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MIXING PROCESS EVALUATION DUE TO SEA LEVEL RISE IN BABITONGA BAY, BRAZIL

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ABSTRACT: The Babitonga bay, located in the state of Santa Catarina, Brazil, is an estuarine system of great social and economic importance, that can be highly affected by climate changes effects. These effects include the water level increasing due to Sea Level Rise (SLR) that can be impact the circulation of the bay. In this work, effects in the circulation and mixing processes in the Babitonga bay due to SLR are evaluated. The Water Renewal Rate (WRR) and the Water Age (WA) are used as indicators for the evaluation of the effects. A hydrodynamic model was calibrated and validated for the year 2019, taken as a baseline scenario, and two representative scenarios of SLR due climate change, defined by the Inter-Governmental Panel for Climate Change (IPCC), for the year 2100, were analyzed. WRR and WA were calculated for the Summer and Winter periods for the year 2019, and also for four different projected scenarios for the year 2100. The renovation process is more efficient in the Summer because of the influence of the freshwater discharge. The results showed a reduction in the WRR for the year 2100, and, consequently, an increase in the WA, using the 2019 as the comparison scenario.

Keywords: Babitonga bay, Climate Change, Sea Level Rise, Water Renewal Rate, Water Age.

RESUMO: *A baía da Babitonga, localizada no estado de Santa Catarina, Brasil, é um sistema estuarino de grande importância social e econômica, que pode ser afetado pelas mudanças climáticas. Esses efeitos incluem o aumento do nível da água devido ao aumento do nível do mar (SLR) que pode afetar a circulação da baía. Neste trabalho são avaliados os efeitos na circulação e nos processos mistura na baía da Babitonga devido ao SLR. A Taxa de Renovação (TR) e a Idade da Água (IA) são utilizadas como indicadores para avaliar os efeitos. Um modelo hidrodinâmico foi calibrado e validado para o ano de 2019, tomado como cenário base, e dois cenários representativos de SLR devido a mudanças climáticas, definidos pelo Painel Intergovernamental para Mudanças Climáticas (IPCC), para o ano de 2100, foram analisados. TR e IA foram calculados para os períodos de verão e inverno para o ano de 2019, e também para quatro diferentes cenários projetados para o ano de 2100. O processo de renovação é mais eficiente no verão devido à influência da descarga de água doce. Os resultados mostraram uma redução no TR para o ano de 2100 e, consequentemente, um aumento no IA, usando o ano de 2019 como cenário de comparação.*

Palavras-chave: *Baía da Babitonga, Mudanças Climáticas, Elevação do Nível do Mar, Taxa de Renovação das Águas, Idade da Água.*

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1. INTRODUCTION

Babitonga Bay, located on the coast of the state of Santa Catarina, Brazil, forms an environmental complex with extensive mangrove regions, that plays a significant ecological role. Babitonga bay is near the Joinville City, the state biggest city, and is surrounded by other cities (Itapoá and Balneário de Barra do Sul), with an approximately permanent population of 620.000 inhabitants (Figure 1). As it constitutes an important natural breeding place for mollusks, crustaceans, and fishes. The bay has two harbors (São Francisco do Sul and Itapoá) and, due to the industrial development of the area surrounding it, it has been subjected to different environmental impacts, such as the increasing in the organic and industrial pollution (Knie, 2002). Few studies concerned with circulation and interaction between mixing processes and circulation, in Babitonga bay, are found in the literature, see, for instance (Truccolo & Schettini, 2010 and Noernberg *et al*., 2020). Bearing in mind that coastal areas can be highly affected by the effects of climate change, it must be noted that there are no studies concerned with these effects on circulation and mixing processes in the bay.

According to the IPCC - Intergovernmental Panel on Climate Change - (IPCC, 2014), global climate change can impact coastal regions, favoring an increasing in the water level due to the sea level rise (SLR), changing the rainfall regimes, as a result of intensified extreme weather events, and altering the wind field. According to Oppenheimer *et al*., 2019, SLR projections indicate a likely rise between 0.29 m and 1.10 m for optimistic and pessimistic scenarios, respectively, by 2100. Among the expected consequences brought by the sea level rise, more frequent inundation in coastal regions, shoreline recession, drastic changes in the hydrodynamic regime in bays and saline intrusion into groundwater (Hu & Deser, 2013; Yin *et al*., 2017; Befus *et al*., 2020) must be expected and taken into account. Current studies on climate change in Brazil emphasize the increase in the average global temperature, the influence that deforestation in Amazon rainforest has on the hydrological cycle, and extreme weather events, considering changes in atmospheric circulation (Marengo *et al*., 2018; Gatti *et al*., 2021). To address this knowledge gap, even if partially, this study investigates the effect of sea level rise on the mixing processes of bays and estuaries. It is important to consider, in this context, the proper management of these areas and a reliable prediction of the effects brought about by global climate changes, as these regions are extremely susceptible to the impacts resulting from these changes.

Renewal time scale is an important parameter for the quantitative assessment of water renewal on estuaries and bays. The Water Renewal Rate (WRR) and Water Age (WA) are commonly used as the mixing parameters in bays, facilitating the identification of stagnation areas. WRR can be understood as the rate of the water exchanged within a domain of interest, representing how much of the water was renewed in different regions of this domain. The complement of the renewal rate is the percentage of the water not renewed. The WA indicates the average time that the water parcels, for a given position of the domain, remain in that position, as the flow circulates through this domain (Aguilera *et al*., 2020).

Sea level rise is a worldwide concern, as a high percentage of the population is in coastal areas. Studies that show the impacts of climate change in coastal regions can be found in the literature. Yang *et al*., 2015, using a hydrological model and a hydrodynamic model applied to the estuary of the Snohomish River, in Washington, USA, investigated the estuarine hydrodynamic response to sea-level rise and change in river flow due to the effect of future climate changes and human development. The results suggest that in the inundated areas the average water depth increases linearly with sea-level rise, but at a slower rate. Prandle & Lane, 2015 investigated how tidally dominated estuaries will adapt to the increasing of the mean sea level and to the changes, associated with global climate change, in river discharges. They developed generic vulnerability Indices to provide indications of relative resilience or sensitivity and applied them to 96 estuaries in England and Wales. The results suggest that a mean sea level rise of 1 m will have little effect on mass transport but will have significant impacts on energy dissipation levels, especially in depths less than 10 m, small impacts on levels of vertical mixing in deeper estuaries, but a significant impact in shallow estuaries. Polli *et al*., 2020 evaluated the effects on the circulation of the Paranaguá Estuarine Complex (PEC), caused by wind, freshwater flow, and sea level rise due to climate change for the year 2050. A harmonic analysis showed that the diurnal harmonics are amplified and that the higher increase occurs in the internal regions of the PEC.

Babitonga Bay will be impacted by the sea level rise due to climate changes, and the major consequences will be the increase of the salinity intrusion length, the increase in flooding area and alterations on the circulation and the mixing processes. The main purpose of this work is to evaluate the response of the Babitonga bay to the sea level rise due climate changes from the point of view of the mixing processes. With this aim, a hydrodynamic model was calibrated and validated for the year 2019. Then, two simulations were carried out for year 2100, for different sea level rise scenarios, as projected by the IPCC. As changes in sea level inevitably alter the hydrodynamics, a comparative study was developed to show how the sea level rise will modify the internal circulation, the water renewal rate and the water age of the estuarine region, between the baseline year, 2019, and the year 2100. This study aims to address the following questions: (1) What forcings influence the mixing processes? (2) How does sea level rise influence mixing processes? (3) Which regions of Babitonga bay will be affected by the sea level rise?

2. MATERIALS AND METHODS

2.1 Study area

Babitonga bay is located at Southern Brazil, longitude 46.67º W and latitude 26.26º S (Figure 1), with an area of 160 km^2, extending 30 km from SE to NW, forming one elongated and narrow axis, and its central channel, with about 24 km, is oriented to NE/SW. Figure 2b present Babitonga bay's bathymetry, with mean depth varying from 5.7 m up to 27 m, in the main channel, and less than 5 m in most of the bay. As shown in Figure 2a, the bay is separated from the Atlantic Ocean by one connection. The drainage basin has an area of 1560 km^2 (Paitach *et al*., 2017). The region is under a Humid Tropical Climate; with the mean annual precipitation about 2000 mm (Mello *et al*., 2015). The intense precipitation occurs in the period between October and March, in the austral Summer, which also presents higher temperatures, and the monthly means precipitation is close to 250 mm. In the austral Winter, between April and September, the influence of polar air masses causes a decline of temperature and precipitation, with monthly means less than 100 mm.

The Babitonga bay is dominated by a microtidal regime that presents semidiurnal tide with diurnal inequalities. The main components of astronomical tides are M2 and S2. The longitudinal distribution of salinity is controlled by a combination of tidal effects and freshwater input. According to Noernberg *et al*., 2020, Babitonga bay has been classified as a weakly stratified estuary with small seasonal variations. The seasonal variation in the freshwater affects the salinities but not enough to change the weakly stratified pattern. In the Summer, especially in the neap tide, the bay condition can change to well mixed during Winter springs, when the fluvial contribution is significantly smaller than it is in the Summer. Indeed, the intratidal and spring–neap cycle is more important in governing the circulation at Babitonga Bay than the seasonal scale. Water temperature and salinity present a seasonal variation – the former varies from 27 ºC to 32 ºC in Summer, and between 18 ºC and 23 ºC in Winter, and the latter varies from 17 to 27 psu during Summer and, in Winter, between 15 and 28 psu (Noernberg *et al*., 2020).

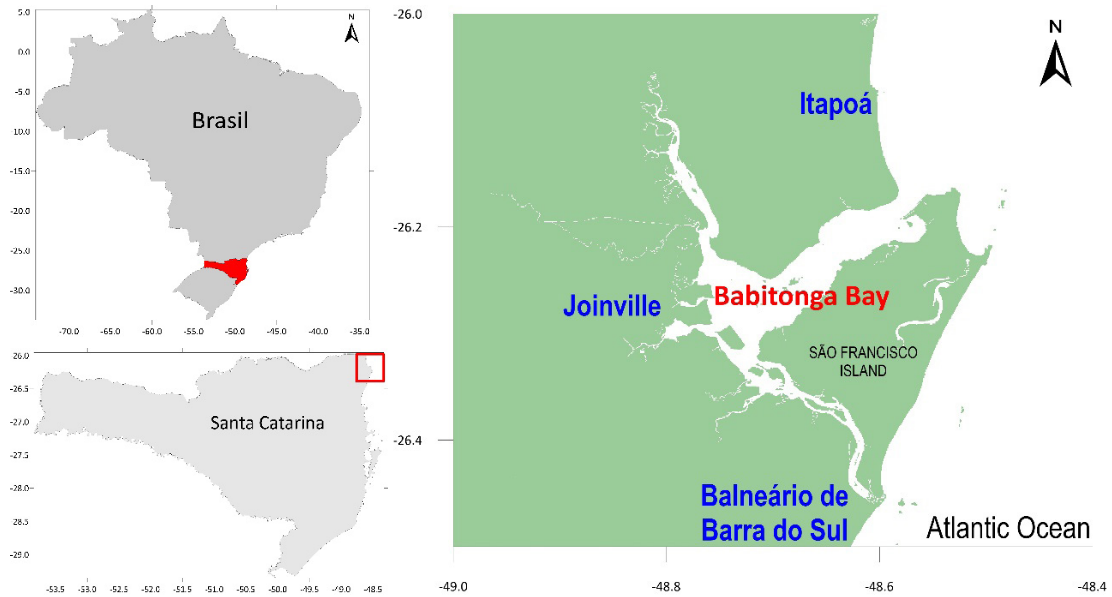


Figure 1. Location of the Babitonga bay.

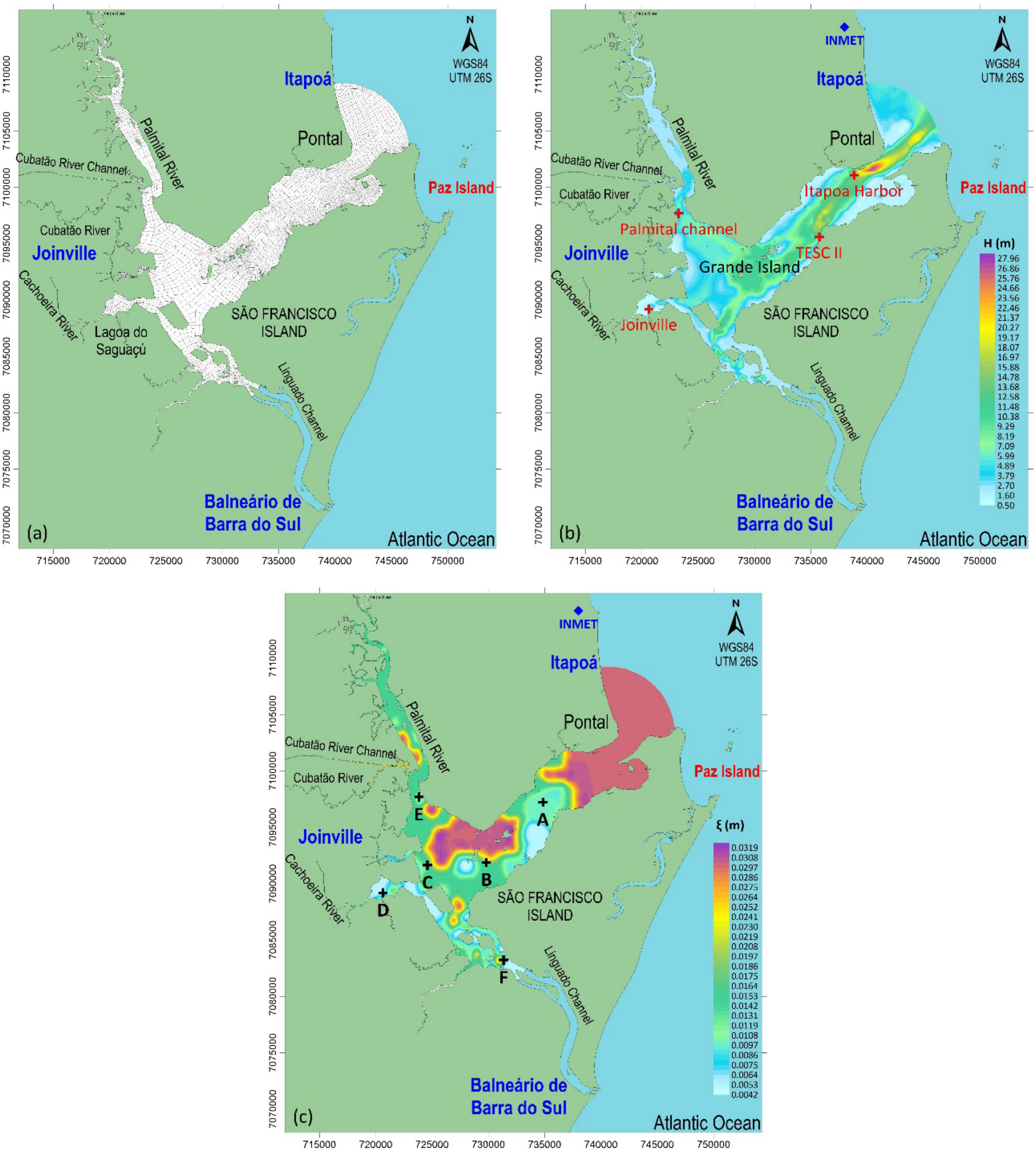


Figure 2. Modelling domain of Babitonga Bay. a) SisBaHiA modeling domain, main rivers and finite element mesh, b) bathymetry and locations of stations where water levels, velocities and wind were measured in 2019 and c) amplitude of the equivalent bottom roughness, ξ, as well as the other monitoring stations, labelled as A-F.

2.2 The hydrodynamic and transport models

The hydrodynamic and transport modelling were performed using the Hydrodynamic Environmental System called SisBaHiA® (Portuguese acronym for Base System of Environmental Hydrodynamics). For more information, the interested reader is referred to Rosmanm, 2021 and www.SisBaHiA.coppe.ufrj.br.

Two models were used in this work: the hydrodynamics model, used to simulate the Babitonga bay hydrodynamics, and the transport model, used to analyse the water renewal, i.e., WRR and WA.

The transport model uses an Eulerian approach for non-conservative parameters, which permits the analyses of parcels of water at different locations over time, to obtain the time evolution of the renewal rates at different points of the study domain. The transport model also uses the same spatial grid applied for the hydrodynamics model and allows for the use of different time step lengths in the analyses. The advantage of coupling the two models, as in the current work, appears in the determination of the velocities and turbulence coefficients, which is done previously in the hydrodynamic model, and that can be used directly in the transport model (Rosman, 2021).

WRR was calculated for simulating the transport of a conservative constituent along the domain by advection and diffusion processes. At the initial moment, 0 % WRR was assigned to all the waters inside the domain of interest, i.e., the conservative constituent concentrations are assumed to be equal to zero. As for the waters entering the domain by the open boundaries or through other inflows, such as rivers, they have a reference value equal to 100%, meaning that the conservative constituent concentrations are equal to 100. Thus, new water with 100% reference value is mixed with initial water of 0% reference value and an intermediary value is computed, indicating the percentage of mixing at any given point in time (Aguilera *et al*., 2020). The values resulting from these simulations represent the percentage of the mixing of new and old waters in each position of interest.

In this work, the decay of an age-marker passive substance presented in water, is estimated as the WA. For this being possible, it is necessary that this age-marker substance has a first-order decay kinetic reaction with a constant and positive decay rate, and that other effects of loss or gain in mass are not taken into account. Thus, it is assumed that a uniform well-mixed volume of water in the whole domain has an initial concentration of the age-marker substance equal to 1.0. Consequently, the WA is zero. The new waters that enter the domain by the open boundaries or through other inflows have WA equal zero, i.e., the concentrations of the age-marker substance are equal to 1.0. As the initial waters and the new waters, both with WA = 0, were mixed and transported through the domain, and the concentration of the substance will decrease due to the decay process, consequently, the WA value will become different at each point because it depends on the magnitude of the currents and on the turbulence at each location (Aguilera *et al*., 2020 and Rosman, 2021).

2.3 Setup of calibration and validation of the hydrodynamic model

The calibration and validation of the hydrodynamic model were performed for the year 2019. The calibration period was performed between 01/12/2019 and 03/12/2019, in Summer, and the validation period carried out between 05/01/2019 and 06/30/2019, in Winter. During these periods, water levels were measured (tidal elevation) by the Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina (EPAGRI) at four stations: Paz Island, Itapoá Harbor, TESC II and Joinville (Figure 2b), with measurements collected at 15-minute intervals. Water levels measured at Paz Island station were used as an ocean open boundary condition and data measured at Itapoá Harbor, TESC II and Joinville stations were compared with the ones furnished by the model (the sites are identified in Figure 2b). Figure 3 shows the tide curves between January 12th- March 12th and May 1st- June 30th. The Babitonga bay exhibits a semidiurnal tidal regime, with maximum ranges of 1.78 m and 1.60 m and maximum tide heights of 1.98 m and 1.80m, in Summer and Winter, respectively. In the Summer, the storm surges were observed between 01/19/2019 and 01/21/2019, 02/03/2019 and 02/06/2019, 02/11/2019 and 02/15/2019. During the calibration (Summer 2019) and validation (Winter 2019) periods, Noernberg *et al*., 2020 carried out measurements of North-South and East-West components of the current at Palmital channel (the site is identified in Figure 2b), between 01/25/2019 and 02/10/2019, and 06/19/2019 and 06/30/2019. For current measurements, an ADCP (Acoustic Doppler Current Profile) anchored at 5.0 m depth was used in both Summer and Winter periods, with values recorded at every 15 minutes.

The mesh consists of 1455 sub-parametric Lagrangian quadrilaterals elements, 6669 nodes, available from baiasdobrasil.coppe.ufrj.br is shown in Figure 2a. The bathymetry of the Babitonga Bay - mean depth is 5 m, was obtained through nautical charts from DHN (Diretoria de Hidrografia e Navegação, in English: Directorate for Hydrography and Navigation) number 1804 (scale 1: 27,000) and studies carried out in the region with the collaboration of EPAGRI, shown in Figure 2b. The bottom friction coefficient depends on the amplitude of the equivalent bottom roughness (ξ) defined from the composition and distribution of bottom sediments. Babitonga bay is characterized by the predominance of fine and medium sand (ξ< 0.030 m); but coarse sand banks (ξ > 0.035 m) can be found at the entrance and, in an inner region of the bay and near the mouth of the rivers, silt (ξ < 0.02 m) predominates (Figure 2c). The time interval used in the hydrodynamic circulation simulations was 60 seconds, which corresponds to an average Courant number equal to 5.6.

There is no accurate information concerning the discharges data of the contributing rivers of Babitonga bay in the literature (Noenrberg *et al.*, 2020). For the calculation of river discharges for the year 2019, using the Rational method. With the data of areas, slopes, axial length of rivers and monthly rainfall data, available from INMET (Instituto Nacional de Meteorologia, in English: National Institute of Meteorology), it was possible to calculate the average monthly discharges for the Summer and Winter months for each watershed. The largest contributor is the Cubatão River, which represents 33.6% of the total freshwater input into the bay, followed by the Sambaqui, Parati and Três Barras rivers, which together represent 18.8%. It is estimated that the sum of the average monthly discharges in the Summer is approximately 71 m³/s, which is about three times greater compared to the Winter, in which is approximately 24 m³/s.

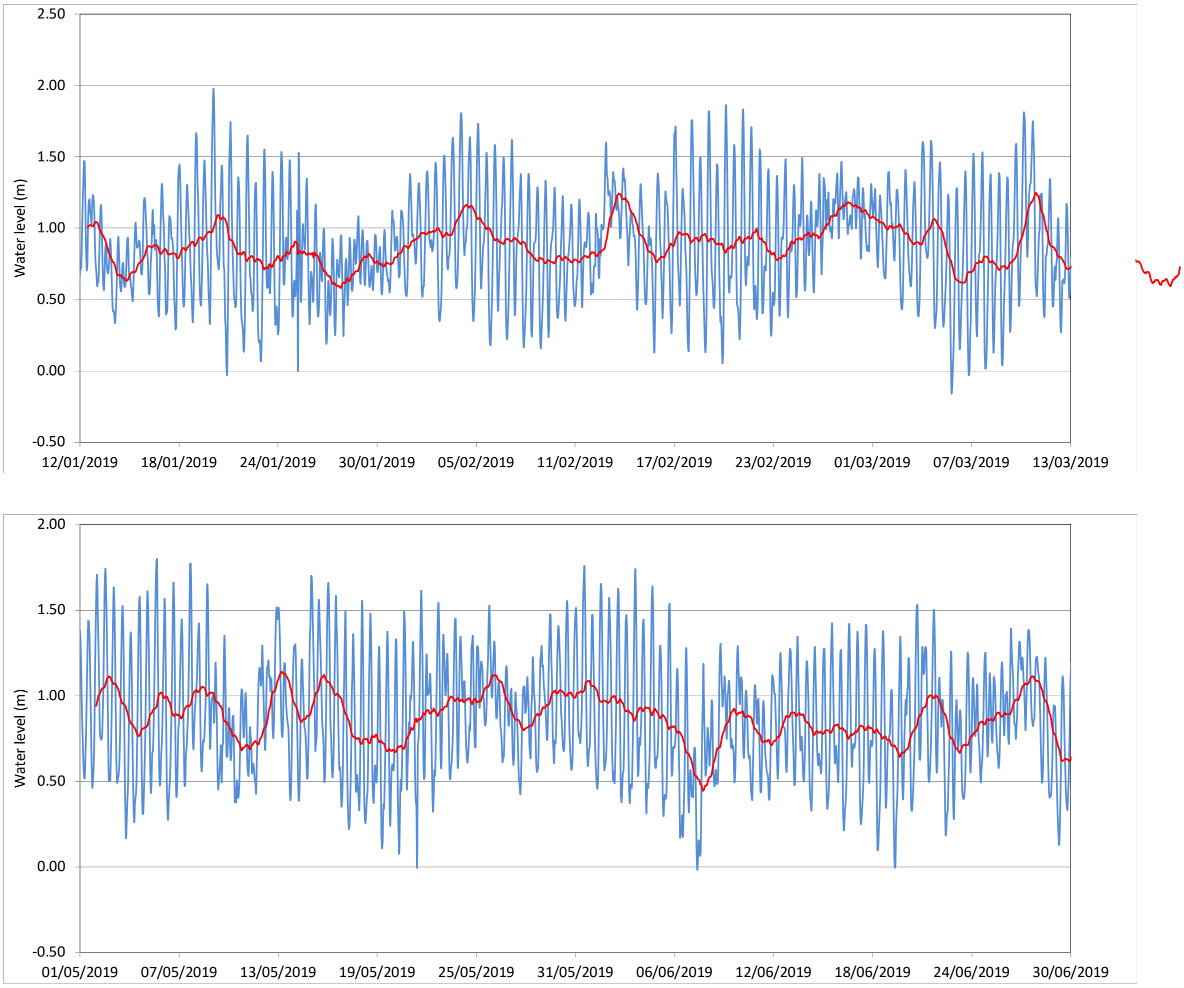


Figure 3. Water level (m) at Paz Island from 12 January to 12 March 2019 and 01 May to 30 June 2019. The red curve corresponds to the 24-hour moving average.

Wind conditions were assumed unsteady but spatially homogeneous. Wind speed and direction were provided by INMET Station (Figure 2b). Figure 4 shows the wind rose for Summer, between January and February 2019, and for the Winter, between May and June 2019. In the Summer, winds from the WSW and ENE are most frequent, about 25% of the time with an average speed of 1.38 m/s (maximum of 5.9 m/s); in the Winter, winds from the WSW and SW are the most frequent, 27% of the time with an average speed of 0.44 m/s (maximum velocity equal to 5.1 m/s). In order to simulate the hydrodynamic circulation, water level (Figure 3), freshwater discharge and wind (Figure 4) from the 2019 data were provided for the two periods.

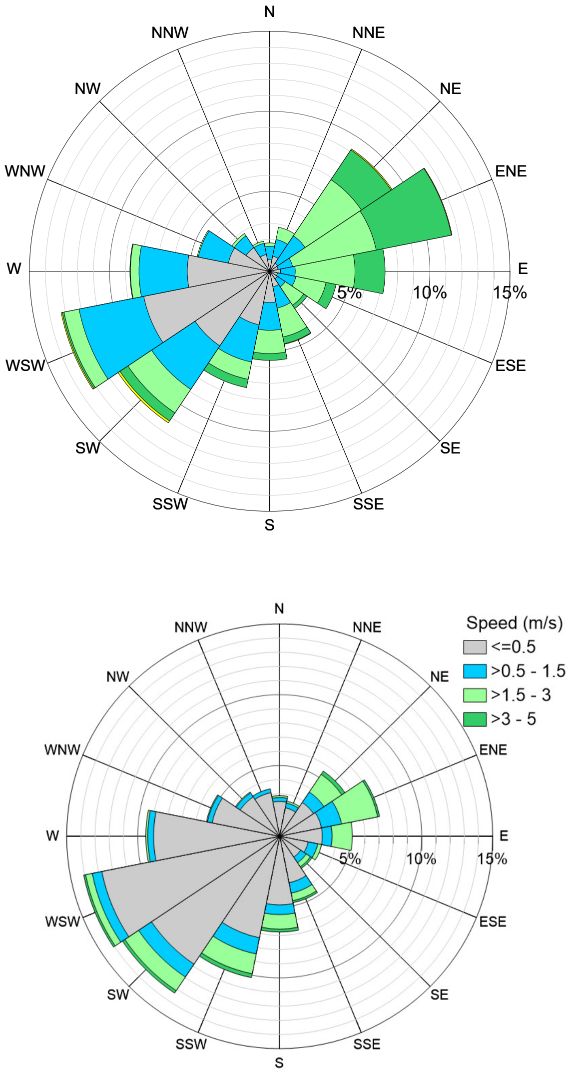


Figure 4. Wind rose for data obtained at INMET station in the Summer (above) and Winter (below) 2019.

2.4 Climate change data set – SLR projections

The year 2019 constitutes the baseline scenario and future scenarios for the year 2100, that can be classified either as middle range/optimistic or as pessimistic, were built considering two Representative Concentration Paths (RCPs), RCP 4.5 and RCP 8.5, from IPCC (Moss *et al*., 2010). Wind field and river discharges for the two future scenarios are the same used in the calibration and validation simulations. Polli *et al*., 2021 analyzed variations in the wind field and freshwater due to climate change in the circulation of the Paranaguá Estuarine Complex (CEP), and concluded that the differences in the wind field and freshwater discharge were relatively small for the different IPCC scenarios for year 2050. Considering that CEP and the Babitonga Bay have similar climatic characteristics, it seems reasonable that the wind field and the river discharge data from 2019 could be used in the simulations of future climate change scenarios.

The global projections of the Mean Sea Level (MSL) presented by the IPCC indicate values on a global scale. For the projections on a regional scale and, more specifically, for the region of the Babitonga bay, the values used in this work were generated through projections carried out by the Coastal Modelling System of Brazil (SMC-Brazil). The SMC-Brazil is a set of methodologies and numerical tools that allow for better understanding of coastal systems, as well as a more reliable design of actions on the coast. SMC-Brasil can estimate global and regional sea level rise for IPCC scenarios along the Brazilian coast. The historic sea level rise database includes series of monthly distributions of large-scale sea level variability and changes over the period from 1950 to 2000 for the global ocean. This database is included as a set of series along the Brazilian coast, which are used to estimate sea level trends. The database considers two scenarios (RCP 4.5 and RCP 8.5) and two projections (2070 and 2100) (Quetzalcóatl *et al*., 2019).

After the calibration and validation simulations, called as scenarios C and V, respectively, four simulations for the climate change scenarios, for the year 2100, were performed: RCP 4.5, Summer period, scenario S1; RCP 8.5, Summer period, scenario S2; RCP 4.5, Winter period, scenario S3; RCP 8.5, Winter period, scenario S4. In all six scenarios, the total simulation time was 60 days in the hydrodynamic circulation. In the S1, S2, S3 and S4 scenarios, mesh, bathymetry, bottom roughness, wind data and river discharges, corresponding to Summer and Winter periods of 2019 were used, with only the open boundary condition being altered.

Sea level risings equal to 67 cm and 86 cm were prescribed, respectively, for S1 and S2, and for S3 and S4 scenarios. Then, these prescribed values are added to the tidal curves measured for the Summer and Winter periods of 2019. Then, the Eulerian transport model were applied for the above mentioned six hydrodynamic scenarios, for 230 days, accounting approximately for 3.0 cycles of hydrodynamic circulation.

3. RESULTS

3.1 Calibration and validation of the hydrodynamic model

The calibration and validation of the hydrodynamic model were performed for the year 2019. Figure 5 shows the simulated water level vs. the field data for the three monitoring stations – Itapoá Harbor, TESC II and Joinville during calibration period, scenario C. The model showed excellent agreement with the phase and the amplitude. The calculated statistical parameters show that the measured data were accurately reproduced by the model. The correlation coefficients (R^2) are close to 1.0: 0.9712, 0.9529 and 0.9471 for Itapoá Harbour, TESC II and Joinville stations, respectively. Mean Absolute Errors (MAE) were calculated and show deviations of less than 0.161 m, also an excellent result. The results for Itapoá Harbour, TESC II and Joinville were 0.062 m, 0.080 m and 0.161 m, respectively. The Root Mean Square Errors (RMSE) were 0.085 m, 0.123 m and 0.130 m for Itapoá Harbour, TESC II and Joinville, respectively. It is possible to observe that the Joinville station, in the shallowest region from the three monitoring stations evaluated, presents the worst adjustment. This behaviour is common in the inner regions of the bays due to the presence of shallower regions. Therefore, at this station, the adjustment is worse due to the tidal wave amplification processes. These processes are strongly influenced by bathymetry; however, the bathymetry of the Saguaçu lagoon, used in the modelling, is outdated, and its impact on the results should be considered with caution.

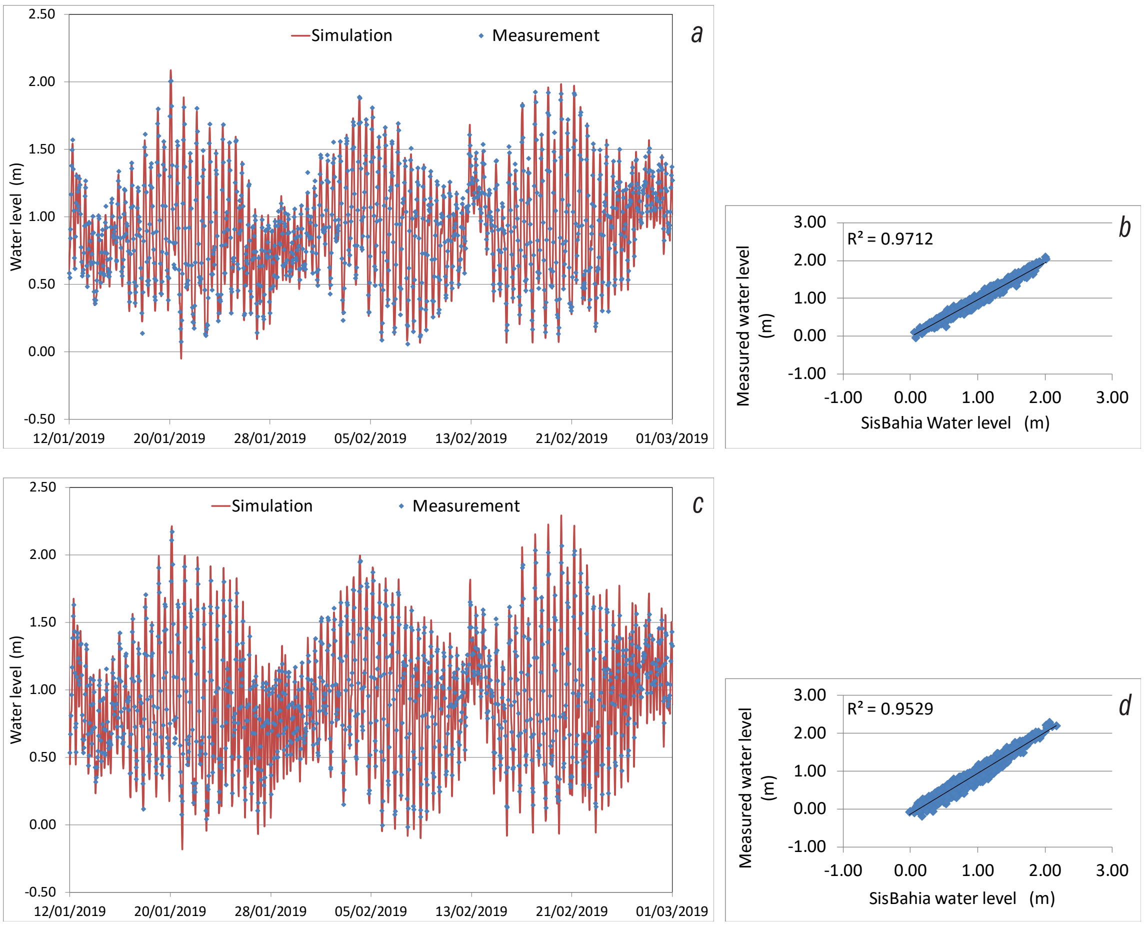
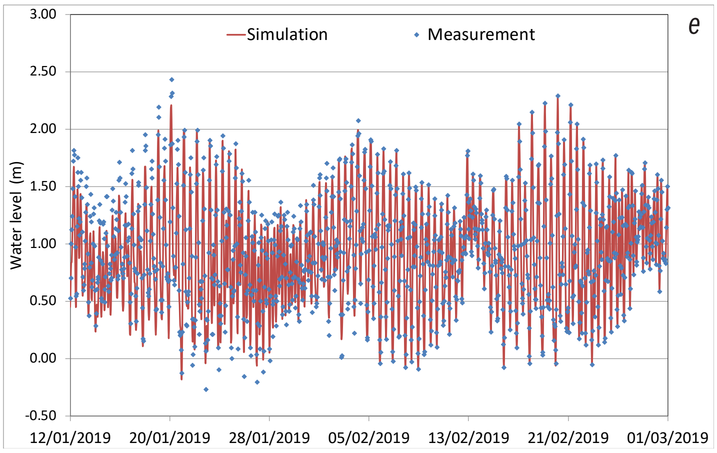


Figure 5. Water level simulated vs. field data at: a) Itapoá Harbor, c) TESC II, and e) Joinville stations, during calibration period, scenario C. Measured and simulated water elevation dispersion diagram at: b) Itapoá Harbor, d) TESC II, and f) Joinville.



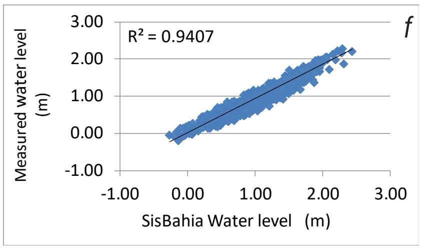


Figure 5 (continuation). Water level simulated vs. field data at: a) Itapoá Harbor, c) TESC II, and e) Joinville stations, during calibration period, scenario C. Measured and simulated water elevation dispersion diagram at: b) Itapoá Harbor, d) TESC II, and f) Joinville.

Figure 6 shows the comparison between the measured data, measured data filtered at 4 hours and the results calculated by SisBaHiA® for the North-South (NS) and East-West (EW) components of the current for the Summer period. The comparison between the simulated vs. field data for the NS component showed a good adjustment in what concerns the phase. At high water spring, the values obtained by the model are amplificated relatively to the measured data filtered. The same behaviour can be observed in relation to the EW component of the current. The values of the RMSE, MAE and R^2 can be considered acceptable for NS component. The R^2 is 0.6770, indicating a good correlation, MAE is 0.149 m/s and RMSE is 0.183 m/s. It is worth mentioning that the loss of the model quality, for the EW component, is probably due to the inconsistency of the bathymetric data for the region (R^2=0.4512, MAE=0.065 m/s, and RMSE = 0.080 m/s).

Figure 7 shows the water level elevation for the three monitoring stations during the validation period. The model showed excellent agreement with the phase and amplitude, with R^2 equal to 0.9779, 0.9698 and 0.9176. MAE was also calculated, and the results are: 0.065 m, 0.086 m, and 0.183 m; RMSE are: 0.081 m, 0.098 m and 0.269 m. Figure 8 shows the results obtained by the model during validation periods for the North-South (NS) and East-West (EW) components of the current. The R^2 are above 0.670, with a greater RMSE equal to 0.151 m/s, and with MAE smaller than 0.126 m/s.

3.2 Water renewal rate and water age: current and future scenarios

Six stations, labelled as A, B, C, D, E and F, were established (locations shown in Figure 1c), with the aim of characterizing the different compartments of Babitonga Bay. WRR and WA were calculated for the following scenarios: C, V, S1, S2, S3 and S4. After 230 days of simulation, all the stations reached the equilibrium. In natural flows, the equilibrium is dynamic, and, after enough time of simulation has elapsed, the WRR fluctuates around a value, depending on the hydrodynamic forcings, such as tides or river flows, for example.

Figure 9 shows the temporal evolution of the WRR in the six stations, for Summer period. Stations A and E showed the greatest oscillations. The oscillations observed at station A are due to the tidal effect, while in station E they are influenced by the river flows. The WRR's difference between the scenarios is small at station A, considering that the region is close to the ocean boundary, with little influence from the river flows. It is also possible to observe that the fluvial flow is an important forcing in the renewal process in the regions close to the tributaries, promoting a significant increase in the WRR's, as occurs in Saguaçu Lagoon (station D). The differences between the WRR's considering climate change (scenarios S1 and S2) and the current situation (scenario C) are minimal in the Summer, which shows the great influence of river flows on the water renewal process. However, the waters are renewed more slowly in the S2 scenario for all the stations.

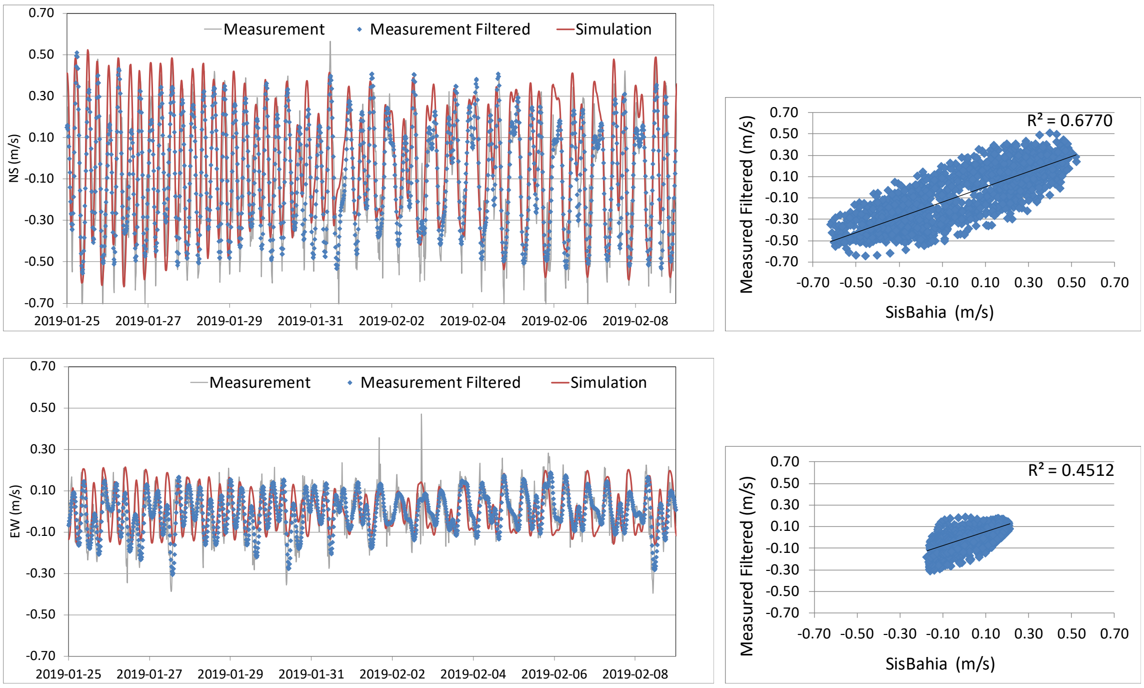


Figure 6. NS and EW components of the current simulated vs. field data and dispersion diagram at Palmital Channel station during calibration period, scenario C.

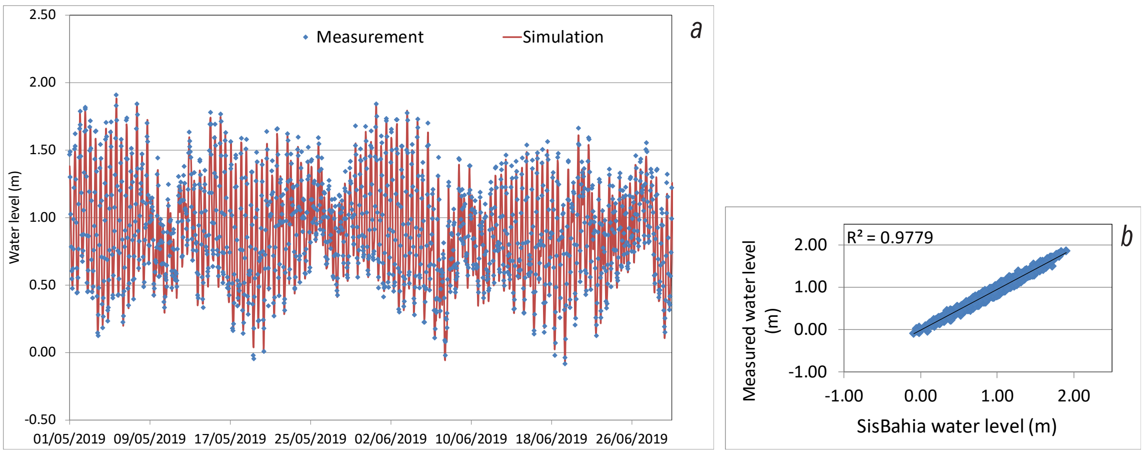


Figure 7. Water level simulated vs. field data at a) Itapoá Harbor, c) TESC II and e) Joinville stations during validation period, scenario V. Measured and simulated elevation dispersion at a) Itapoá Harbor, c) TESC II e) Joinville.

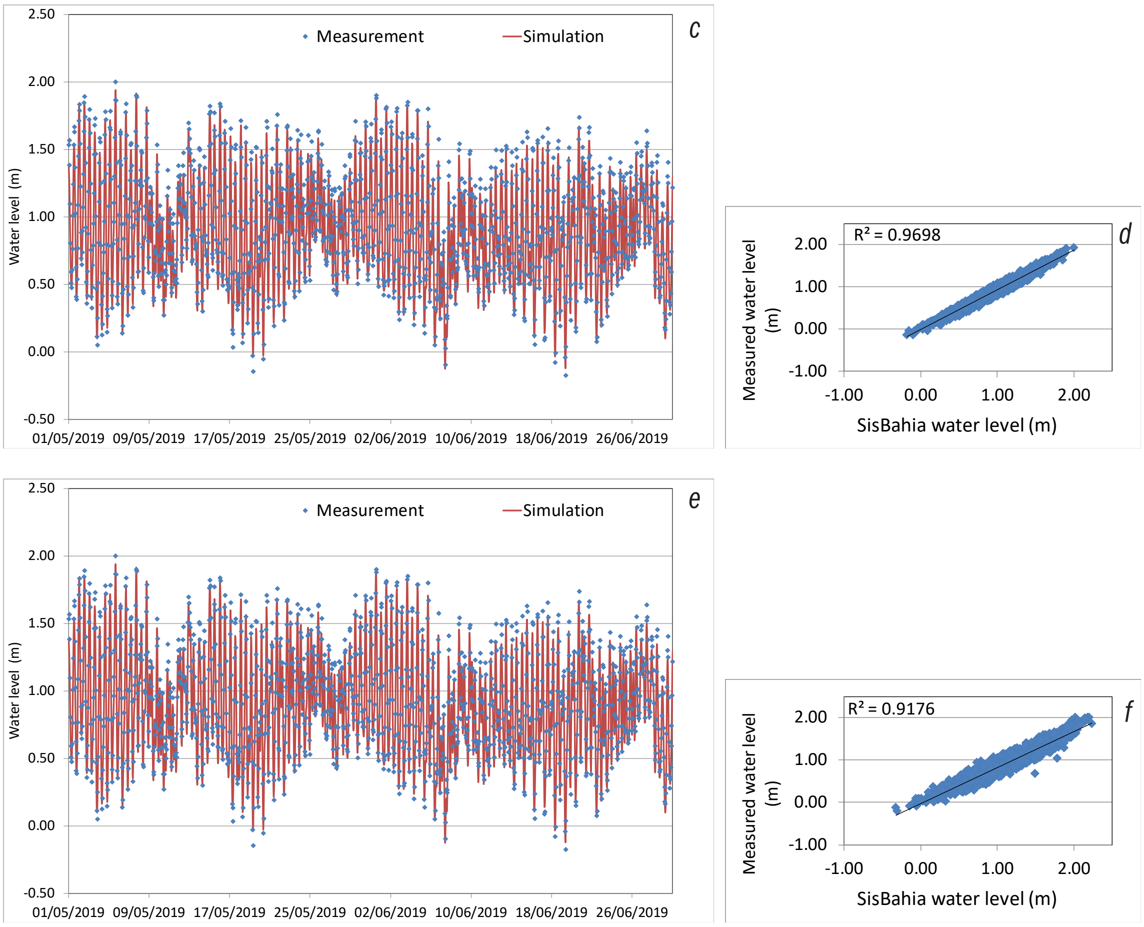


Figure 7 (continuation). Water level simulated vs. field data at a) Itapoá Harbor, c) TESC II and e) Joinville stations during validation period, scenario V. Measured and simulated elevation dispersion at a) Itapoá Harbor, c) TESC II e) Joinville.

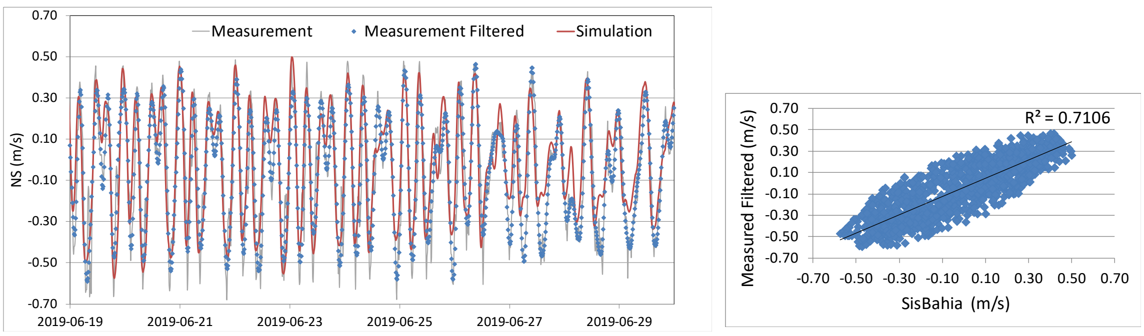


Figure 8. NS and EW components of the current simulated vs. field data and dispersion diagram at Palmital Channel station during validation period, scenario V.

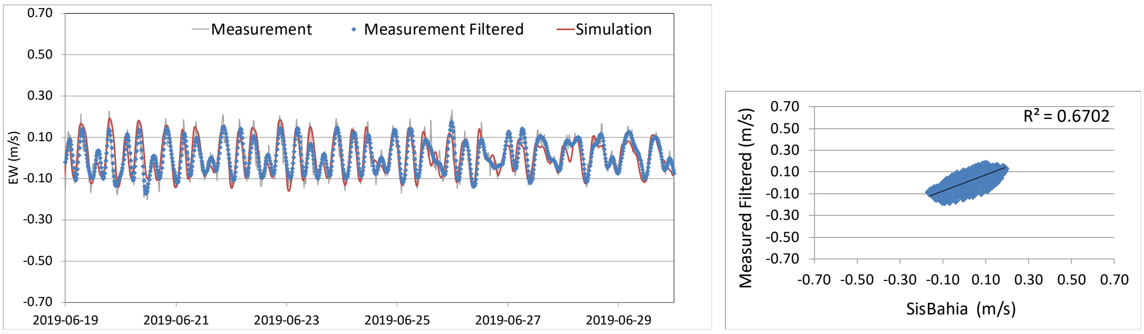


Figure 8 (continuation). NS and EW components of the current simulated vs. field data and dispersion diagram at Palmital Channel station during validation period, scenario V.

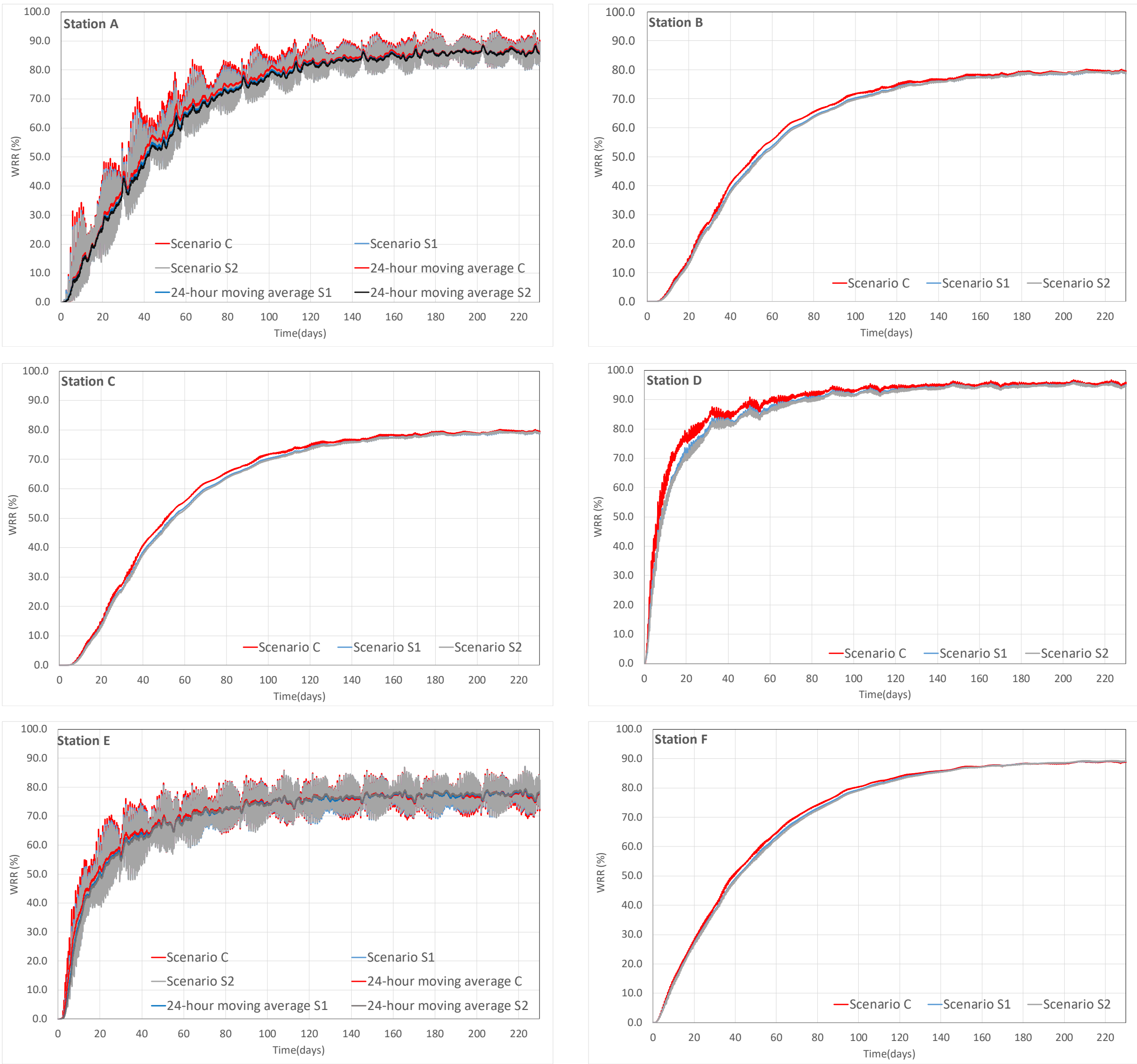


Figure 9. Water Renewal Rates in scenarios C (2019), S1 (2100 RCP 4.5), and S2 (2100 RCP 8.5) at the stations A, B, C, D, E and F.

Figure 10 shows the temporal evolution of the WRR's for Winter scenarios. As for the representative Summer scenarios, the waters are renewed more slowly in the S4 scenario, which is the most pessimistic scenario of climate change. Despite the differences between S3 and S4 scenarios be smaller than the differences between the S1 and S2 scenarios, because the river flows are significantly lower in the Winter than are in the Summer, it can be stated that the river flow remains important in the process of water renewal. For scenarios S3 and S4, considering the sea level rise, there is a reduction in the WRR, the difference between S3 and S4 being more significant than the difference between S1 and S2. The WA is inversely proportional to the WRR, so it will present a more significant increase for the scenarios that correspond to the Winter period.

Figure 11 presents of isolines of WA's for the scenarios V, S3 and S4 at the end of the simulation. Considering that in the Winter the fluvial contribution is small, the results clearly show the influence of river flows in the Saguaçu Lagoon (station D), and the influence of tides in the northeast part (station A); at station D, the WA values double from Summer to Winter.

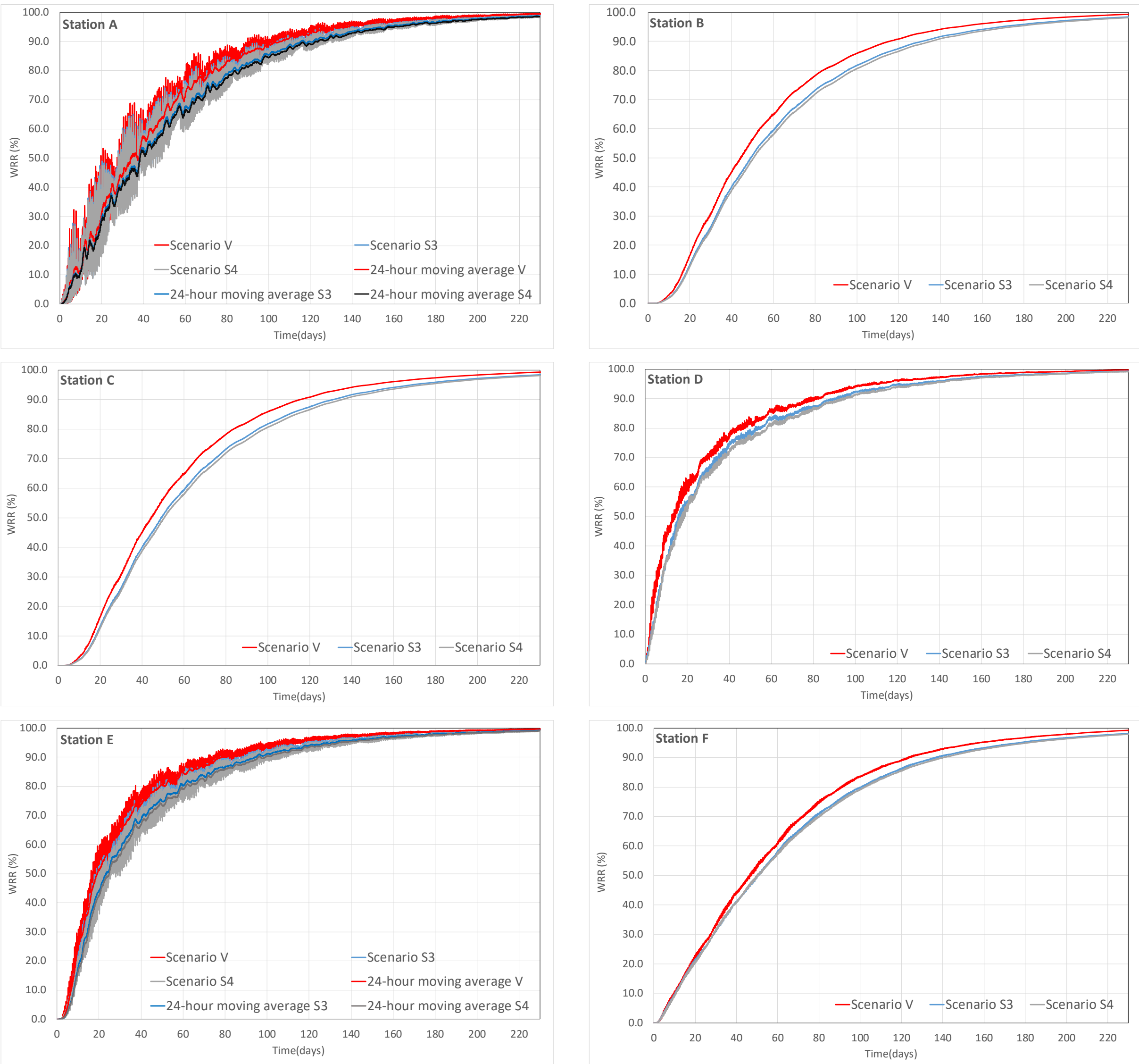


Figure 10. Water Renewal Rates in the scenarios V (2019), S3 (2100 RCP 4.5) and S4 (2100 RCP 8.5) at the stations A, B, C, D, E and F.

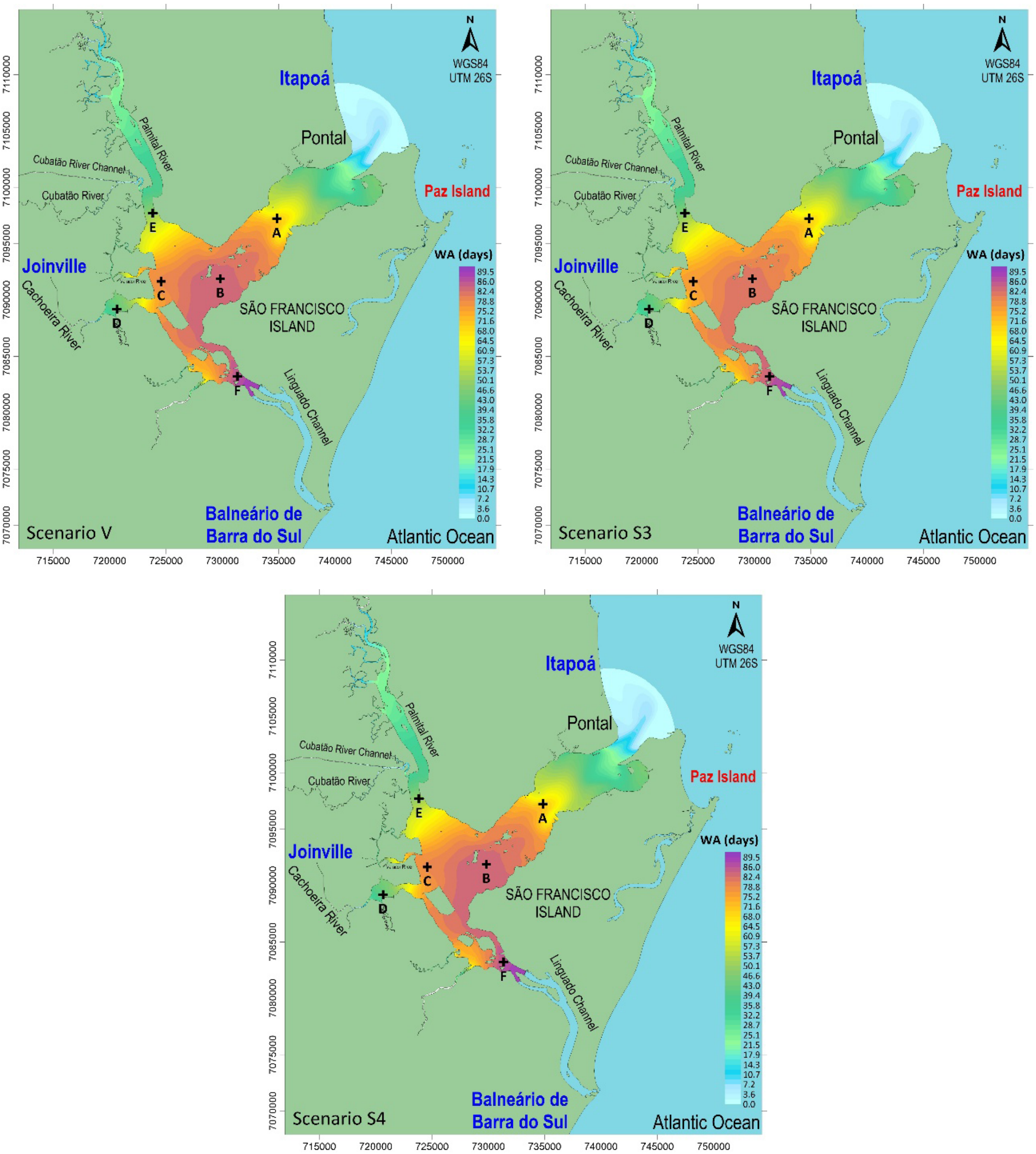


Figure 11. Map of isolines of Water Ages at the end of the simulation for the scenarios V (Winter 2019), S3 (Winter 2100, RCP 4.5) and S4 (Winter 2100, RCP 8.5).

4. DISCUSSION

The results of the hydrodynamic model indicate that in both periods, Summer and Winter, a good agreement between simulated and measured data were observed. However, the results showed good phase agreement, but with amplified values for the NS and EW components in relation to the measured data filtered. As the data were measured in a shallow and narrow channel, where the bathymetry and the width can be very irregular, deviations in the direction of the currents can be caused by the smoothing of the bathymetry, artificially introduced by the model, and also by the small local irregularities, that are not properly taken into account by the model. The Palmital channel is close to the Cubatão river mouth and, certainly, the currents are influenced by the river discharge, which is greater in the Summer, the calibration period, than it is in the Winter, the validation period. As the discharges imposed in the model are permanent for both periods, variations in discharge data can also influence the measurements and were not considered by the model.

One of the consequences of sea level rise, caused by the climate changes, is the possibility of flooding in coastal regions, as well as in internal regions of the bays and lagoons. Bearing this in mind, it was possible to calculate, for each scenario, the maximum water level in the different stations, considering the Summer and Winter periods (year 2019), for the year 2100, scenarios S1, S2, S3 and S3 (Table 1). At Joinville station, the predicted maximum water level increase was 0.71 m, for 2100 RCP 4.5 scenario, when compared to 2019, showing how much the level variations can impact the internal and shallow regions of the bay; in the most pessimistic scenario (RCP 8.5), this variation of the maximum water level is even greater, 0.89 m being the computed value. The same behavior can be observed in the other stations, with significant differences when comparing the years 2019 and 2100.

Water renewal rate and water age

At the Cubatão river mouth (station E), the main contributing river in the bay, the differences between WRR values for the different scenarios are also small: there, the variation in mean sea level is not very relevant when compared to the fluvial flow. At stations B, C, D and F, there is a slight deceleration in the renewal process for scenarios S1 and S2, which may be caused by the set-up on the free surface in the bay. It is also observed that the central part of the bay (station B), the region at the exit of Saguaçú Laggon (station C), and the region close to the Linguado channel (station F) present renewal processes slower than in the other areas, a condition that is slightly accentuated with the sea level rise, which indicates the possibility of these areas being under the effect of set-up.

Table 1. Maximum Water Level (MWL) and difference between MWL for different scenarios at Itapoá Harbour, TESC II and Joinville stations.

	Itapoá Harbour	TESC I	Joinville
MWL 2019(m)	2.06	2.10	2.21
MWL 2100, RCP 4.5 (m)	2.75	2.80	2.92
MWL 2100, RCP 8.5 (m)	2.93	2.98	3.10
Differences between MWL 2019 and 2020, RCP 4.5 (m)	0.69	0.70	0.71
Differences between MWL 2019 and 2020, RCP 8.5 (m)	0.87	0.88	0.89

Table 2 presents the values of WA's for all scenarios at the end of the simulation. In Summer, water renewal is more efficient for the scenario C. However, there is a worsening in the renewal capacity due to the climate change, with a significant fall considering the S4 scenario. Stations B, C and F represent the most critical regions, with the highest Water Age, with Station F having the worst WA, 85.5 days. The lowest WA was obtained for the Summer period of the year 2019 (scenario C), at station D.

It is possible to observe a more directly influence of the fluvial flows over the water exchange process in the inner compartments of the bay. In other regions of the bay, the difference in WA between the different scenarios is minimal, indicating that changes in river flows do not cause great differences in the process of water renewal in these regions. During summer, water ages are less than 70 days; in the winter, the values are higher.

Observing the results of isolines of Water Ages obtained by SisBaHiA®, two possible stagnation areas were identified, which presented lower renewal rates and higher water ages when compared to the other regions: the central part of the bay, the region close to Grande Island, and the Linguado channel. In this sense, it is possible to state that these areas are more prone to stagnation.

Table 2. Water Ages (days) at the stations A, B, C, D, E and F for different scenarios, with emphasis on the highest and lowest value of the age.

Stations	Scenarios					
	C	S1	S2	V	S3	S4
A	55.4	57.2	57.7	63.8	68.7	70.1
B	67.9	69.9	70.5	72.9	80.7	82.8
C	57.6	60.7	61.4	66.9	76.6	79.1
D	16.9	20.5	21.2	32.9	39.0	41.9
E	41.6	42.8	43.0	39.5	46.7	48.6
F	50.7	52.0	52.6	78.7	84.7	85.8

In the region close to Grande Island, the mixing processes should be studied in detail, as this region presents a low rate of renewal when compared to other regions of the bay. This region, which can be identified as the turbidity maximum zone (TMZ) of the system, with the formation of possible areas of stagnation, has the lowest renewal rates. Comparing the results of the 2019 scenario with the 2100 scenarios, it is possible to verify an increasing in these stagnation regions, indicating the zone of maximum turbidity.

5. CONCLUSIONS

With the definition of mixing parameters or renewal indicators (WRR and WA), it was possible to observe the areas of greatest stagnation, critical points that should be the focus of attention in future studies and projects to be carried out in Babitonga Bay. The regions that deserve attention are Linguado channel and those close to the Grande Island. It was also verified that the regions close to the river's mouth present the best renewal rates and the lowest water age: such are the regions close to the Saguaçu lagoon and to the Palmital Channel.

The Linguado channel's region, identified as one of the most critical regions in relation to mixing processes, due to the little influence of river flows, is where the worst mixing rates occur, which possibly affects the water quality. The reopening of the channel has been the focus of studies and projects, which should be better evaluated mainly due to the projection of future scenarios with the sea level rise, which could further reduce the renewal rate in the region.

It is possible to compare the mixing parameters between the different simulated scenarios. The main evidence is that there is a reduction in the WRR for the year 2100, in both scenarios and, consequently, an increase in the WA as the mean sea level is modified. For the WA, there was an average variation for the 2100 scenarios with RCP 4.5 and 8.5, compared to the year 2019, of 2.71 days for the Summer and 8.93 days for Winter. These scenarios of reduced mixing parameters are intensified for the Winter, as a consequence of the lower river flows in this period.

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