Costi, Juliana; Forster, Aldair; Marques, Wiliam Correa; Duarte, Raquel de F.; Arigony-Neto, Jorge

Application of the TELEMAC-3D to simulate flooding and hydrodynamic patterns of Southern Brazilian wetlands

Application of the TELEMAC-3D to simulate flooding and hydrodynamic patterns of Southern Brazilian wetlands

Juliana Costi, Aldair Forster, Wiliam C. Marques
Instituto de Matemática, Estatística e Física
Universidade Federal do Rio Grande
Rio Grande, Brazil
ju.costi@gmail.com

Raquel de F. Duarte, Jorge Arigony-Neto
Instituto de Oceanografia
Universidade Federal do Rio Grande
Rio Grande, Brazil

Abstract—**Wetlands are highly productive systems that provide valuable ecosystem services. In the extreme south of Brazil, extensive wetlands are protected areas with global importance recognized by the RAMSAR convention (www.ramsar.org). The Mirim – São Gonçalo system is comprised by a shallow coastal lagoon (Mirim lagoon) that receives the discharge of three main tributaries at its southern region, and drains towards the Patos Lagoon estuary through a 78 km long channel (São Gonçalo Channel), at its northern tip. The system lies on a wide coastal plain with flat topography and very low permeability, favouring the occurrence of extensive wetlands surrounding the permanent water bodies. The system is the main source of water for agricultural irrigation and urban supply. The establishment of a binational (Brazil – Uruguay) waterway is under discussion, though very few studies have addressed the circulation of the lagoon and the channel, and their impacts on the wetlands. In this study, we ran a one-year simulation using the TELEMAC-3D to investigate the hydrodynamics of the Mirim – São Gonçalo system, to understand how the permanent water bodies hydrodynamics can affect the flooding patterns of wetlands. We validate the model results using European Remote Sensing 2 mission (ERS-2) derived flood maps of seven different dates, and water level time series measured in two different locations. The average agreement between the simulated flood extent and the ERS-2-derived flood maps was 65%. Regarding water level, the average error was -0.6 m and the correlation coefficient was 0.61. The prevailing winds from the northeast over the lagoon imply that, normally, higher water levels occur in the south of the lagoon. However, the wetlands that fringe the northern sector of the lagoon show average water levels higher than those observed for the southern wetlands. This may be explained by the chocked configuration of the lagoon at its northern sector. Once the prevailing current is northwards, the constriction of the connection between the lagoon and the channel causes a damming effect, resulting in further overflow towards the fringing wetlands. On the other hand, the highest standard deviation of the free surface elevation was found for the southern wetlands, which is related to the effects of the passage of cold fronts. These atmospheric systems cause the inversion of the prevailing northeast wind toward the southwest and, consequently, the direction of the barotropic gradient and the prevailing current. Thereafter, the flooding patterns observed for the wetlands that fringe the Mirim lagoon are not directly associated to the water level in the lagoon, but to the circulation forced by the wind and to the geomorphology of the region. Such patterns are in agreement with the velocity fields observed for the Mirim lagoon, which are more variable in the southern sector, whereas in the northern region it is consistently directed towards the wetlands.**

I. Introduction

The conservation of wetlands is highly relevant for maintaining the multiple ecosystem services that they provide. Understanding the physical processes acting on wetlands and their variability is primary for their correct management and sustainable development. In the extreme South of Brazil, extensive wetlands surround the largest lagoon complex of Latin America, formed by the Mirim (ML) and Patos lagoons connected by the São Gonçalo channel (SGC). Even though they are legally protected areas, agricultural, urban and industrial activities constantly pressure the natural system.

This bi-national (Brazil – Uruguay) hydrological system has enormous environmental and socio-economic importance. Surrounding the lagoon and the channel, highly productive wetlands shelter a rich biodiversity [1]. Moreover, wetlands have a part in the carbon biochemical cycle, being the largest source of methane for the atmosphere [2,3]. The establishment of a bi-national waterway is under discussion, which will require dredging operations and impose further risks for the environmental safety. Though, wetlands of the extreme South of Brazil have been the subject of a limited number of studies.

In the present study, we employed the TELEMAC-3D model to investigate the flooding patterns and hydrodynamics of the wetlands that surround the Mirim lagoon and the São Gonçalo channel during the year 2000. We focus the analysis on the identification of spatial variations of wetlands that can be related to the hydrodynamics of the water bodies that they fringe. By applying the TELEMAC-3D, the representation of the hydrodynamics was improved compared to TELEMAC-2D, with an additional computational cost that was considered worth for the objective of this study.

A. Study Area

The southern Brazilian coast, located between 29.5°S and 32°S, comprises a large coastal plain shaped by recent sea level fluctuations led by glacial-eustatic adjustments. The system developed and evolved after successive marine regressions and transgressions during the Quaternary, resulting in the sequential deposition of four barrier-lagoon depositional systems [4].

The coastal plain is formed by typical barrier-lagoon deposits, which explains its flat, micro-topographical terrain, and the occurrence of several lakes and lagoons. The lagoon complex formed by the Mirim and Patos lagoon, both connected by the 78 km long São Gonçalo channel (Fig. 1), is the largest lagoon complex of Latin America. These water bodies are fringed by extensive wetlands and floodplains that are often flooded.

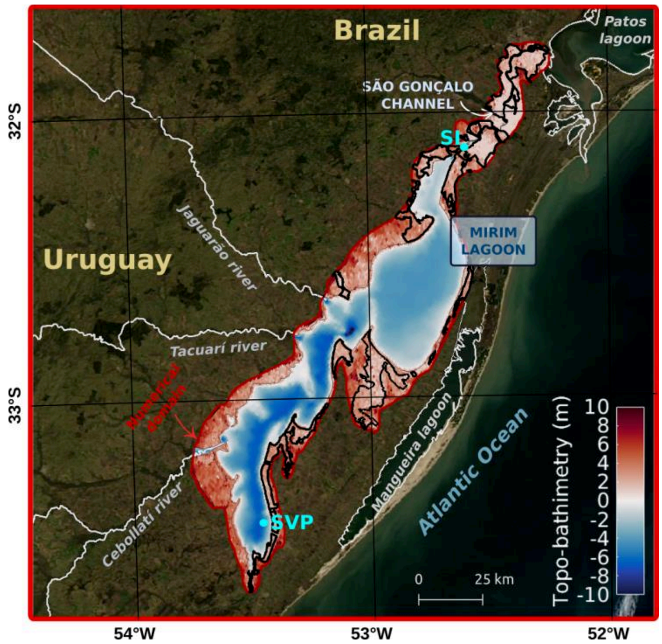

Figure 1: Map showing the location of the Mirim Lagoon, the São Gonçalo channel and their surrounding wetlands (black polygons). The red polygon corresponds to the numerical domain, and the cyan dots show the location of the Santa Izabel (SI) and Santa Vitoria Port (SVP) gauge stations.

The Mirim lagoon is a shallow transboundary coastal lagoon, with maximum depths reaching 12 m and covering an area of approximately 3,749 km^2. Its catchment basin drains a large area, with abundant and well-distributed precipitation over the year [5], and includes Brazilian and Uruguayan rivers. The main tributaries are the Jaguarão, Tacuari and Cebollati rivers.

The Mirim lagoon does not have a direct connection with the ocean, but is connected with the estuary of the Patos lagoon. Though, a sluice gate built near the São Gonçalo channel's mouth prevents the inflow of brackish towards the ML. Its major axis has an azimuth of 43°, which is nearly the orientation of the prevailing winds. The system works as a water reservoir, supplying water for human consumption, agricultural production and industrial processes. Large inputs of fresh, nutrient-rich waters are exported towards the estuarine region and, subsequently, to the coastal sea.

The prevailing winds are from Northeast over the year. During the passage of cold fronts and extra tropical cyclones, winds are from the Southern quadrant. The wind strongly influences the lagoon hydrodynamics in the synoptic time scale, and river discharge dominates the water level variability from annual to intra-seasonal time scales [6].

II. Methods

We ran a simulation using the TELEMAC-3D model covering the period starting on 1 January 2000, until 31 December 2000. This is the first year when discharge data of the main Mirim lagoon tributaries is available.

A numerical grid with 63,401 nodes was constructed using the Blue Kenue software. Bathymetry data of the water bodies was obtained from navigation charts, provided by the Brazilian Navy. Elevation data of the surrounding areas was extracted from the TANDEM-X digital elevation model [7]. The bottom friction was set to Manning's coefficient of 0.035 inside the ML and the SGC and to 0.05 in the flooding areas, in accordance with the values estimated by [8] for muddy to silty bottoms and grasslands.

We activated the treatment of tidal flats, using the default option (equations solved everywhere with correction on tidal flats). We considered constant viscosity for horizontal and vertical turbulence with coefficients of 10^{-6}. Density law was set to density as function of temperature. The implicitation value for depth and velocity was set to 1. The advection schemes for velocities and advection of tracers was set to 14 (N-scheme for tidal flats).

The superficial conditions were forced using ERA-interim reanalysis data interpolated for each node of the mesh. We used time series of the u and v components of wind velocity, atmospheric pressure at the surface and air temperature at 2 m above surface obtained each 6 hours. Air temperature is taken into account through direct programming in the BORD3D subroutine, allowing representing the heat exchanges between water and atmosphere. Fig. 2 represents the average time series of the superficial conditions and the total discharge of the tributaries during the simulation period. As the initial conditions were not known, we ran a warm-up simulation of 1 year using an average time series of river discharge calculate from measurements carried out over 5 years (2000 – 2004) to force the liquid boundaries, and atmospheric data corresponding to the year 1999.

The computational domain was defined considering the topography of the region, with four open liquid boundaries: the Jaguarão, Tacuari, and Cebollati rivers and the mouth of the São Gonçalo channel. The liquid boundaries are forced with discharge data measured in gauge stations placed in the three most important tributaries and water level measurements carried out near the SGC mouth. The Brazilian National Water Agency distributes these data through its website (http://hidroweb.ana.gov.br).

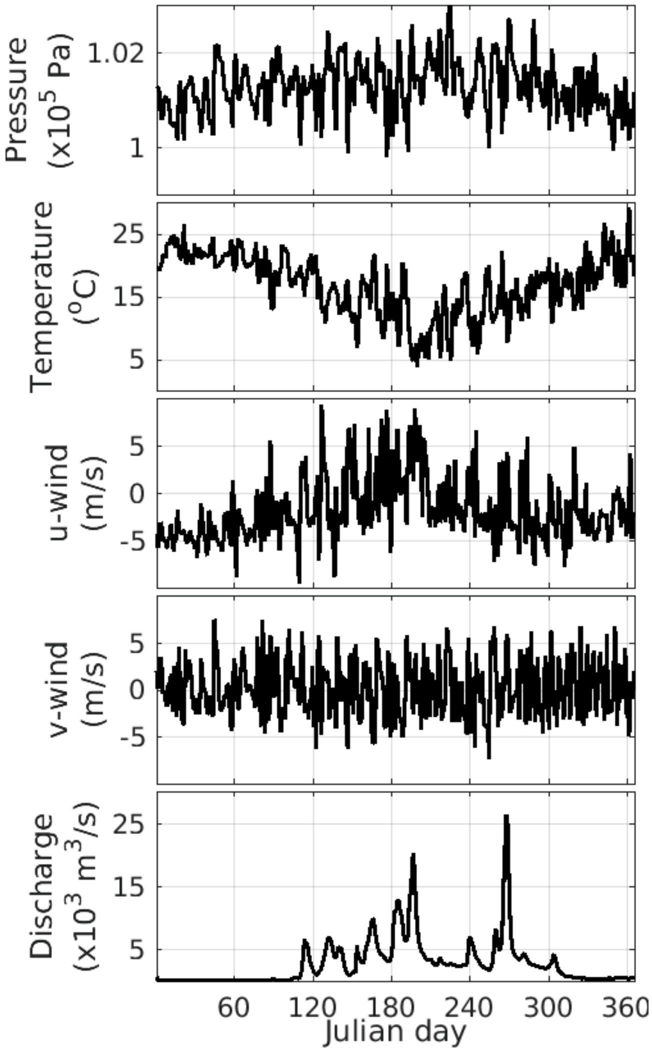

Figure 2: Time series of the average surface boundary conditions considered in the present study, and total discharge of the three main tributaries of the Mirim lagoon (Jaguaro, Tacuari and Cebollati rivers).

To validate the model results, we used water level time series measured at two different gauge stations and flood extents derived from ERS-2 imagery covering the Sao Goncalo channel wetlands. The Santa Vitória gauge station is located at the south of the lagoon, and the Santa Izabel gauge station is located in the São Gonçalo Channel, near its connection with the lagoon (Fig. 1). The measurements are performed in a daily basis by the Mirim Lagoon Agency (https://wp.ufpel.edu.br/alm/agencia/).

A dataset of ERS-2 imagery from 7 different dates was used to derive flood extent maps and validate the modelled flood extent. The ERS-2 derived flooding extents were obtained using a threshold method, developed specifically for the study area, based on the image histogram analysis and the visual inspection of the ERS-2 [9] imagery in combination with a LANDSAT ETM+ image [10]. The pixels located on the floodplain with backscattering values lower than -8 dB and higher than -12 dB are classified as wet, while those presenting backscattering values smaller than -12 dB are classified as flooded [10].

The calibration, geometric correction and speckle-filtering were performed using the SNAP software. The water bodies were masked out, and the pixels were then classified as flooded and not flooded using the regional algorithm, developed specifically for the study area.

Considering the hydrodynamics of the study area, we sub-divided the wetlands in three larger groups: wetlands that surround the São Gonçalo Channel, the northern Mirim lagoon (north of Jaguarão river), and the southern Mirim lagoon (south of Jaguarão river). This division of the lagoon was based on the study of [6], which showed that water levels are, in average, higher in the southern region due to the action of the prevailing winds. Moreover, the lagoon width abruptly increases at the Jaguarão river latitude, whereas the tributaries discharge at the southern sector.

III. RESULTS AND DISCUSSION

To investigate the hydrodynamic behaviour of the Mirim Lagoon, the São Gonçalo channel and their adjacent wetlands, we performed a one-year simulation using the TELEMAC-3D model. Considering the morphological and hydrodynamic characteristics of the study area, the wetlands were divided in three sectors. The São Gonçalo channel group comprises the wetlands that fringe the channel, whereas the North and South groups comprise the wetlands that fringe the northern and southern sectors of the Mirim lagoon, respectively. The Jaguarão river was considered the limit between North and South sectors, i.e., wetlands fringing the Mirim lagoon and located north (south) of the Jaguarão river were grouped in the North (South) sector.

Figure 3 presents a comparison of the water level time series measured at Santa Izabel (3.a) and Santa Vitória Port (3.b) gauge stations, and the ERS2-derived flooded area (3.c), against the modelled results. The simulated water level presented an average error of -0.6 m and the correlation coefficient between the simulated and measured data was 0.61. The largest discrepancies occur concomitantly with the two most pronounced discharge peaks, when the model overestimated the water level.

The flooded area simulated with TELEMAC-3D showed a general good agreement with the ERS2-derived, except for the first image, when TELEMAC-3D largely underestimated the flooded area. This may be explained by the uncertainties involved in the beginning of the simulation period, as the initial conditions were unknown. The spatial average agreement between modelled and ERS2 flooded area was 65%.

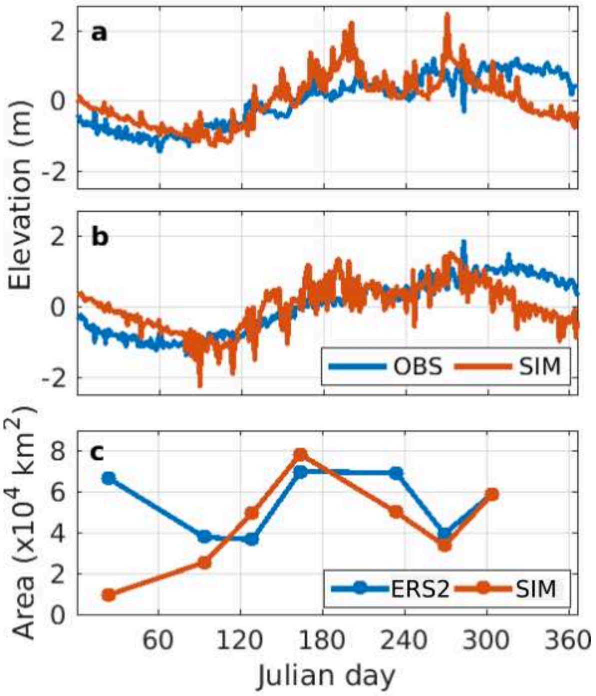

Figure 3: Blue (red) lines indicate observed (simulated) water levels in a) Santa Izabel and b) Santa Vitória Port gauge stations. The c panel present the flooded area as estimated by ERS2-derived mapping (blue line) and TELEMAC-3D (red line).

In comparison with the flooding area simulated by [6] using the TELEMAC-2D model, TELEMAC-3D provided a better estimative of the flooding temporal behaviour. The TELEMAC-2D failed in represent the decrease of the flooded area after the peak near the middle of the year, whereas TELEMAC-3D provided results that better approximate to those observed by the ERS2 data. Despite the higher computational costs for running three-dimensional hydrodynamic simulations, the improved representation of the physical processes may justify their employment, especially for regions where field measured data is poor and/or scarce, representing considerable sources of error. The computational time for running a 1-year simulation with TELEMAC-3D was about 5 times larger than for running the TELEMAC-2D (1 day with an Intel core i7 processor of 8 cores).

The water depth time series for each sector is represented in Fig. 4 a (wetlands) and Fig 4 b (permanent water bodies). The overall variability of the water depth time series present patterns similar to those observed for the water bodies. The seasonal variability is associated to higher discharges during the autumn and winter, which causes the most pronounced variations in water levels. The higher frequency oscillations are associated to the hydrodynamic response of the system to the incident wind direction.

The prevailing wind direction in the study area is from Northeast, which implies in higher water levels at the southern Mirim lagoon during most of the time. The establishment of a wind-induced barotropic gradient northward, allied to the tributaries discharge, induces a prevailing northward current. However, the passage of atmospheric systems such as cold fronts and cyclones causes the inversion of the wind direction to Southwest. These synoptic events are more frequent during the winter and spring, and cause temporary inversions of the prevailing current to southwards. Considering this behaviour, it would be expected that wetlands surrounding the southern Mirim lagoon would show higher water levels compared to those fringing the northern sector of the lagoon. Nevertheless, the opposite is observed, and further higher depths are found at the SGC wetlands.

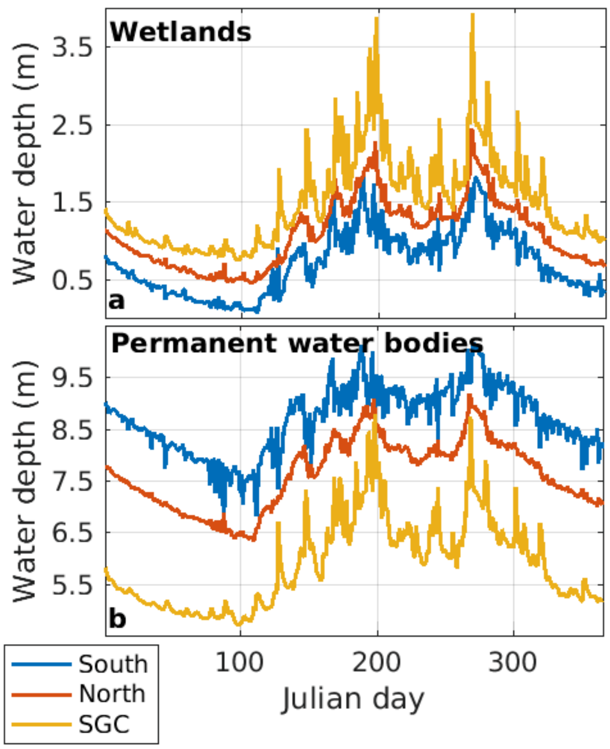

Figure 4: Time series of the water depth simulated by TELEMAC at the South, North and SGC wetlands (a) and water bodies (b).

The difference among the SGC and Mirim lagoon wetlands water depth may be explained by the terrain elevation. The SGC wetlands average elevation is 1.6 m, whereas either southern and northern Mirim lagoon wetlands is 2.9 m. On the other hand, the difference among North and South cannot be explained by the terrain topography, as both wetlands groups have nearly the same average elevation.

By analysing the time series of currents velocity at the wetlands (Fig. 5) we observed that the zonal (u) component of the southern group is considerably more variable, and present more pronounced negative values compared to the north. Once the southern wetlands are located to the east of the lagoon, the circulation favours the water to flow back towards the lagoon, decreasing the storage of water in the wetlands. The fact that the southern sector of Mirim lagoon presents slightly higher depths may also contribute to less water being stored in the wetlands.

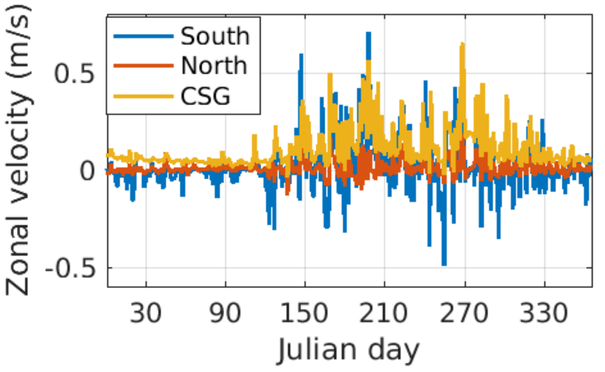

Figure 5: Time series of the average zonal (u) velocity of each wetland group.

[11] simulated the behaviour of lagrangian drifters to investigate the water residence time of Mirim lagoon. The authors observed less drifters being transported to the wetlands in the southern Mirim lagoon in comparison to the northern region. Nevertheless, higher residence times are observed in the south as a result of the dynamic circulation barrier imposed by the Cebollati river discharge.

The northern sector of the Mirim lagoon, on the other hand, presents a physical circulation barrier imposed by its chocked connection with the São Gonçalo Channel. Allied to the shallower depths, it may explain the larger water levels simulated on northern wetlands compared to the south. Once the water flows preferably towards north, larger amounts of water are being exported to the wetlands at the northern Mirim lagoon, despite the normally higher water levels observed in the south.

The average water depth of the wetlands is represented in Fig 6 for each season of the year 2000. All wetlands present minimum water depth in summer, increasing in autumn and reaching the maximum in winter, and decreasing again in spring. This general pattern follows the tributaries discharge behaviour, which is the dominant factor determining the wetlands flooding. However, it is worth noting that the highest discharge peak occurred in the spring, which did not determine higher levels in the wetlands compared to winter.

IV. Conclusions and Outlooks

In the present paper, we analysed the results of a one year hydrodynamic simulation of the Mirim-São Gonçalo complex. The temporal variability of the wetlands water depth is dominated by the river discharge, but spatial differences are associated to the hydrodynamics of the lagoon and the terrain elevation.

Our results showed that the zonal (u) component of the current velocity is different for the North and South Mirim lagoon wetlands. The wind action is responsible for imposing an average setup in the southern part of the Mirim lagoon, though the wetlands of this sector present lower water levels, which may be explained by larger zonal velocities directed toward the lagoon during the winter.

To better address the relationship between the hydrodynamics the water bodies and their fringing wetlands, it is important to perform simulations covering longer periods of time. River discharge and winds are the main factors controlling the hydrodynamic temporal variability in the study region, and both are largely influenced by climate teleconnections such as the El Nino – Southern Oscillation and the Southern Annual Mode. The investigation of such lower frequency variability requires longer-term simulations.

Future studies are being designed to include the Patos lagoon and its surrounding wetlands in the numerical domain, including salt marshes. Additionally, it will allow the representation of a transient connection of the São Gonçalo channel wetlands with the Patos lagoon, which is not considered in the present study.

Acknowledgements

The authors acknowledge the support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the Post-Doctoral fellowships and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under contract 304227/2016-1. Further acknowledgements go to the Brazilian Navy for providing detailed bathymetric data for the coastal area; the Brazilian National Water Agency and ERA-Interim reanalysis project for supplying the validation and boundary conditions data sets, respectively; the Open Telemac-Mascaret Consortium for freely distribution of the TELEMAC system making viable this research, the Deutsches Zentrum für Luft- und Raumfahrt for the TADEM-X digital elevation model, to the Supercomputing Center of the Federal University of Rio Grande do Sul (CESUP-UFRGS) and the National Laboratory of Scientific Computing (LNCC), where most of the computational work was carried out. Although some data were taken from governmental databases, this paper is not necessarily representative of the views of the government.

References

[1] Asmus, M. L. (1998). A PlanícieCosteira e a Lagoa dos Patos. In U. Seeliger, C. Odebrecht, & J. P. Castelo (Eds.), Os ecossistemas costeiro e marinho do extremo sul do Brasil (pp. 9–12). Ecoscientia.

[2] Wang, Z., Zeng, D., & Patrick Jr, W. H. (1996). Methane emissions from natural wetlands. Environmental Monitoring and Assessment, 42, 143–161.

[3] Meng, L., Roulet, N., Zhuang, Q., Christensen, T. R., & Frolking, S. (2016). Focus on the impact of climate change on wetland ecosystems and carbon dynamics. Environmental Research Letters, 11, 1–4.

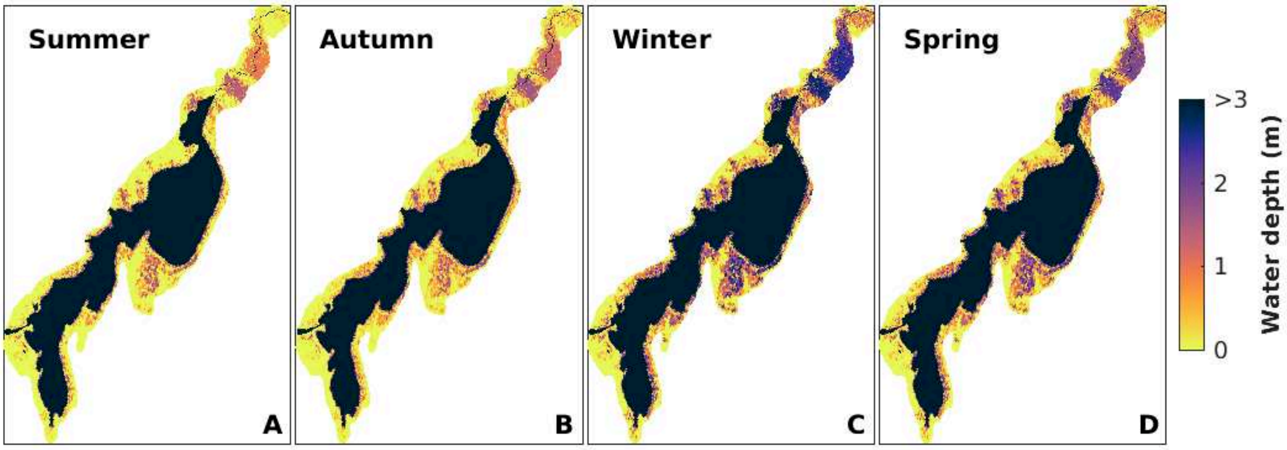

Figure 6: Seasonal average of water depths for the year 2000.

[4] Tomazelli, L. J., Dillenburg, S. R., &Villwock, J. A. (2000). Late Quaternary Geological History of Rio Grande do Sul Coastal Plain, Southern Brazil. Revista Brasileira de Geociências, 30(3), 474–476.G.

[5] Maier, E. L. B., Costi, J., Barreira, S., & Simões, J. C. (2016). Precipitation in South America: climatic means and variability patterns from 1979 to 2008 (Precipitação na América do Sul: medias climáticas e padrões de variabilidade de 1979 a 2008). Revista Brasileira de Geografia Física, 09(01), 32–46.

[6] Costi, J., Marques, W. C., Paula Kirinus, E. de, Freitas Duarte, R. de, & Arigony-Neto, J. (2018). Water level variability of the Mirim - São Gonçalo system, a large, subtropical, semi-enclosed coastal complex. Advances in Water Resources, 117(May), 75–86

[7] DLR, August 2019. TanDEM-X science service system.https://tandemx-science.dlr.de.

[8] Medeiros, S. C., & Hagen, S. C. (2013). Review of wetting and drying algorithms for numerical tidal flow models. International Journal for Numerical Methods in Fluids, 71(4), 473–487.

[9] G. Duchossois, P. Martin, "ERS-1 and ERS-2 Tandem Operations," ESA Bulletin, No. 83, August 1995, pp. 54-60.

[10] Duarte, R. F. (2013). Monitoramento das areas úmidas e inundadas adjacentes ao Canal São Gonçalo com uma série de imagens ERS-1/2 SAR e Envisat ASAR adquiridas entre 1992 e 2007 (Universidade Federal do Rio Grande).

[11] da Silva, D. V., Oleinik, P. H., Costi, J., de Paula Kirinus, E., & Marques, W. C. (2019). Residence time patterns of Mirim Lagoon (Brazil) derived from two-dimensional hydrodynamic simulations. Environmental Earth Sciences, 78(5), 163.