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Sandbar breaching promotes long lasting changes on limnological dynamics along the water column of a tropical coastal lagoon

Aberturas de barra provocam mudanças de longa duração na dinâmica limnológica ao longo da coluna de água de uma lagoa costeira tropical

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Abstract: Aim: In this study, we investigated the impact of an episodic marine intrusion on the water column characteristics of Jurubatiba lagoon, a tropical coastal ecosystem, for 12 months following a sandbar breaching event to elucidate the duration of its effects. **Methods:** Monthly, we sampled the physical, chemical, and biological characteristics along the water column for one year after a sandbar breaching event and seawater inflow. We assessed the temporal (monthly) and spatial (along depth profiles) associations among these variables and the temporal correlation among vertical heterogeneities in these variables and environmental drivers of stratification. **Results:** Marine intrusion resulted in salt wedges formation in the short-term, leading to stratification in dissolved oxygen, pH, salinity, and chlorophyll-a concentration along the water column for at least four months. However, temperature and solar incidence also emerged as crucial factors associated with vertical heterogeneity in limnological variables, influencing water density and pH throughout the study period. Precipitation and wind speed had only marginal effects on thermal and ectogenic stratifications, probably mediated by water colour, nutrient inputs, water column depth and lagoon's orientation in the landscape.

Conclusions: Our data unveiled that, despite their shallowness and wind exposure, coastal lagoons can exhibit considerable vertical heterogeneities in limnological variables due to various climatic and hydrodynamic aspects. Notably, the effects of marine intrusions on salinity and ectogenic column stratification can persist for several months, affecting water quality and, probably, biotic communities and ecosystem functioning. Once human activities and climate change may intensify marine intrusions on coastal lagoons, understanding spatiotemporal dynamics and their drivers is fundamental to anticipating their effects and conserving such vulnerable ecosystems.

Keywords: sandbar breaching; vertical heterogeneity; depth profile; salinity; water density.

Resumo: Objetivo: Neste estudo, investigamos o impacto de uma intrusão marinha nas características da coluna d'água da lagoa de Jurubatiba, um ecossistema costeiro tropical, por 12 meses após um evento de abertura da barra de areia, a fim de elucidar a duração de seus efeitos na lagoa. **Métodos:** Amostramos mensalmente as características físicas, químicas e biológicas ao longo do perfil vertical da coluna d'água após a abertura da barra de areia e entrada de água do mar. Avaliamos a associação temporal (mensalmente) e espacial (ao longo do perfil de profundidade) entre essas variáveis e a correlação temporal na heterogeneidade vertical dessas variáveis e condições ambientais que promovem a estratificação. **Resultados:** A intrusão marinha resultou na formação de cunhas salinas em curto prazo, levando à estratificação na concentração de oxigênio dissolvido, pH, salinidade e clorofila-a ao longo da coluna de água por, pelo menos, quatro meses. No entanto, a temperatura atmosférica e a incidência solar também emergiram como fatores cruciais associados à heterogeneidade vertical nas variáveis limnológicas, influenciando a densidade da água e o pH ao longo do período de estudo. A precipitação e a velocidade do vento tiveram apenas efeitos marginais nas variações térmicas e ectogênicas, provavelmente mediadas pela cor da água, entrada de nutrientes, profundidade da coluna d'água e orientação da lagoa na paisagem. **Conclusões:** Apesar de rasas e expostas a ação dos ventos, as lagoas costeiras podem apresentar uma considerável heterogeneidade vertical nas condições limnológicas devido a vários fatores climáticos e hidrodinâmicos. Notavelmente, os efeitos de intrusões marinhas na salinidade e na estratificação da coluna d'água podem persistir por vários meses, afetando a qualidade da água e, provavelmente, as comunidades bióticas e o funcionamento do ecossistema. Uma vez que as atividades humanas e as mudanças climáticas podem intensificar as intrusões marinhas em lagoas costeiras, compreender seus efeitos na dinâmica limnológica é fundamental para nossa capacidade de prevê-los e conservar ecossistemas tão vulneráveis.

Palavras-chave: abertura da barra de areia; heterogeneidade vertical; perfil de profundidade; salinidade; densidade da água.

1. Introduction

Coastal lagoons are shallow aquatic ecosystems distributed worldwide along continental coastlines, situated at the interface between terrestrial and marine ecosystems. Their limnological dynamic are determined by the interaction between geomorphology, watershed land use, atmospheric processes (e.g., temperature, precipitation, solar radiation, wind speed and fetch), and hydrological connectivity with the adjacent sea (Kjerfve, 1994; Esteves et al., 2008). Coastal lagoons can be permanently connected (tidal) or intermittently separated (non-tidal) from the adjacent sea by sand barriers, formed by marine sediment deposition (Kjerfve, 1994). In non-tidal lagoons, episodic sandbar breaching events are the principal mechanism of water exchange, connecting them to the ocean by one or more channels (Gönenç & Wolflin, 2004; Esteves et al., 2008).

Sandbar breaching can occur naturally when a lagoon's water level exceeds the sandbar crest, during rising tides or heavy wave action. However, artificial sandbar breaching events are becoming more frequent, given that the distribution of coastal lagoons coincides with densely populated areas (Esteves et al., 2008; Conde et al., 2015). Thus, they are among Earth's most human-dominated and threatened ecosystems (Berkes & Seixas, 2005). Sandbar breaching modifies the water column, causing seawater intrusion into coastal lagoons, and a drastic and sudden change in water level, transparency, pH, salinity, and nutrient concentrations (Palma-Silva et al., 2002; Kozlowsky-Suzuki & Bozelli, 2004; Faria et al., 1998). Additionally, sandbar breaching can lead to significant modifications in biological communities (Santos & Esteves, 2002; Kozlowsky-Suzuki & Bozelli, 2004; Santangelo et al., 2007; Crippa et al., 2013; Setubal et al., 2013; Collins & Melack, 2014). These sudden changes can also have a significant impact on human communities that rely on these ecosystems for their livelihoods (Esteves, 1998a).

Because of their shallow depth and wind exposure, coastal lagoons are usually mixed and non-stratified ecosystems (Esteves, 1998b; Panosso et al., 1998). However, seawater intrusions can lead to the formation of salt wedges and thermal stratification and can limit water column homogenization (Kozlowsky-Suzuki & Bozelli, 2004). This can affect other limnological variables, leading to physical-chemical stratifications such as changes in dissolved oxygen, electrical conductivity, pH and redox potential (Esteves et al., 1988; Casamayor et al., 2001). Water stratification can also cause the vertical partition of aquatic organisms (Lima et al., 2008; Fontes et al., 2011). Following the re-establishment of sandbars, ecosystem functioning and structure regeneration entails complex processes involving local extinctions and re-colonisations, mainly based on the recovery of earlier physical and chemical conditions (Moreno-Mateos et al., 2015).

There have been limited studies on the long-term vertical dynamics of limnological variables in temperate ecosystems, especially after marine intrusion events (Casamayor et al., 2001; Cousins et al., 2010; Collins & Melack, 2014; Harvey et al., 2023). This is even more scarce in tropical ecosystems, mainly considering physical, chemical, and biological parameters, simultaneously. Understanding the effects of sandbar breaching on water column dynamics is crucial to understanding the structure and functioning of tropical coastal lagoons, particularly in the context of climate change effects on sea-level rise and precipitation in coastal ecosystems (IPCC, 2023). Such studies are fundamental to better plan conservation policies, develop sustainable natural resources management practices and prevent anthropogenic impacts on coastal areas. Therefore, we monitored the Jurubatiba lagoon, a tropical coastal aquatic ecosystem, for 12 months after a sandbar breaching event. We assessed changes and associations between physical, chemical, and biotic conditions along the water column. We also investigated how climatic and limnological conditions are associated with heterogeneity in limnological variables within the water column during the studied period.

2. Material and Methods

2.1. Study area

In the present study, sampling was held in Jurubatiba lagoon, a coastal aquatic ecosystem situated in the Restinga de Jurubatiba National Park, in the northeastern region of Rio de Janeiro state, Brazil (22°00' - 22°23'S; 41°15'-41°45'N). Jurubatiba lagoon is a 0.35Km^2 shallow oligotrophic ecosystem with an average depth of 3.2m (Petrucio, 1998). It has high organic matter inputs from partially decomposed terrestrial material accumulated in groundwater, especially after rainfall, leading to high dissolved organic carbon (DOC) concentrations, and slightly acidic dark waters (Suhett et al., 2007). Despite being situated on a conservation unit, Jurubatiba lagoon is occasionally impacted by anthropogenic sandbar breaching events, particularly during the summer season (Santos & Esteves, 2002; Santangelo et al., 2007; Setubal et al., 2013). This represents the main human-made impact on this ecosystem, what makes it an interesting site to evaluate the duration and magnitude of sandbar breaching effects on natural coastal lagoon characteristics. Moreover, comprehending such temporal dynamics might lead to insights about the effectiveness of natural regeneration on limnological conditions over time.

Sampling was conducted in the deepest part of Jurubatiba Lagoon, located approximately 100 meters from the sandbar. According to the Köppen-Geiger climate classification system, the study site has an Equatorial Savannah climate with a dry winter (AW), as identified by Kottek et al. (2006). The area is characterized by hot and rainy summers and mild and dry winters, with total monthly precipitation below 60mm (Kottek et al., 2006). The climate is tropical sub-humid/humid, with average temperatures ranging from 25 °C in the summer to 19 °C in the winter and an average annual relative humidity of around 83% (Caliman et al., 2010).

The region is under the influence of subtropical climate and orographic precipitation, with average annual rainfall around 2,000 mm, with dry seasons lasting from April to October and mean total precipitation around 520 mm, while rainy seasons last from November to March, with mean total precipitation around 1,480 mm (Magalhães et al., 2022). Mean wind speed (± standard deviation; SD) corresponds to 2.4 ± 0.3 m.s^{-1}, with predominant east-southeast and south-southeast winds all along the year, except for December to January, when north-northwest and north-northeast winds tend to predominate (Correia Filho et al., 2022).

2.2. Sampling

Monthly samplings were conducted between January 20th and December 17th, 2021, following a sandbar-breaching event on December 17th, 2020. Vertical limnological profiles of temperature (ºC), salinity ($g.L^{-1}$), density ($g.m^{-3}$), pH, redox potential (ORP; mV), dissolved oxygen (DO; $mg.L^{-1}$), chlorophyll-a fluorescence (Chlo-a; RFU), and turbidity (NTU) were measured using an AquaTROLL 600 multiparameter In-Situ® device. Salinity and density were automatically estimated, based on electrical conductivity and temperature (In-Situ, 2022). Total solids concentrations (TS; $mg.L^{-1}$) were calculated by summing dissolved and suspended solids, which were estimated based, respectively, on electrical conductivity and temperature (Rusydi, 2018; In-Situ, 2022) and turbidity (Williamson & Crawford, 2011). Before samplings, the equipment was calibrated according to the manufacturer's instructions (In-Situ, 2022). Photosynthetically active radiation along the water column (PAR, $\mu mol.m^{-2}.s^{-1}$) was also measured using an underwater fluorometer Diving PAM-II with a miniature planar spectrometer MINI-SPEC (Walz®, Germany; see Prado et al., 2023 for measurement details).

The probe and spectrometer were submerged and set to continuously record the depth and limnological parameters along the water column. Measurements were always taken between 11:00 AM and 1:00 PM to maintain consistency. Both equipments registered data at approximately 20 cm intervals from the water's surface to the bottom of the lagoon. This allowed for a detailed analysis of the limnological depth profiles over the 12 months that were sampled. However, chlorophyll-a fluorescence was only estimated from March to November of 2021.

In addition, sub-superficial (~20cm) water samples were collected, immediately filtered in glass-fiber filters (Ø = 20 mm, ~1.2 µm pore size, GF/C Whatman), and stocked in 30-mL amber flasks. In the laboratory, water colour derived from humic organic matter was determined by spectrophotometry at 430 nm in 1 cm-cuvette (Strome & Miller, 1978; Suhett et al. 2013). Hourly climatic data (atmospheric temperature, relative air humidity, precipitation, and wind speed) were obtained from the National Institute of Meteorology (INMET), station 83749 – Macaé, about 10 Km from Jurubatiba Lagoon.

2.3. Data analysis

To assess vertical and temporal dynamics of limnological variables, that is, the magnitude of limnological heterogeneity within the water column, we plotted the vertical trends for each investigated variable over the 12 months, using the package "plotly" in R statistical software version 4.0.5 (R Development Core Team, 2021). To assess the association between limnological variables across depth profiles and throughout the sampling period, we first evaluated residuals distribution, using the 'shapiro.text' function in R. Then, we used Spearman correlation matrix and visually represented correlation coefficients ($r_{Spearman}$) using the R packages "corrgram" and "corrplot," respectively. An alpha value = 0.05 was considered as the significance level.

To identify the association of stratifications between limnological variables along the sampling period, we estimated the degree of vertical heterogeneity (Δ) for each limnological variable, based on the range of differences between their maximum and minimum values for each sampling event (day in a month). These metrics were considered a reliable indicator of vertical heterogeneity in limnological parameters since extreme values (the highest or lowest) were consistently observed at the surface or bottom of the lagoon for all variables during the sampling period, with only minimal exceptions (3 out of 117 estimated Δs). We then used a Spearman correlation matrix to evaluate the association between the vertical heterogeneities in ΔPAR, ΔTemperature, ΔSalinity, ΔDensity, ΔpH, ΔORP, ΔDO, ΔTS, ΔTurbidity and ΔChlo-*a*, and a set of climatic and limnological variables (mean air temperature 24h prior to sampling, monthly precipitation, total sum of hourly mean wind speed 24h prior to sampling, and water colour). These conditions are typically associated with stratification on physical, chemical and/or biological variables in aquatic ecosystems (Esteves, 1998b). Temporal trends in such climatic and limnological variables are described in Supplementary Material.

3. Results

3.1. Temporal and vertical patterns of limnological variables

During the study period, the mean water depth ranged from 2.87m in January, soon after the sandbar breaching event, to 4.05m in December. Assessed limnological variables presented distinct dynamics within the water column along the observed period (Figure 1). The incident PAR in the water surface ranged from 2,946 $\mu mol.m^{-2}.s^{-1}$ in January to 755 $\mu mol.m^{-2}.s^{-1}$ in July (Figure 1a). However, the PAR drastically reduced to less than 100 $\mu mol.m^{-2}.s^{-1}$ below 1.4m and was always less than 10 $\mu mol.m^{-2}.s^{-1}$ below 2.8m all along the period (Figure 1a). The PAR registered along depth

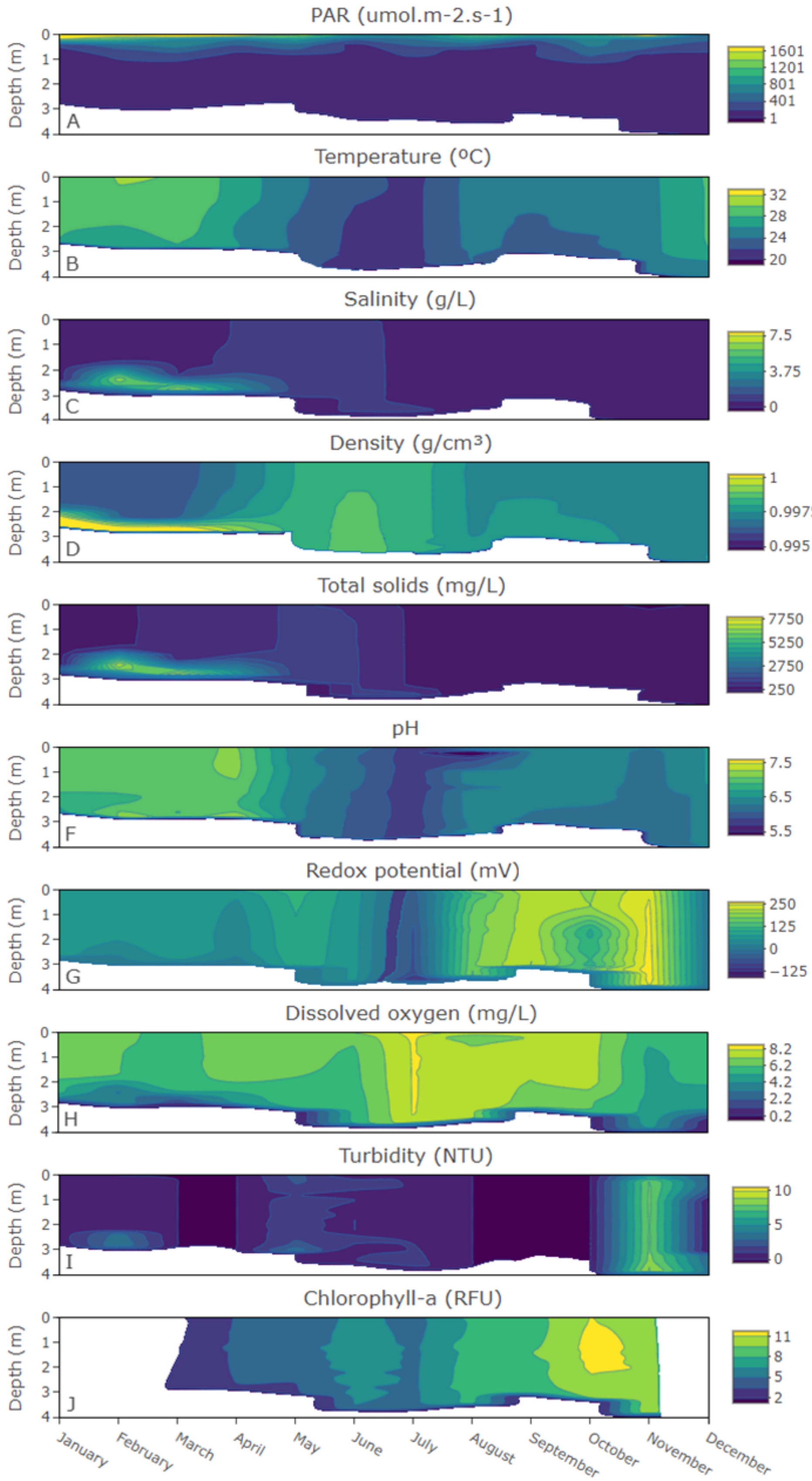

Figure 1. Water column vertical profiles of (A) Photosynthetic active radiation (PAR), (B) Temperature, (C) Salinity, (D) Density, (E) Total solids, (F) pH, (G) Redox potential, (H) Dissolved oxygen, (I) Turbidity, and (J) Chlorophyll-a from January-2021 to December-2021 at Jurubatiba lagoon. See colour legends on the right sidebar of each graph.

profiles was moderately and positively (0.7 > r > 0.5) associated with density (0.696; Figure 2).

Mean water temperature (± SD) ranged from 28.82 ± 0.47 ºC (January) to 21.43 ± 0.04 ºC (July). It tended to be slightly lower in the bottom than in the surface of Jurubatiba lagoon all along the study period, except for July, when the water column was thermally homogeneous (Figure 1b). Thermal vertical heterogeneity was mainly observed between January and April, when surface and bottom mean temperature (± SD) were 29.70 ± 0.55 ºC and 27.85 ± 1.73 ºC, respectively, and in December when the differences between superficial and bottom temperature were around 3.2ºC (Figure 1b). During the study, temperature was significantly and strongly positively (0.9 > r > 0.7) associated with pH (0.745; Figure 2).

Mean water salinity (± SD) was 1.97 ± 2.17 g.L^{-1} in February, gradually decreasing to 0.2 ± 0.02 g.L^{-1} in December (Figure 1c). Salinity was considerably higher in the bottom from January to April and homogeneous within the water column after that, changing water conditions from brackish (salinity between 0.5 and 30 g.L^{-1}) in May and June to freshwater (<0.5 g.L^{-1}) in the following months (Figure 1c). During the study, salinity exhibited a strong negative correlation with DO (-0.733), and a very strong (r > 90) negative correlation with chlorophyll-a (-0.903), whereas presented a strong positive association with pH (0.854) and a very strong positive correlation with TS (0.975; Figure 2). TS presented the same vertical and temporal trend described for salinity (Figure 1d; Figure S.2 available in https://doi.org/10.48331/scielodata.3EN9FX), whereas water density presented a similar pattern, especially from January to April (Figure 1e; Figure S.2 available in https://doi.org/10.48331/scielodata.3EN9FX). After that period, water density started to show intermediate values, and heterogeneity within the water column decreased compared to the beginning of the year (Figure 1e). The association with salinity also varied considerably thereafter (Figure S.2 available in https://doi.org/10.48331/scielodata.3EN9FX), such that few variables were significantly associated when the complete dataset was correlated (Figure 2). The water density presented a strong positive correlation with both PAR (0.696) and DO (0.721).

Mean water pH (± SD) was higher (7.08 ± 0.09) in April, gradually decreased to 5.77 ± 0.02 in July,

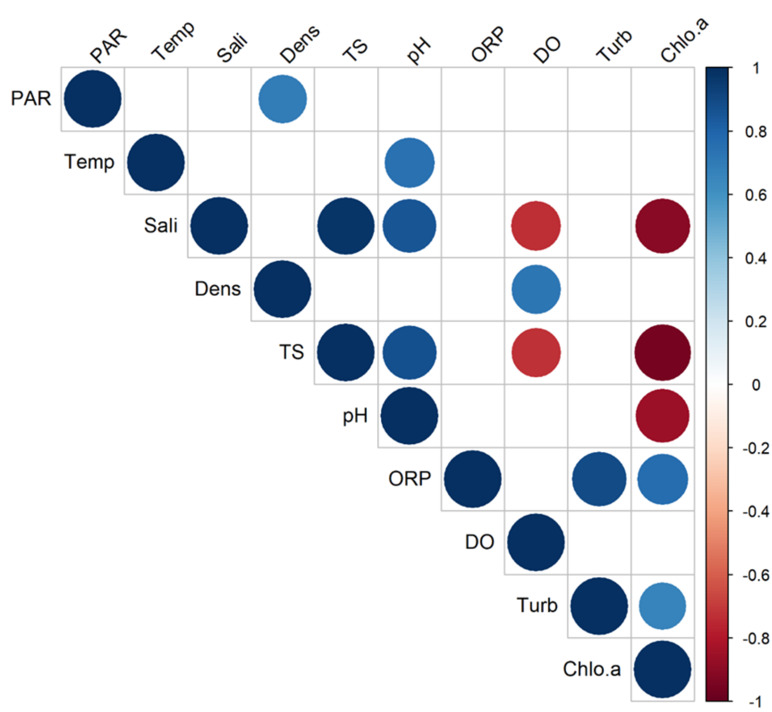

Figure 2. Correlation matrix between limnological variables along depth and all along the study period. The size and colour of circles indicate Spearman's correlation coefficients, according to the legend in the right side of the figure. Only significant correlations are presented. Legend: PAR - Photosynthetic active radiation; Temp – Temperature; Sali – Salinity; Dens – Density; TS - Total solids; ORP - Redox potential; DO - Dissolved oxygen; Turb – Turbidity; and Chlo.a - Chlorophyll-a.

and then increased again thereafter, presenting intermediate values by the end of the year (6.31 ± 0.12; Figure 1f). The pH tended to be slightly lower in the bottom than in the surface of Jurubatiba lagoon all along the period, except for March (when there was no vertical heterogeneity for pH), April (when similarly higher pH values were registered on both water column strata), and July (when lower pH values were registered all along the water column; Figure 1f). The pH was strongly positively associated with salinity (0.854), TS (0.854), and temperature (0.745), whereas it was strongly negatively associated with chlorophyll-a (-0.854) during the study period (Figure 2).

Jurubatiba lagoon always presented positive ORP values (ranging from 41.32 ± 12.59 mV in April to 257.79 ± 6.10 in November), except for July, when it suddenly became negative all along the water column (-53.69 ± 14.41 mV; Figure 1g). The ORP tended to be slightly lower (or less oxidative and, sometimes, even reductive) in the bottom than in the surface along the period, except for May and December, when no vertical heterogeneity was registered (Figure 1g). The ORP was strongly positive associated with turbidity and chlorophyll-a, and negatively associated with salinity and TS (Figure 2).

Mean DO concentration increased from 5.44 ± 1.26 $mg.L^{-1}$ in February to 8.25 ± 0.09 $mg.L^{-1}$ in July and gradually decreased until the end of the year (Figure 1h). DO concentrations tended to be consistently higher on the surface than at the bottom of Jurubatiba lagoon, except for July, when the highest concentrations measured in the sampling period (8.25 $mg.L^{-1}$) were registered from surface to 3m depth (corresponding to approximately 90% of the lagoon water column; Figure 1h). The DO was strongly negatively associated with salinity (-0.733) and TS (-0.721), and strongly positively associated with density (0.721) during the study (Figure 2).

Water turbidity was very low (<5 NTU) along the sampling period, except for that comprising the rainy season at the end of the year (October to December; Figure 1i). Turbidity tended to be slightly higher at the bottom than on the surface of Jurubatiba lagoon along the period, except from March to April and from August to September (Figure 1i). Turbidity presented a strong positive association with ORP (0.891) and a moderate positive correlation with chlorophyll-a (0.661; Figure 2).

Finally, chlorophyll-a fluorescence increased almost continuously from March (1.95 ± 0.33 RFU) to October (12.00 ± 0.67 RFU). It tended to be homogeneously distributed within the water column (Figure 2j). The main exceptions to this trend occurred in June, August, and October when higher chlorophyll-a values were registered right below the water surface or somewhat in the middle of the water column (Figure 1j). There was a strong negative correlation between chlorophyll-a and pH (-0.854), and a very strong negative correlation of chlorophyll-a with TS (-0.951) and salinity (-0.903). Additionally, chlorophyll-a exhibited a moderate positive correlation with turbidity (0.66) and a strong positive correlation with ORP (0.769; Figure 2).

3.2. Vertical heterogeneity in limnological variables

During the study period, mean air temperature and monthly precipitation were significantly correlated to vertical heterogeneities with several limnological variables (Figure 3). It was also true for summed mean wind speed before sampling and water colour (Figure 3). Air temperature was strongly positively correlated to ΔDO (0.828) and ΔTemp (0,806), and only moderately to ΔSalinity (0.732), ΔTS (0.727) and ΔDensity (0.696; Figure 3). Precipitation exhibited a strong negative association with ΔPAR (-0.833) and water colour (-0.718), and a moderate negative association with ΔDensity (-0.657; Figure 3). Only moderate negative correlations were identified between wind speed and ΔSalinity (-0.587) and ΔTS (-0.591), except for a strong positive association with ΔpH (0.775; Figure 3). Water colour presented strong positive correlations with ΔPAR (0.898) and ΔDensity (0.762), a moderate correlation with ΔSalinity (0.569) and ΔTS (0.573), and only moderate negative associations with Δ Chlorophyll-a (-0.65; Figure 3).

Concerning the associations among vertical heterogeneities in limnological variables, the ΔDensity, ΔSalinity, ΔTS, and ΔDO were significantly and positively correlated with each other (Figure 3). The ΔTemperature presented a very strong association with ΔDO (0.974), and a moderate association with ΔSalinity (0.67), ΔTS (0.666) and ΔTurbidity (0.639). The ΔPAR presented a very strong positive correlation with ΔDensity (0.912), a strong association with ΔSalinity (0.758) and ΔTS (0.762), and a strong negative correlation with ΔChlorophyll-a (-0.701; Figure 3). The ΔpH was only positively correlated to ΔDO (-0.534; Figure 3). The ΔORP presented a strong positive association with ΔChlorophyll-a

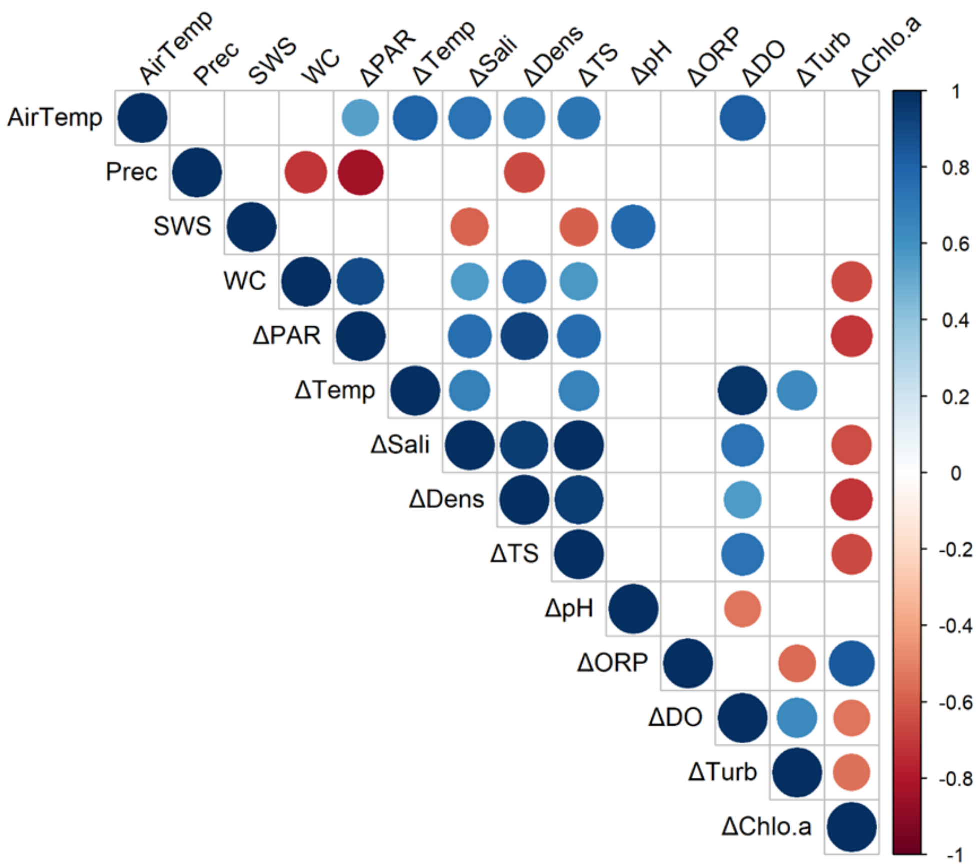

Figure 3. Correlation matrix between climatic data (air Temperature, precipitation, and wind speed), water colour and vertical heterogeneity (Δ) in limnological variables along the study period. The size and colour of circles indicate Spearman's correlation coefficients, according to the legend in the right side of the figure. Only significant correlations are presented. Legend: AirTemp – Air Temperature; Prec – Precipitation; SWS – Summed wind speed; WC – Water Colour; ΔPAR - ΔPhotosynthetic active radiation; ΔTemp - ΔTemperature; ΔSali - ΔSalinity; ΔDens - ΔDensity; ΔTS - ΔTotal solids; ΔpH - ΔHydrogen potential; ΔORP - Δ Redox potential; ΔDO - ΔDissolved oxygen; ΔTurb - ΔTurbidity; and ΔChlo.a - ΔChlorophyll-a.

(0.832), and a moderate negative association with ΔTurbidity (-0.564; Figure 3). Finally, ΔDO was negatively associated, whereas ΔORP was positively associated with ΔChlorophyll-a (-0.534 and 0.832, respectively).

4. Discussion

4.1. Effects of marine intrusions on temporal variations of limnological characteristics along water column

Studying limnological variations in the water column over time is key to understanding the degree and duration of sandbar breaching effects on the functioning of coastal lagoons. Our results demonstrate that marine intrusions caused by sandbar breaching promoted the formation of salt wedges on Jurubatiba lagoon, which can be traced by the variations in salt concentrations across the water column. After marine intrusions, increases in salts concentration increase water density, and its vertical differences along the water column form salt wedges (Cousins et al., 2010; Harvey et al., 2023). In our study, salt wedges were the initial and most prominent effect of sandbar breaching on limnological conditions, which remained for four months after seawater intrusion, corroborating previous studies demonstrating that vertical gradients of dissolved salts may sustain water stratification for extended periods (Boehrer & Schultze, 2008; Collins & Melack, 2014).

The formation of salt wedges at the beginning of the year was associated with the hottest periods, a pronounced vertical temperature difference along water column (ΔTemperature), and high irradiance, coupled with only moderate precipitation. These factors collectively hinder water mixing and contribute to form ectogenic stratifications (Hutchinson, 1957; Cousins et al., 2010; Collins & Melack, 2014). In Jurubatiba lagoon, the ΔSalinity, ΔDensity and ΔTemperature were, in fact, positively associated with vertical heterogeneity on some chemical variables (ΔDO or pH). The persistence of salt wedges limits oxygenation of the deepest layers, possibly through some mechanisms: i) reducing solubility of gases in saltwater (Downing & Truesdale, 1955); ii) restricting oxygen diffusion from the water surface due to limited water mixing (Esteves, 1998b); iii) the reaction of certain substances with dissolved oxygen (Casamayor et al., 2001; Boehrer & Schultze, 2008); iv) via changes in abundance, composition, and activity of aquatic organisms that consume oxygen (Casamayor et al., 2001). As a result, salt wedges may improve the concentration of reduced compounds (Casamayor et al., 2001; Cousins et al., 2010; Lenzi & Cianchi, 2022), which explains the association between salinity, DO and ORP during this period (Figure S.2 available in https://doi.org/10.48331/scielodata.3EN9FX). Chlorophyll-a concentration also reduced as salinity and variations in salinity along the depth profiles (ΔSalinity) increased. Limitations to primary productivity due to oligotrophy and dark water aspect (Guariento et al., 2011; Sanches et al., 2019) may also interact with salinity to reduce DO concentrations.

About five months after marine intrusion, saltwater dispersed to the entire water column, suppressing the limnological differences among layers, and the water column became completely brackish. The concentrations of salts only reduced after a rainy month (June) and a mid-year mixing event (in July), when the water column started to present freshwater conditions (salinity < 0.5 g.L^{-1}). Thus, marine intrusions drive changes in water quality shortly after sandbar breaching. However, its effects can be registered for extended periods (~ 6 months).

Salinity contributed considerably to total solids concentration dynamics. Sea water has an average concentration of dissolved salts around 35g.L^{-1}. Dissolved salt concentration was markedly high in Jurubatiba lagoon after the sandbar breaching. In contrast, the concentration of particulate solids was negligible and almost homogeneous during the period. Despite its shallowness and considerably high wind speeds registered in coastal areas (Correia Filho et al. 2022), Jurubatiba lagoon is a lentic ecosystem, and its limnetic region, where the study was conducted, presents coarse sandy sediments (Zink et al. 2004; Gripp et al. 2013). These aspects may limit sediment resuspension and the availability of particulate solids in the water column. In fact, turbidity tended to be low all along the year, except for the rainy period (from October-2021 on), when drainage usually promotes significant inputs of dissolved organic matter, nutrients and fine sediments to coastal lagoons, stimulates algal production (Suhett et al. 2007; Caliman et al. 2010), and turbidity reaches its maximum value (about 8 NTU). Thus, dissolved salts were the primary source of total solids in Jurubatiba lagoon during the study.

Due to higher salts concentrations, marine water is also more alkaline than that typical of continental aquatic ecosystems (Suzuki et al., 2002). As a result, Jurubatiba lagoon presented a neutral to alkaline pH at the beginning of the year (until April-2021), reducing thereafter. Despite variations in pH along the depth profiles, the effects of the marine intrusion on this variable over time are more evident than those along the water column. Thus, the significant associations between salinity and pH may be attributed to temporal processes rather than the spatial (vertical) dimension.

It has been previously demonstrated that marine intrusions evidenced in several coastal lagoons can impact the distribution, abundance, and diversity of aquatic communities (Kozlowsky-Suzuki & Bozelli, 2004; Crippa et al., 2013; Collins & Melack, 2014). Previous studies in Jurubatiba lagoon demonstrated that aquatic macrophytes (Santos & Esteves, 2002), fish (Camara et al., 2018), and zooplanktonic communities (Santangelo et al., 2007; Setubal et al., 2013) vary considerably in their response and time to recover from marine intrusions. It may have both positive, neutral or negative effects on distinct sets of species (Santangelo et al., 2007; Setubal et al., 2013; Camara et al., 2018). However, some communities become more distinct among coastal lagoons after sandbar breaching events, suggesting they may be responsible for maintaining divergent patterns on biodiversity among coastal ecosystems (Setubal et al., 2013). Salinity is also a crucial regulator of aquatic metabolism, affecting nitrification and methane production rates in coastal lagoons by altering the relationship between sulfate-reducing bacteria and other microbial communities (Santoro & Enrich-Prast, 2009; Minello et al., 2022). The prevalence of salinity effects on other limnological characteristics (i.e.

density, temperature, DO, pH, ORP, etc) may mediate such biological dynamics.

4.2. Environmental drivers of limnological heterogeneity in water column

Not only increases in salinity, but also lower temperatures tend to increase water density (Esteves et al., 1998b). Differences in water density along depth profiles prevent water mixing and are responsible for the formation of different water layers (Hutchinson, 1957; Boehrer & Schultze, 2008). However, ΔDensity was strongly and positively correlated only with air temperature and ΔSalinity, but not with ΔTemperature. Even though salinity affects temperature variation throughout the water column, what may be important for the formation of thermoclines, water density seems to be more affected by salt concentrations than by temperature variations along the water column in this shallow tropical ecosystem.

Water column depth is a crucial factor in heat transference; thus, shallower ecosystems tend to present smaller differences in temperature along depth profiles (Esteves et al., 1998a). However, in Jurubatiba lagoon, no more than 10% of the incident photosynthetically active radiation (PAR) was observed below 1.5m, regardless of the water column depth and solar radiation intensity. This is probably due to the continuous presence of coloured terrestrial dissolved organic matter in this ecosystem (Suhett et al., 2013), which restricts sunlight incidence to the upper layers and prevents heat dissipation to deeper layers. The temperature of the water surface in such ecosystems reflects the heat exchange between the lagoon and the atmosphere, as well as the variation of incoming solar radiation, and thus acts as an indicator of the climate (Boehrer & Schultze, 2008; Esteves et al., 1988). The positive relationship between ΔTemperature and air temperature, but the absence of association with ΔPAR or water colour suggests that the temperature variations along the water column are mediated by temporal variations in climatic heat rather than incident solar radiation or coloured DOC concentration in Jurubatiba lagoon.

Light intensity attenuation along the water column can affect several biotic and abiotic aspects and photosynthetic organisms, thus playing a crucial role in the functioning of aquatic ecosystems (Kahng et al., 2019). In our study, chlorophyll-a concentration became more homogeneous along the water column during periods with high ΔPAR, despite high water colour. It indicates that high incident solar radiation may favour the distribution of photosynthetic organisms along water column, despite low PAR availability. Chlorophyll-a concentration also increased considerably during the rainy period. Precipitation usually promotes inputs of coloured DOC (Suhett et al., 2007, 2013) and nutrients (Setubal et al., 2013) into coastal lagoons. However, it may also dilute their concentrations. A negative association between monthly rainfall and water colour suggests precipitation diluted coloured DOC concentrations. Precipitation was also identified as the primary determinant of photo-oxidation in Jurubatiba lagoon, mainly due to its effects on DOC quality, which improves the availability of dissolved inorganic carbon (CO_2; Suhett et al., 2007). Thus, a bottom-up control (via light, nutrient and CO_2 enrichment) may have increased primary production and chlorophyll-a concentration in Jurubatiba lagoon during the rainy period. Previous studies reported that both light and nutrients availability co-limit peryphitic production, and improve the relative contribution of autotrophic components of such organisms in this ecosystem (Guariento et al., 2011; Sanches et al., 2019). Our results indicate that pelagic primary production may be limited by these factors in Jurubatiba lagoon too.

On the other hand, in such black water coastal ecosystems, the limited availability of sunlight energy along the water column and the considerable DOC and CO_2 availability enhance the relevance of heterotrophic organisms in DOC consumption and oxygen depletion (Thomaz et al., 2001; Sanches et al., 2019). The high abundance, biomass, and diversity of aquatic macrophytes and terrestrial litter also provide a large amount of organic matter for consumption by aquatic microorganisms in Jurubatiba lagoon (Farjalla et al., 1999; Gonçalves Jr. et al., 2004; Gripp et al., 2013). Thus, even during the rainy period, from October-2021 on, the water pH and dissolved oxygen concentration tended to reduce despite high productivity (Figure 1). In such dark water ecosystems, nutrient and DOC availability increase bacterial respiration and secondary production rates considerably, which may be up to 8 times greater than primary production (Tranvik, 1989; Farjalla et al., 2002; 2009). Heterotrophic metabolism, such as bacterial respiration, consumes oxygen and produces carbon dioxide, which reacts with water molecules to form carbonic acid (H_2CO_3), reducing pH and leading to water acidification. Increases in temperature variations along the water column may also contribute to dissolved oxygen stratification, mainly by temperature effects on metabolic rates of heterotrophic organisms.

Precipitation was not directly associated to vertical heterogeneity neither on chemical nor biological variables. However, some variations in limnological conditions may be mediated by its effects on coloured DOC (and its consequences for water colour) and nutrient concentrations, and water column depth as previously discussed. Monthly rainfall throughout 2021 indicated an unexpected precipitation pattern for the considered dry period (Figure S.1 available in https://doi.org/10.48331/scielodata.3EN9FX). High rainfall observed out of the rainy season resulted in a minimum annual depth 0.5m greater than a previous survey in the same lagoon performed by Petrucio (1998), but not affected the average and maximum depth values. However, precipitation is not the only factor regulating this lagoon's water level. The Campos-Macaé channel connects Jurubatiba to neighboring coastal lagoons and the Macaé river estuary, which tidal range might reach 1.2m (Arueira et al., 2022) and buffer water filling and emptying processes in the lagoon, both directly, through water masses movement, and indirectly, through groundwater hydrostatic pressure.

In shallow ecosystems such as coastal lagoons, water column mixing are common during the rainy period, when salt wedges are absent (Esteves, 1998a, b). However, it was also notable in the coldest period (July-2021), with intermediate wind velocities, suppressing both thermal and ectogenic stratifications, and almost resulted in the homogenization of limnological characteristics all along the water column. This event led to water acidification and reducing conditions, despite elevated dissolved oxygen concentrations. In natural conditions, redox potential is determined by the electrochemical form of dissolved elements (which determines the mobility of ions) and mainly by their concentrations (Baas-Becking et al., 1960; Jardim, 2014). Such negative ORP and low pH values reported in Jurubatiba lagoon in July-2021 are among those found in subterranean waters and anaerobic conditions (Jardim, 2014). They are probably associated with the dissipation of interstitial water from organic matter-rich groundwater and marginal sediments into the water column (Boehrer & Schultze, 2008; Marinho et al., 2010; Suhett et al., 2013). It is particularly interesting to find such negative ORP values simultaneously with high oxygen concentrations and slight chemical differences in the water column. It indicates that turbulent mixing and deep-water renewal were influential during this period. To our knowledge, this is the first time that such contrasting pH, ORP, and DO conditions have been documented in coastal lagoons.

From August until the end of the study period, the ecosystem presented an almost permanent thermal stratification despite increases in wind velocities, and chemical stratifications were recorded again (mainly for pH, DO and ORP). Wind speed was only positively associated to ΔpH and negatively correlated with ΔSalinity, indicating that the prevalence of marine intrusion may be related to low wind velocities. However, even after the dissolution of salts, reductions in temperature seems to be a more critical factor for the occurrence of stratification than wind speed during the period mentioned. With wind speed, wind fetch also depends on the relative direction between wind vectors and limnetic zone position (Panosso et al., 1998). Distinct patterns of stratification were previously described for the Iodada and Imboassica lagoons, which are close to our study site and associated with different degrees of wind effects (Bozelli et al., 1990; Esteves et al., 1988). While the Iodada lagoon is perpendicular to the coast, with a narrow limnetic area in the predominant wind direction, the Imboassica lagoon has a greater limnetic area parallel to predominant winds, making it more susceptible to wind stress effects. Considering: i) that Jurubatiba lagoon is a dendritic orthogonal lagoon, southeast–northwest orientated; and ii) that predominant winds in the region are northeast and southwest, wind stress is likely to have a small ecological impact, except under exceptional high wind speed conditions. Thus, although it is a shallow ecosystem, the Jurubatiba lagoon may be stratified because of a minor exposition of its limnetic area (Panosso et al, 1998), as recorded for the Iodada lagoon.

Despite initial salinity and density effects, a significant portion of the heterogeneity in limnological characteristics along the water column in Jurubatiba lagoon was also related to some climatic-induced factors, mainly atmospheric temperature, PAR, and, to a lesser extent, precipitation and wind velocity. It reinforces that there is a hierarchy of controlling factors of the dynamic of limnological variables in coastal lagoons (Caliman et al. 2010), such that the dynamic of physical variables is controlled by factors acting on large scales, such as climate. In contrast, regional and local factors influence physical and chemical variables, while biotic variables result from the interplay between all of them, making them more challenging to predict.

5. Final Remarks

Sandbar breaching and water stratification in coastal lagoons is a globally relevant topic, as these ecosystems are highly vulnerable to climate change and human activities. Although shallow coastal ecosystems are typically described as vertically homogeneous, our results demonstrated that spatial distinctions among layers are identified when water column is completely accessed. Concerning marine intrusions, salinity effects on water quality are almost imperceptible on the surface of such ecosystems, even in the short term. However, they may last for a long period at the bottom of coastal lagoons, affecting aquatic communities and ecosystem functioning. The combined effects of marine intrusions and thermal variations along the year limit water column mixing. Thus, despite being a shallow and wind-exposed ecosystem, Jurubatiba lagoon exhibits a meromictic lake behaviour after sandbar openings and at warmer periods. Only during cold and rainy periods, and when salt wedges are absent, this ecosystem may function as a polymictic lake.

In Jurubatiba lagoon, there is a consistent trend that sandbar breachings occur during summers (Santos & Esteves, 2002; Santangelo et al., 2007; Setubal et al., 2013). This aspect makes long-term studies about the effectiveness of natural restoration difficult to conduct in this ecosystem. Noteworthy, sandbar breachings are becoming a common annual practice in Jurubatiba lagoon due to political and socio-economic pressures, from surrounding human populations. Thus, marine intrusions may become more frequent due to human action, both directly through artificial sandbar breachings, and indirectly through climate-mediated effects on hydrodynamic of coastal areas. It may become more critical and persistent because long-term climate change scenarios predict sea level rises, increases in temperature, temperature extremes, and drought frequency and magnitude in South America (IPCC, 2023). In these scenarios, drier periods may limit salt dissolution, and warmer years may favour thermal stratifications. They both constrain water mixing, reinforcing the meromictic pattern in the Jurubatiba lagoon. However, it is essential to highlight that the position in the landscape and the morphometry of the coastal lagoons are significant predictors of the vulnerability of these environments to the entrance of seawater and, consequently, of the susceptibility to changes in salinity and haloclines.

The results of this study can be helpful in the development of management strategies for the protection of coastal lagoons and the natural resources they provide. However, evaluating how subsequent marine intrusions affect biodiversity and functioning of such coastal lagoons have a fundamental importance for better planning conservation policies, develop sustainable management practices of these natural resources and prevent anthropogenic impacts in coastal areas. Then, future approaches may consider expanding the spatial scale to other sites within and among coastal lagoons and the temporal scales within and among years. Also, only by incorporating the evaluation of biotic communities (mainly microorganisms, phytoplankton, and zooplankton) and ecosystem processes along depth profiles, such approaches may shed light on the proximal causes of marine intrusions' effects on biological dynamics and ecosystem functioning.

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Data Availability

All data, supplementary material and analyses codes are available on the Acta Limnologica Brasiliensia Dataverse in SciELO Data. Access is free. It can be accessed in https://doi.org/10.48331/scielodata.3EN9FX.

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