in the 0 to 3,000 meter oceanic layer, with a variation ratio of $5 \times 10^{21}$ joules by year, due to the greenhouse effect. In this same period there was a temperature increase around 0.10° C in the 0 to 500 meters depth and, as a consequence, there was a mean increase of 3 cm of the steric level.

In this work a LT study was developed about the data of the sea level of Cananéia, filtering the decadal and intradecadal variations. However, the estimative of the LT variation ratio of the fresh water volume added in the sea (eustatic variation), caused by the melting of glaciers, due to the global warming (Mesquita, 2009), was not developed. This study can be a contribution of the South Atlantic to solve the enigma pointed out by Munk (2002) in relation to the global variation of the relative mean sea level.

## MATERIAL AND METHODS

For this analysis, 50.5 years of sea level data (from 1954 up to 2005) were used to develop comparisons with 30 month data of vertical displacement of the Cananéia GPS station. The sea level data were acquired since 1954 by means of the OTT tide gauge in continuous series at GLOSS (Global Sea Level Observing System) station, number 194, in Cananéia city, and the GPS (Global Positioning System) vertical measurements, at SIRGAS (Sistema de Referência Geocêntrico para as Américas) station, were provided by IBGE (Instituto Brasileiro de Geografia e Estatística). The GPS data processing was carried out following international standards, using the GNSS (Global Navigation Satellite System) service, IGS (International GNSS Service) and the ITRF – 2000 (International Terrestrial Reference Frame) accurate coordinate system from any point of the planet, which can be seen in the Geoscience Australia website (AGGA, 2012), according to Abreu et al. (2006).

The calculus of the LT variations of the mean sea level requires the estimative of all tide components that derive from the tide generating potential: dissipative components of tidal energy (shallow depth components), radiation tides, as well as other oceanographic, meteorological and geophysical components, like the polar and the meteorological tides. After the identification of these components, a filtering was carried out to produce LT data for this analysis.

The resulting series of this process is constituted by the eustatic, halosteric and steric components of the region. With the measurements of temperature and salinity of oceanographic session, in the proposal to be submitted to FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo), they can be estimated, allowing the identification of the fresh water volume added to the region by the presently global melting of glaciers (Mesquita, 2009).

### Area of Study

Figure 1 shows the Cananéia region, where the tide gauge and GPS stations are. Part of Comprida Island; Cananéia Island; and Cardoso Island can also be seen. The Southeast region area,

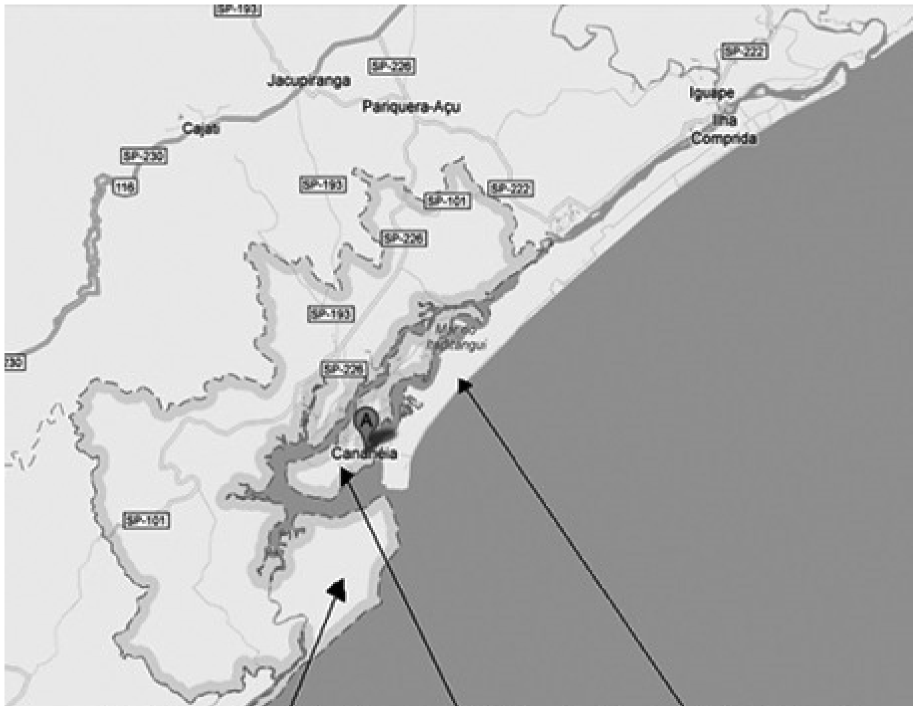


**Figure 1** – Cananéia region (Lat: 25°01,0' S and Long: 47°55,5' W), South coast of São Paulo State.

where Cananéia is, can be seen in Mesquita et al. (2011). There is also a description of the marine lands, which is a matter of great interest for residents near the beaches of the Brazilian coast.

The Cananéia research base was founded in 1954 and it is operated by Instituto Oceanográfico of Universidade de São Paulo (IO-USP). In 2002 a GPS station was installed and its antenna was placed near the German OTT sea level gauge.

Were obtained 30 months of double frequencies, which are used in this communication. A planialtimetric levelling is often carried out between the GPS station and the OTT tide gauge, following casual changes of the land where the research base is (Mesquita et al., 2005). The JASON and TOPEX/POSEIDON (JPL, 2015) satellite data are received and transmitted in real time to IBGE, that disclose them to the national and international scientific community.

## RESULTS

Figure 2 shows the set of original time data of the relative mean sea level of Cananéia, obtained from 1954 to 2005, that after filtering showed a systematic error of 5 cm in the measurements. This error correction allowed the accurate calculus of the trend showed by the continuous line of the figure (Mesquita et al., 2005).

The continuous line of Figure 2 corresponds to the filtered series of the decadal, intradecadal and meteorological influences. From the linear regression analysis, it was obtained the value of the coefficient of line $a_1$ and of its intercept a, that produced the following values: a = 158,872 $\pm$ 0.094 mm; $a_1$ = 5.66 $\pm$ 0.07 mm/year. In the figure it can be noted an adjustment of the 5 mm records, that occurred in 1971.

The Figure 3 shows the daily average data, calculated from the original time data of the sea level showed in Figure 2. The fluctuations observed in Figure 3 outline the decadal and intradecadal fluctuations resulting from the ENSO (El Nino & Southern Oscillation) phenomenon, (Morettin & Mesquita, 1984), which results from the oceanic and meteorological interaction that occurs in the equatorial part of the Pacific Ocean.

The ENSO phenomenon influence is also recorded in many other series. In the atmospheric precipitation series of Fortaleza (Mesquita & Morettin, 1984); in the sea level series of San Francisco city, in the series of river flow in the basins near to São Paulo city (Mesquita & Corrêa, not published); and in the flux series of the large rivers of the Earth planet (Kaiser et al., 1990).

The Figure 4 shows the spectrum obtained from the filtered data of the tide components, keeping the meteorological variations in the series. The periods of these spectral peaks demonstrate the

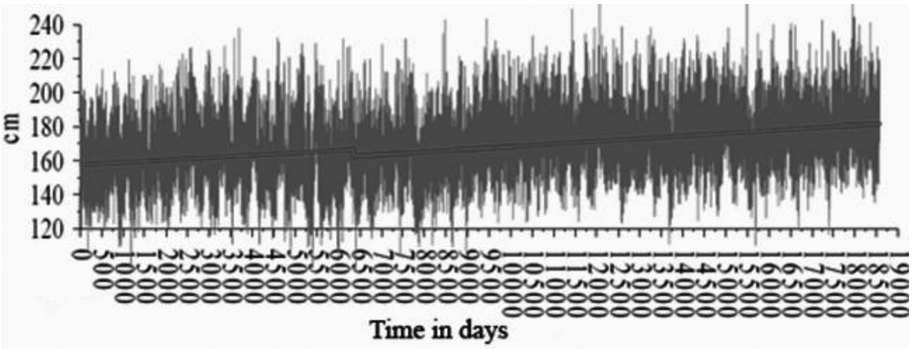


**Figure 2** – Relative mean sea level trend in Cananéia (Mesquita et al., 2005).

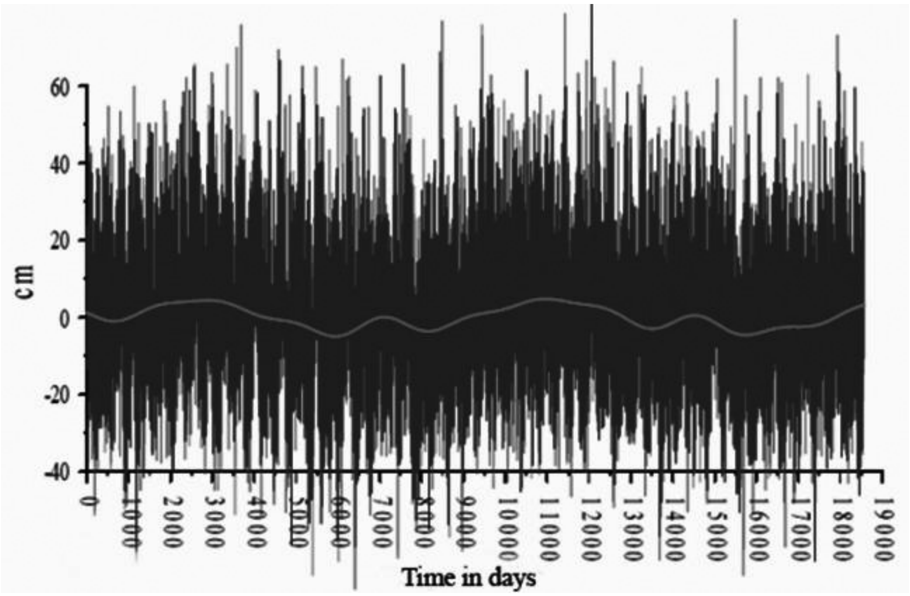


**Figure 3** – Series of time values of sea level of Cananéia. The continuous gray line corresponds to the daily averages (Mesquita et al., op. cit.).

influence of the ENSO phenomenon on the sea level of Cananéia. Amplitudes of intradecadal (from 2 up to 3 years) and decadal (12 years) periodicities are obtained with statistical assurance of 95%. The periods corresponding to these spectral peaks were obtained for the first time by Mesquita et al. (op. cit.).

The Figure 5 shows the temporal series of vertical heights in the period from 2003 to 2005, derived from the GPS measurements, produced in Cananéia base of IO-USP, in the south coast of São Paulo State, indicating the negative inclination of the regression line.

The estimated value of the variation ratio of the vertical movement (negative), that is, the sinking of the crust in this port, is given by the inclination of the regression line, which is $a_2 = -3.8 \pm 1.1$ mm/year. It can be noted that the data are not continuous as there are many interruptions caused by diverse circumstances resulting from the maintenance operations of the GPS data acquisition system.

## DISCUSSION

The results indicate that the crust in Cananéia is sinking at the ratio of 3.8 mm/year. Values of the LT trend of the sea level of Cananéia were calculated as the inclination of the regression line ($a_1 = 5.66$ mm/year) and the trend of the GPS vertical values were $a_2 = -3.8 \pm 1.1$ mm/year, showing that part of the rise of the relative mean sea level of Cananéia is caused by the sinking of the crust in the region. The $a_3 = 1.8$ mm/year value results from the difference between $a_1$ and $a_2$, corresponding to the eustatic variation, due to the melting of glaciers, together with the halosteric

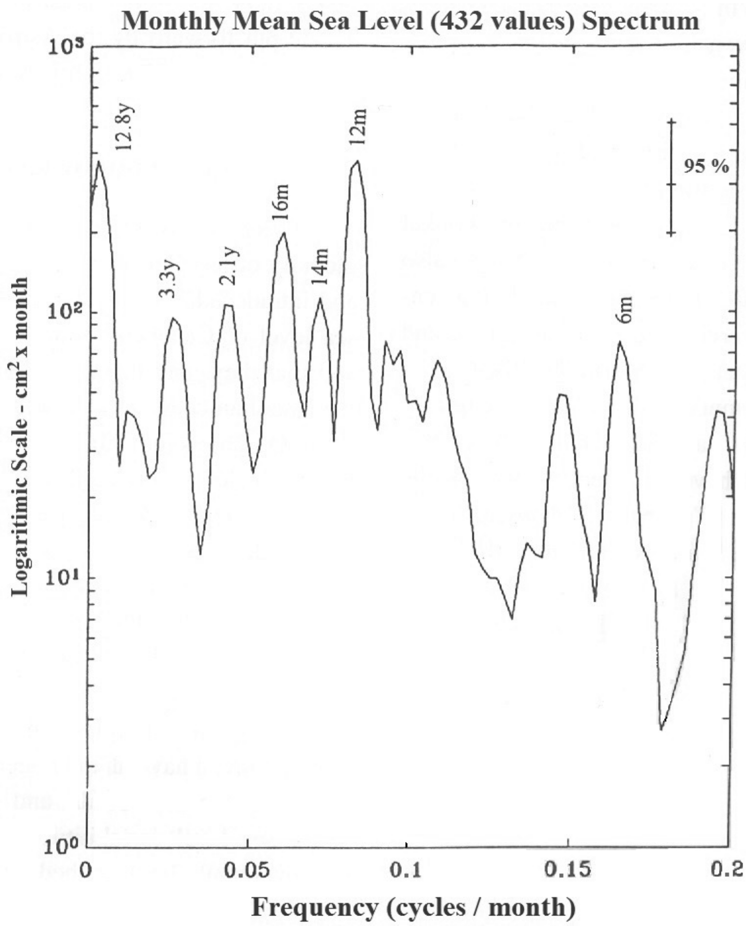


**Figure 4** – Sea level spectrum, showing intradecadal and decadal values of the sea level variation in Cananéia (Mesquita et al., 1996).

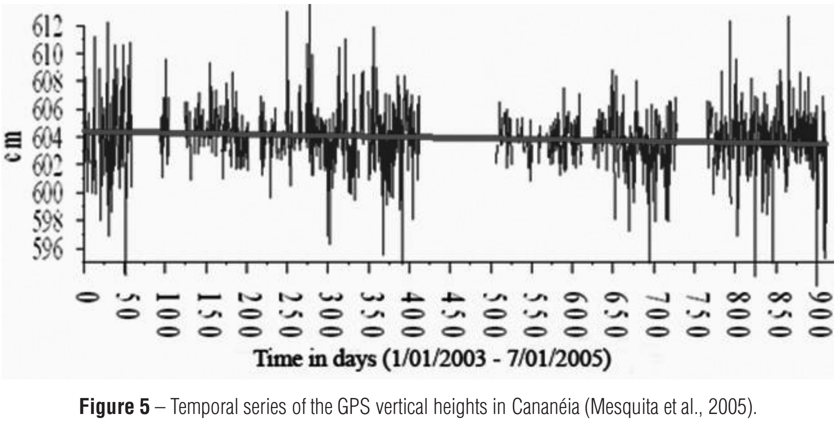


**Figure 5** – Temporal series of the GPS vertical heights in Cananéia (Mesquita et al., 2005).

and steric components, that occurred in the period.

In other words, $a_3$ value results from:

a) the water mass volume increase, due to the melting of glaciers (eustatic variation);

b) the decrease of the seawater salinity, due to the consequent fresh water addition (halosteric variation); and

c) the seawater temperature increase (steric variation).

All of them resulting from the global warming.

Munk (2002) worked with global values of temperature in the period from 1960 to 2000, and observed an increase of 0.1 degree centigrade of temperature in the 0 to 500 meter oceanic layer, with a variation ratio of 0.0025 degrees by year, producing as a result an increase of approximately 3 cm of the sea steric level, with a variation ratio of $b_1 = 0.75$ mm by year.

The annual undertaking of the oceanographic session called Capricórnio, previously proposed and mentioned, will be required in order to estimate the halosteric component apart from the steric component, and to have a complete overview of all variables of the sea level process of Cananéia. Also, it will be necessary to establish the decadal and intradecadal variations discovered 30 years ago in the atmospheric precipitation data of Fortaleza in the Brazilian northeast and in the sea level data of San Francisco. Variations of this kind were exposed by Mesquita et al. (1988), Mesquita & Morettin (1984), Morettin & Mesquita (1984), Morettin et al. (1994) and Kaiser et al. (1990), who considered the flows of the large rivers of the Earth (Amazonas, Nilo, Mississipi, Volga etc.).

These values were detected not only in those publications, but they were also estimated by Hastenrath (1985) and detected after by Munk (2002), in the global lamina of oceanic temperature that covers the Earth planet.

During the last 40 years, results obtained by Faria (2005) show that the Brazilian coast did not present signs that there is any change of the beach line in many regions along the coast, including the Southeast region where Cananéia is. Other works look for showing that the climatic variations are studied considering short temporal continuance and that it is not possible to clearly establish the presently sea level variation.

Tamisiea & Metrovica (2011), based on modeling results of the Earth's mantle, taking into account the Peltier (2000), GIA (Global Isostatic Adjustment), showed that in all Brazilian coast, including the Southeast region, the GIA impact is responsible for subtracting the mass of the Earth's mantle. The values of this subtraction produce an increase of the sea level of approximately $b_2 = 0.6$ millimeters/year, that is, 60 mm/century in all Brazilian coast.

Although these results are quiescent to the present variation estimatives of the relative mean sea level of Cananéia, they are not yet convenient nor in accordance with the reality of present days. Furthermore, they oppose the results of other authors. To achieve results closer to reality, it will be necessary to carry out annual sampling in Capricórnio oceanographic session. Being so, probably along 13 years of research project continuance, it will be possible to estimate LT global values of the sea level of the Southeast region (Mesquita & Harari, 2011), as well as to carry out the first content estimative of ice converted into fresh water, as a consequence of the warming in Santos Basin (Mesquita, 2009).

## CONCLUSION

The values of the sea level trend of Cananéia ($a_1 = 5.66$ mm/year) and of the trend of the GPS vertical values ($a_2 = -3.8$ mm/year) demonstrated that the increase of the relative mean sea level of Cananéia is largely caused by the sinking of the crust in the region. The difference of $a_1$ and $a_2$ that produces $a_3 = 1.8$ mm/year corresponds to the eustatic, halosteric and steric variation, that is, to the sum of the fresh water mass volume in the sea, as a consequence of the melting of glaciers, plus the sea level increase, due to the water temperature increase and the decrease of the oceanic salinity. All these variations (components) occur due to the global warming.

In order to achieve final conclusions about the eustatic, halosteric and steric components in all Brazilian southeast coast, it will be necessary measurements of the LT values, of the fresh water volume added in the Southeast region, and of the salinity and temperature values of these water masses, which can only be detected by means of measurements observing at least 13 years of continuance in an oceanographic session in Santos basin.

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## NOTES ABOUT THE AUTHORS

**Cristiano de Salles Almeida.** Undergraduate in Biological Sciences (licentiate – 2009) and (Bachelor's Degree – 2010), at Universidade Nove de Julho (UNINOVE). Master's degree in Biological Oceanography at Instituto Oceanográfico of Universidade de São Paulo (IO-USP); Postgraduate – Lato Sensu – Specialization in Measurement, Analysis, Forecasting and Modelling of Sea Level at IO-USP. Areas of interest: Physical Oceanography; Biological Oceanography; Sea level; Geophysics.

**André Ribeiro Lopes da Silva.** Bachelor's degree in Biological Sciences (2007) at Universidade Estadual de Goiás (UEG); Postgraduate – Lato Sensu. Specialization in Measurement, Analysis, Forecasting and Modelling of Sea Level at IO-USP. Areas of interest: Physical Oceanography; Biological Oceanography; Sea level; Geophysics.

**Mauro Sznelwar.** Bachelor's degree in Statistics (2004) at Instituto de Matemática e Estatística of Universidade de São Paulo (IME-USP); Postgraduate in Measurement, Analysis, Forecasting and Modelling of Sea Level at IO-USP (2010). Areas of interest: Statistics; Physical Oceanography; Sea level; Geophysics.

**Afrânio Rubens de Mesquita.** Bachelor's degree in Physics (1964) at Institute of Physics of Universidade de São Paulo (IF-USP), Master's degree in Physical Oceanography (1968) at IO-USP, Master of Philosophy in Oceanography (1972) at University of Southampton, Doctor's degree (1981) and Full Professor (1983) in Physical Oceanography at IO-USP. Created and coordinates the course Specialization in Measurement, Analysis, Forecasting and Modelling of Sea Level of IO-USP. Areas of interest: Physical Oceanography; Sea level; Geophysics.