TURBIDITY DISTRIBUTION IN A SUBTROPICAL ESTUARY: THE ESTUARINE COMPLEX OF PARANAGUÁ

Edson Filisbino Freire da Silva [1,2], Ligia Ferreira Granja da Luz[2], Claudio Clemente Faria Barbosa[1], Mauricio Almeida Noernberg [2]

[1]National Institute for Space Research - INPE, 515, 12227-010, São José dos Campos, Brazil, edson.freirefs@gmail.com, claudio.barbosa@inpe.br; [2]Federal University of Paraná – Center for Marine Studies, 83255-976, Pontal do Paraná, Brazil, ligialuz.oceano@gmail.com, m.noernberg@ufpr.br

ABSTRACT

Turbidity has an essential role in aquatic systems, controlling phytoplankton biomass and pelagic fauna distribution. Therefore, the objective of this study is to map turbidity in the Estuarine Complex of Paranaguá. Remote sensing reflectance (R_{rs}) and biogeochemical parameters were measured in situ, on June, 9th, 13th, 16th, 24th, and 30th 2016. R_{rs} in situ was used to model the relationship between turbidity and Landsat-8 OLI bands which were then applied to the imagery. Results showed that biogeochemical parameters could have been influenced by a harmful algae bloom, and band B4 were suitable for monitoring turbidity (R^2 = 0.72). The highest turbidity occurred in the delta of Cachoeira river, the inner region of the estuary, the coastal waters, and the north region of the estuarine mouth; in the Laranjeiras Bay, low turbidity was predominant.

Keywords — coastal oceanography, water transparency, water quality, Landsat-8 OLI.

1. INTRODUCTION

Turbidity is the reduction of water transparency through absorption and scattering of electromagnetic radiation, caused by the optically active constituents (OACs). The significant OACs in the aquatic systems are suspended particulate matter (SPM), colored dissolved organic matter (CDOM), and algae pigments, such as chlorophyll a (chl-a).

Turbidity has an essential role in aquatic systems. The high turbidity can reduce primary production, controlling phytoplankton biomass and distribution [1], and it can be able to induce algae blooms [2]. Furthermore, turbidity can change pelagic fauna distribution. For fish that rely on vision to detect their predators and their prey, laboratory experiments indicated turbid waters changes the predator-prey interactions, causing fish to feed in dangerous areas [3]. Moreover, field studies in estuaries showed that high turbidity supports the survivability of juvenile fish [4].

Because of the importance of turbidity in aquatic systems, the objective of this study was to map the turbidity distribution in the Estuarine Complex of Paranaguá (ECP). First, the association between turbidity and biogeochemical parameters were investigated; then, the fittest band of Landsat-8 OLI to retrieve turbidity were assessed and used to map turbidity distribution.

2. MATERIAL AND METHODS

2.1 Study Area

The study was conducted in the ECP, located in Paraná State, Southern Brazil (Figure 1). The estuary is composed by four bays (Antonia, Paranaguá, Laranjeiras, and Pinheiros), connecting to the Atlantic Ocean through three tidal channels, with the main entrance adjacent to Mel Island [5].

River runoff and tide are the major factors controlling the hydrodynamics. The highest tide is semidiurnal during spring tides, varying from 1.7m in the estuarine mouth to 2.7m in Antonina Bay. The major rivers are the Cachoeira and Nhundiaquara, with a mean inflow of 21 and 16m^3s^{-1}, respectively; where river runoff in the summer is 5 times more intense than the river runoff in the winter. The waves are only relevant in the estuarine mouth, with a mean height of 0.5m, reaching 3m in storm events [5].

2.2 Sampling

Turbidity, chl-a, Secchi depth (Z_{sd}), salinity, SPM, and R_{rs} were estimated. The dataset is composed by 32 samplings of biogeochemical parameters and 17 of R_{rs}, obtained in surveys conducted on June, 9th, 13th, 16th, 24th, and 30th 2016 from the inner Paranaguá Bay to estuarine mouth.

Turbidity and chl-a (ugL^{-1}) were estimated using an ECO FLNTU sensor from Wet Labs WQM. Turbidity is in nephelometric turbidity units (NTU), measured at 700 nm, which is not influenced by CDOM [6]. Therefore, CDOM was not analyzed in this study. The sensor was sunk 30 cm in the water and measured ten replicates. The mean of turbidity and chl-a at each station were calculated. All Z_{sd} measurements were carried out by the same person. Practical salinity was estimated in psu using a CTD JFE Alec.

For SPM (mgL^{-1}), bottle samples (1.5l) of surface water were collected at each sampling station, stocked and cooled until the laboratory analysis. In the same day, SPM concentration was determined by the Strickland and Parsons method [7].

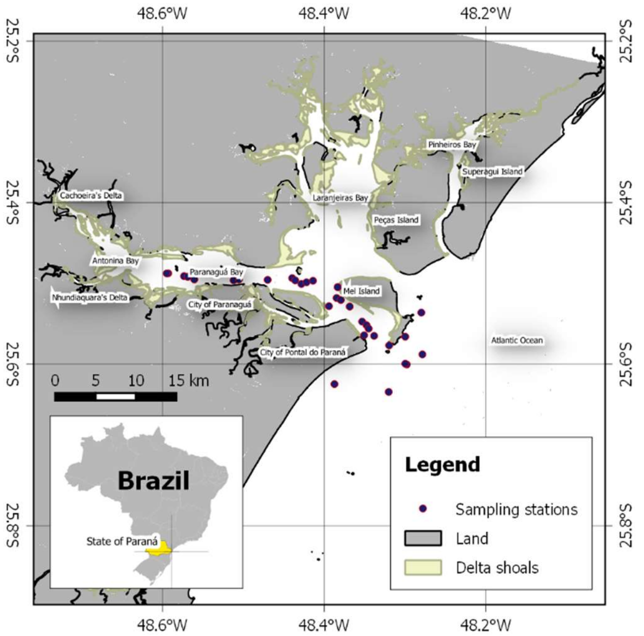

Figure 1. The Estuarine Complex of Paranaguá location and the sampling stations.

R_{rs} in situ were obtained using a HandHeld 2 VNIR according to Mobley method [8]. Measurements were carried out with a sensor-viewing geometry of 45º zenith angle and approximately 135º azimuth angle taking the Sun direction as a reference. It is worth mentioning that some variability in the azimuth orientation was expected due to the operational constraints (boat positioning).

The R_{rs} was calculated from the equation:

$$R_{rs}(\lambda) = (L_t(\lambda) - pL_s(\lambda)) / \pi L_p(\lambda)$$

where L_p is the radiance ($Wm^{-2}sr^{-1}$) onto a pre-calibrated Spectralon plaque, L_t is de radiance above the water, and L_s is the radiance from the sky (135º zenith angle), and p is related to the proportion of $L_s(\lambda)$ reflected in the ocean-air interface, obtained from the rho table (2015) on < http://www.oceanopticsbook.info/>.

2.3 Mapping Turbidity

Using the R_{rs} in situ, we simulated Landsat-8 OLI bands B1 (435 - 451 nm), B2 (452 - 512 nm), B3 (533 - 590 nm), and B4 (636 - 673 nm). The spectral response of the OLI sensor was modeled using the table available in <https://landsat.gsfc.nasa.gov/>. The ordinary least squares method was used to obtain linear models between each simulated band and turbidity (n = 17). The performance of each empirical model was evaluated by its coefficient of determination (R^2) and its mean absolute percent error (MAPE).

Turbidity was mapped using the Landsat-8 OLI image of June, 12th 2016. The image was downloaded using the Earth Explorer platform <https://earthexplorer.usgs.gov/> from the United States Geological Survey (USGS), in reflectance at the top of the atmosphere, geometrically corrected and projected in WGS 84. The influences of atmospheric scattering and absorption were removed using the 6S atmospheric correction [8]; next, we divided the obtained surface reflectance by π to retrieve the R_{rs} of each band. The performance of atmospheric correction was assessed for each band (n = 4), comparing the R_{rs} of the image and the R_{rs} in situ of June, 13th 2016. The fittest empirical model was applied and the map of turbidity retrieved.

3. RESULTS AND DISCUSSION

3.1 Association of Turbidity and Biogeochemical Parameters

Results showed a positive correlation between chl-a and salinity (R = 0.5), and no relationship between chl-a and turbidity (R = 0.12) (Figure 2). This correlation is not in agreement with past studies in the ECP, which indicated chl-a is related to low salinities caused by freshwaters from rivers runoffs, where nutrient concentration is higher [9]. Moreover, the same study showed turbidity is a limiting factor in phytoplankton growth. Thus, more turbid waters should induce to lower chl-a concentrations.

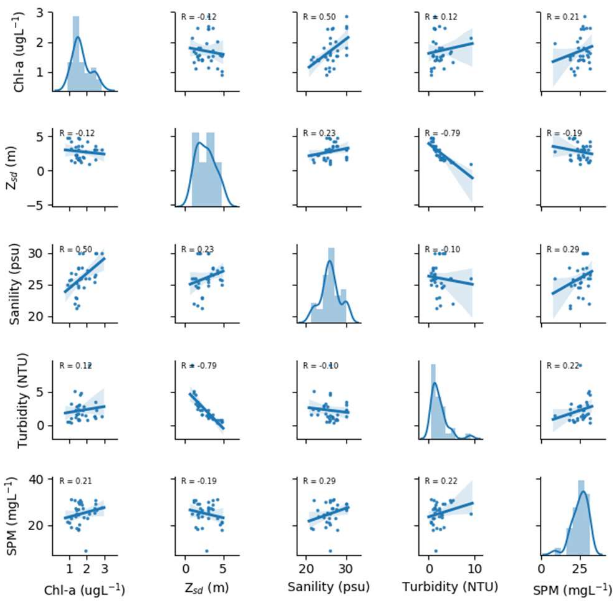

Figure 2. Distribution and relationship between the biogeochemical parameters. Diagonal graphs are the density distribution of each parameter.

In the late May 2016, a massive toxic bloom of *Dinophysis acuminata* happened along the southern coast of Brazil [10]. This bloom occurred in offshore waters, where salinity is higher than the inner inlet. Consequently, higher salinity from oceanic waters could have more chl-a concentration and explain the different relationship found in our dataset. Additionally, the association of lower turbidity and higher chl-a concentration should be specific for species of phytoplankton. Hence, *Dinophysis acuminata* biomass could not be limited by turbidity in this specific case, causing the poor relationship of turbidity and chl-a concentration.

SPM concentration was not the major constituent influencing turbidity. Turbidity using light beam at 700 nm is only affected by concentration, size, and composition of suspended particles [6]. The weak correlation of turbidity and SPM concentration (R = 0.22) suggests a higher influence of particles size and composition in turbidity. Different sources of SPM composed our dataset, such as resuspension by tidal currents and rivers flows [11]; moreover, resuspension by oceanic waves in the coast and the algae bloom could have increased the variety of composition and size of SPM. Thus, SPM concentration was not the only determinant changing turbidity.

Last, turbidity presented a satisfactory correlation (R = -0.79) with Z_{sd}. The backscattering of particles must have increased the attenuation. Thus, turbidity was the main factor controlling Z_{sd}, limiting the energy available to photosynthesis.

3.2 Mapping Turbidity

The Landsat-8 OLI band B4 showed the best agreement to retrieve turbidity in the ECP. The statistical results analysis (Figure 3) for the empirical models shows the bands B3 (R^2 = 0.72; MAPE = 36.65%) and B4 (R^2 = 0.76; MAPE = 36.05%) with satisfactory results, and bands the B1 (R^2 = 0.15; MAPE = 87.46%) and B2 (R^2 = 0.4, MAPE = 62.48%) failed to estimate turbidity. Thus, the simulated bands B3 and B4 were capable of estimate turbidity.

Comparing the R_{rs} of simulated bands with the R_{rs} of image bands (Figure 4), the overall matching showed a satisfactory agreement (R^2 = 0.84; MAPE = 40.43%). Analyzing the MAPE for each band, the R_{rs} of band B3 from the image had the worst result, overestimating the R_{rs} in situ (MAPE = 68.08%), while B2 had the best agreement (MAPE = 7.97%).

Bands B1, B2, and B3 should not be used to map turbidity in the ECP. Empirical models of simulated bands B1 and B2 had an unsatisfactory relationship with turbidity; while R_{rs} of band B3 from the image overestimated R_{rs} in situ. Hence, band B4 produced the best empirical model and was not overestimated by the sensor (MAPE = 34.49%), so, it was utilized to map turbidity in the ECP.

In the Paranaguá Bay, two main hotspots of higher turbidity occurred in the Cachoeira river's delta and next to the Paranaguá city (Figure 5). Turbidity reached up to 10 NTU next to the delta shoals, decreasing eastward and southward, and increasing again next to the city of Paranaguá. One of the primary sources of SPM in Paranaguá Bay is the Cachoeira river [11]; thus, the river inflow increased turbidity from the river mouth to 10 km east at the north side of the bay. Additionally, the city of Paranaguá has the principal port of grains of Brazil; the higher turbidity in this area suggests the port of Paranaguá is influencing the turbidity. However, we are not able to assure the causes.

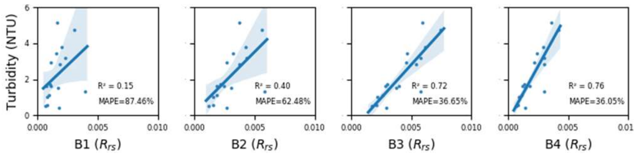

Figure 3. Relationship of the OLI simulated bands and turbidity.

Laranjeiras Bay was characterized by low turbidity with some exceptions in the tidal flats. Turbidity reached up to 7.5 NTU next to delta shoals, while turbidity lower than 3 NTU occurred in the major area, reducing in the inner inlet. Resuspension of SPM from tidal currents could increase turbidity near delta shoals. Hence, tidal currents could have the foremost importance in turbidity distribution in the Laranjeiras Bay.

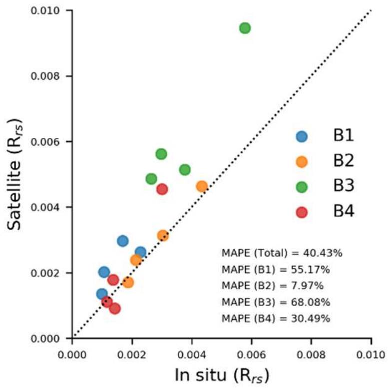

Figure 4. Comparison of OLI bands in situ and from the image after the atmospheric correction.

In the inner shelf, two turbid regions occurred. In the south at the coast of Pontal do Paraná, and in the north region along the Superagui island. These plumes present turbidity values up to 10 NTU, reducing to 0 NTU oceanward. Oceanic waves breaking onto the delta shoals and beaches could have resuspended sediments, causing the high turbidity. Further, rip currents transported the SPM towards the sea, and the flood tide moved the turbidity plume into the Pinheiros Bay.

4. CONCLUSION

We mapped turbidity in the ECP using the Landsat-8 OLI sensor. Band B4 had a satisfactory performance to estimate turbidity, while bands B1, B2, and B3 failed. The highest turbidities were found in Antonina and Paranaguá bays, Cachoeira river's delta and near the Paranaguá port. Lowest values were found in Laranjeiras Bay, with higher values close to delta shoals. The turbidity decay oceanward with highest values occurring in the coastal waters, both south and north to mouth drive by the rip and tidal currents.

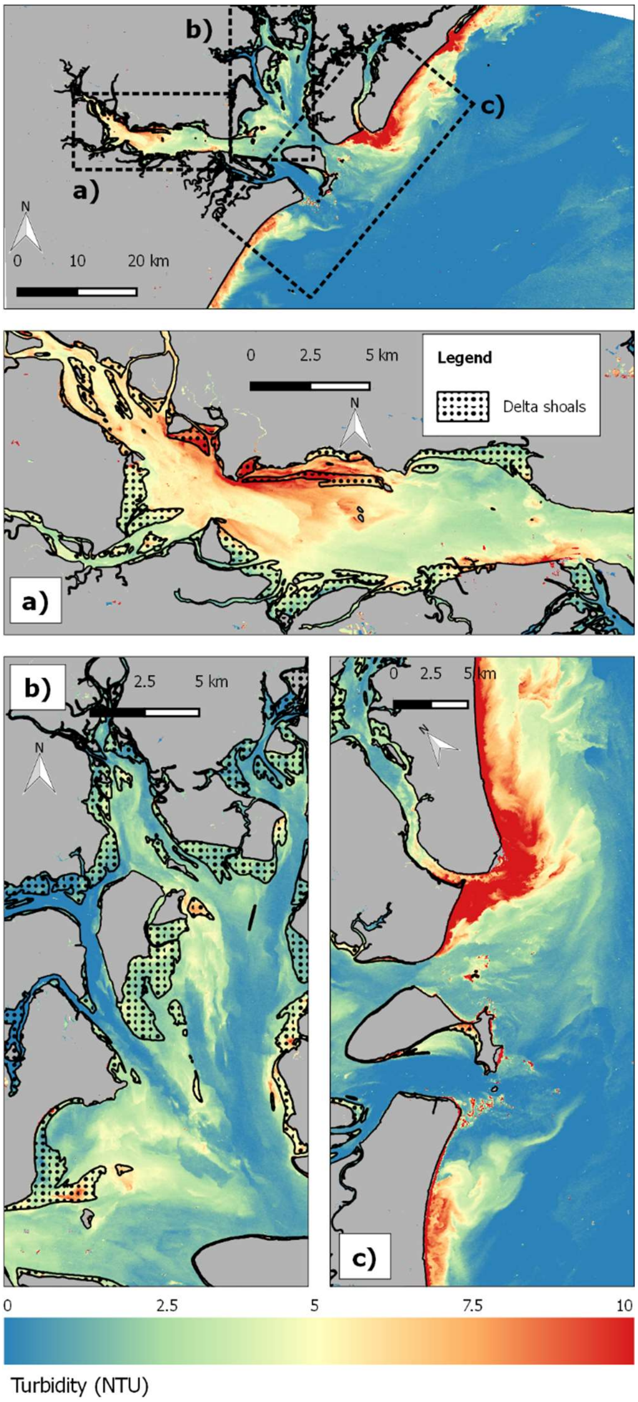

Figure 5. Turbidity distribution in the estuarine complex of Paranaguá, in 12th June of 2016

5. ACKNOWLEDGMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. This study was partially supported by the Office of Naval Research Global Americas Sao Paulo. We thank the National Institute for Space Research, Brazil, for lending the spectroradiometer HandHeld 2 VNIR.

6. REFERENCES

[1] Cloern, J. E. “Turbidity as a control on phytoplankton biomass and productivity in estuaries”. *Continental Shelf Research*, v. 7, n. 11–12, p. 1367–1381, 1987.

[2] May, C. L.; Koseff, J. R.; Lucas, L. V.; Cloern, J. E.; Schoellhamer, D. H. “Effects of spatial and temporal variability of turbidity on phytoplankton blooms”. *Marine Ecology Progress Series*, v. 254, p. 111–128, 2003.

[3] Abrahams, M.; Kattenfeld, M. “The role of turbidity as a constraint on predator-prey interactions in aquatic environments”. *Behav Ecol Sociobiol*, p. 169–174, 1997.

[4] Cyrus, D. P. “The influence of turbidity on juvenile marine fish in the estuaries of Natal, South Africa”. *Continental Shelf Research*, v. 7, p. 1411–1416, 1987.

[5] Lana, P. C.; Marone, E.; Lopes, R. M.; Machado, C. “The Subtropical Estuarine Complex of Paranaguá Bay, Brazil”. *Coastal Marine Ecosystems of Latin America*. v. 144, 2001.

[6] Gippel, C. J. Potential of turbidity monitoring for measuring the transport of suspended solids in streams. Hydrological Processes, v. 9, n. 1, p. 83–97, 1995.

[7] Strickland, J. D. H.; Parsons, T. R. “A Practical Handbook of Seawater Analysis”. *Fisheries Research Board of Canada,* v. 167, 1972.

[8] Mobley, C. D. “Estimation of the remote-sensing reflectance from above-surface measurements”. *Applied optics*, v. 38, n. 36, p. 7442–7455, 1999.

[8] Vermote, E. F.; El Saleous, N.; Justice, C. O.; et al. “Atmospheric correction of visible to middle-infrared EOS-MODIS data over land surfaces: Background, operational algorithm and validation”. *Journal of Geophysical Research*, v. 102, p. 131–141, 1997.

[9] Brandini, F. P. Ecological studies in the bay of Paranaguá, horizontal distribution and seasonal dynamics of the phytoplankton. *Boletim do Instituto Oceanográfico*, v. 33, p. 139–147, 1985.

[10] Alves, T. P.; Mafra, L. L. “Diel variations in cell abundance and trophic transfer of diarrheic toxins during a massive dinophysis bloom in Southern Brazil”. *Toxins*, v. 10, n. 6, 2018.

[11] Mantovanelli, A.; Marone, E.; da Silva, E. T.; et al. “Combined tidal velocity and duration asymmetries as a determinant of water transport and residual flow in Paranaguá Bay estuary”. *Estuarine, Coastal and Shelf Science*, v. 59, n. 4, p. 523–537, 2004.