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Oceanographic and climatic processes as predictors of *Chelonia mydas* strandings

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ABSTRACT

Strandings of marine turtles along coastal beaches can provide valuable scientific insights into the biological and ecological factors influencing interannual fluctuations in organism abundance and distribution. The postmortem drifting of carcasses is intricately linked to oceanographic and climatic processes, emphasizing the need to understand the relationships between these variables and strandings to enhance our comprehension of marine animal occurrences along the Brazilian coast. This study aims to analyze local oceanographic and climatic parameters and spatiotemporal variability associated with strandings of the green turtle, *Chelonia mydas,* between 2016 and 2021. Data on 485 green turtle strandings in two different regions of northern Santa Catarina state were utilized. A generalized additive model was used to quantify and explore the effects of oceanographic and climatic variables on strandings. While no seasonality was detected in the number of green turtle strandings, interannual variations were observed. High stranding densities exhibited discernible trends along the edges of the beaches within the study area. Our analysis of oceanographic processes suggests a significant correlation between green turtle strandings and sea surface temperature variation, average and variability of wave height, wind intensity and variation, and sea level oscillation. These findings underscore the pivotal role of oceanographic and climatic processes in governing the drift and transport of animal carcasses to coastal regions, influencing both temporal fluctuations and spatial distribution of strandings.

1. Introduction

Marine turtle strandings are a recurrent phenomenon that holds significant scientific importance for understanding the biological and ecological factors affecting individuals and species. These events are not only of ecological interest but also play a crucial role in conservation efforts, offering critical insights into movements, migrations, diseases, diet, anatomy, genetics, and interactions with environmental drivers (Epperly et al., 1996; Shaver and Teas, 1999; Brusius et al., 2021).

The green turtle (Chelonia mydas, Linnaeus 1758) is the most frequently stranded sea turtle species along the southeast and south coasts of Brazil, with extensive research dedicated to documenting these events (Reis et al. 2009; Poli et al. 2014; Monteiro et al. 2016; Reis et al., 2017; Tagliolatto et al., 2020; de Farias et al., 2019; Cantor et al. 2020). These areas serve as key foraging grounds, particularly for juveniles throughout the year (Wallace et al. 2010; Guebert-Bartholo et al. 2011; Santos, 2011; Naro-Maciel et al. 2012; Coelho et al. 2018; Guimarães et al. 2021). This species is considered as "endangered" globally (Seminoff, 2023) but for Brazil it is classified as "near threatened" (Thome et al., 2023), facing numerous threats that stem from both natural and anthropogenic factors. Their life history traits, such as slow growth, late sexual maturity, and extensive migratory behavior, increase their vulnerability to environmental changes and human impacts (Bolten et al., 2003; da Silva Valente et al., 2022; Plotkin et al., 2002; Cantor et al., 2020; Trigo, 2000)

Understanding the environmental factors that influence green turtle strandings is crucial for improving conservation strategies and better assessing their extinction risk both globally and locally. Previous studies have highlighted the role of oceanographic and climatic conditions in affecting the likelihood of marine turtles reaching the shore (e.g. wind, waves, ocean currents, and atmospheric systems), suggesting that variations in these processes may significantly impact stranding patterns (Brusius et al., 2021; NRC, 1990; Lewison et al. 2003; Moore et al. 2020; Crowder et al. 1995; Epperly et al. 1996; Monteiro et al., 2016; Hart

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et al., 2006; Cook et al., 2021). However, gaps remain in understanding how oceanographic and climatic processes specifically impact stranding patterns along different coastal regions, particularly in south/southeast Brazil. This study aims to fill this gap by investigating green turtle strandings and exploring the underlying environmental drivers along the beaches of Itajaí and Navegantes in Santa Catarina, Brazil, where green turtle strandings are prevalent.

2. Methods

2.1. Study area

The study area encompasses beaches in Itajaí and Navegantes municipalities, on the central-northern coast of Santa Catarina state (Fig. 1). These beaches exhibit a north-south orientation, with varying morphodynamic characteristics (dissipative, intermediate, and reflective) (Heidrich and Abreu, 2012). The region's oceanographic and climatic conditions are influenced by humid winds from the North/Northeast, driven by the South Atlantic high-pressure system, which dominates atmospheric circulation (Monteiro and Furtado, 1995; Schettini et al., 2005). Winds from the South/Southeast, associated with the Atlantic Polar Maritime mass, are the most intense (Rodrigues et al., 2004; Oliveira et al., 2019). The area is classified as a sub-warm temperate climate zone, with weather patterns governed by the interaction of polar and tropical air masses (Nimer, 1989; Oliveira et al., 2019).

The tidal regime is mixed, predominantly semi-diurnal, with an average tide height of 0.8 m, reaching up to 1.1 m during spring tides and 0.3 m during neap tides (Schettini et al., 2005). Water temperatures fluctuate seasonally, ranging from 17.9°C in winter to 24.7°C in summer (Carvalho et al., 1998).

The wave regime is shaped by cyclones associated with cold fronts and polar anticyclones (Alves, 1996). Wave characteristics vary throughout the year, from south swells with a 12-second period to east swells with an 8-second period, influenced by frontal systems (Araújo et al., 2003; da Silva et al., 2012). Average wave height is 0.88 m, but extreme events can push heights above 4.55 m (Melo et al., 2006).

On the Santa Catarina continental shelf, the dominant southwestward flow is primarily driven by the subtidal component, with tidal forces inducing perpendicular flows (Casares Pinto,1998; Cecílio, 2006; Palma et al., 2008). Winds from the southern quadrant facilitate onshore water transport, while northern winds drive offshore movement (Andrade et al., 2016). Low-frequency sea level variations and platform waves from the south also play a significant role in continental shelf circulation (Pimenta et al., 2006; Hirata, 2008; Palma et al., 2008).

2.2. Data source

2.2.1. Strandings records

The data on green turtle strandings were obtained from the Santos Basin Beach Monitoring Project (Projeto de Monitoramento de Praias da Bacia de Santos - PMP-BS), The PMP-BS is part of the federal environmental licensing requirements defined by IBAMA (Brazilian Institute of Environment and Natural Resources) for PETROBRAS' oil and natural gas production and transport in the Santos Basin. The project aims to assess the possible impacts of these activities in the area on marine tetrapods, including seabirds, turtles, and marine mammals, through systematic beach monitoring between Laguna/SC and Saquarema/RJ. All animals were collected under permit ABIO No. 640/2015.

Monitoring effort is regular, with each beach having a pre-defined survey strategy, being either daily or weekly. Only beaches with daily monitoring were used, to avoid biases related to different survey efforts

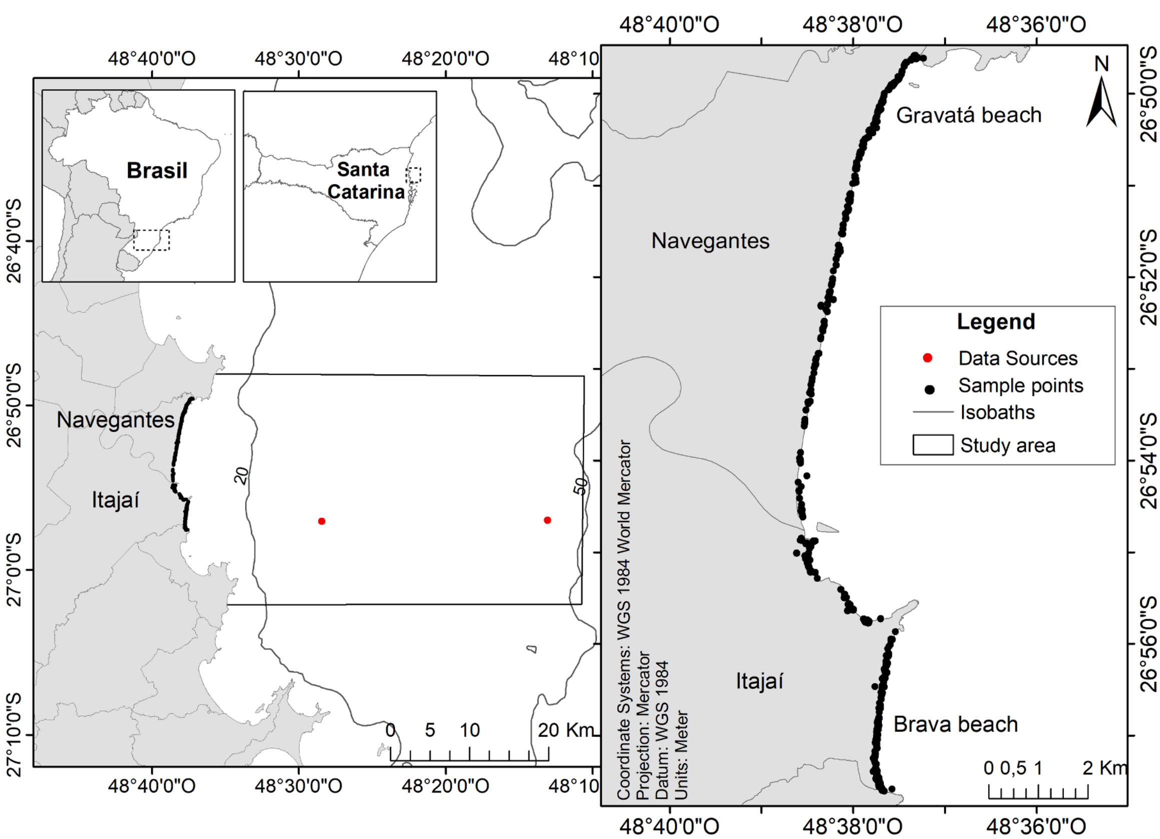

Fig. 1. Geographic representation of the study area highlighting the positions of Itajaí and Navegantes relative to the state of Santa Catarina and Brazil. Isobaths of 20 and 50 m are delineated, and a rectangular boundary outlines the spatial extent of the study area. Red dots denote the locations where oceanographic and climatic variables were acquired, while black dots represent stranded green turtles.

within the area. All animals stranded on the beaches are recorded by the field teams, without exceptions. Animals documented by PMP-BS undergo comprehensive data collection, using standardized forms. One evaluated aspect refers to the carcass' decomposition stage, which is classified into five levels: 1 - live animal, 2 - fresh carcass, 3 - moderate decomposition, 4 - advanced decomposition, 5 - mummified carcass or skeleton remains (PETROBRAS, 2019). Green turtles are classified in three age classes, either by field teams or during necropsy, using the curved carapace length (CCL): young (CCL $<$ 30 cm), juveniles (CCL between 30 cm and 50 cm) and adults (CCL $>$ 50 cm).

All data was obtained from the PMP-BS' open-access database called SIMBA (Aquatic Biota Monitoring Information System), available at https://simba.petrobras.com.br. Although SIMBA holds all data generated by the PMP-BS, stranding data for this specific area can also be obtained from published datasets (Dick et al., 2019; Barreto et al., 2023). Records were filtered by taxonomy (*Chelonia mydas*), life status (deceased animals), and location, maintaining only beaches from Itajaí (4.5 km) and Navegantes (9.8 km) municipalities. Stranding data included turtles reported by the public and those found during active monitoring by field teams between 2016 and 2021. To create a continuous time series of strandings, missing values were treated as zeros. Stranding records were then aggregated into various time intervals (weekly, monthly, seasonal, and yearly) for subsequent analysis.

2.2.2. Oceanographic and climatic data

In this study, we focused on an area extending approximately 50 km offshore, up to the 50 m isobath (Fig. 1). This area was chosen based on the foraging ecology of juvenile and adult green turtles, as it encompasses critical feeding habitats (Wallace et al., 2010; Guebert-Bartholo et al., 2011; Santos, 2011; Naro-Maciel et al., 2012; Coelho et al., 2018; Guimarães et al., 2021). Beyond the 50 m isobath, islands with rocky substrates are absent, limiting potential foraging grounds.

Environmental data were sourced from the Copernicus Marine Environment Monitoring Service (https://data.marine.copernicus.eu/products) and ERA-5 model (European Center for Medium-Range Weather Forecast (ECMWF) - https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview), with spatial resolutions of 0.25º and 0.5º, and hourly temporal resolution. We selected variables related to physical processes that influence mass transport, which may impact stranding events. These include surface currents (UO, VO), 10-meter winds (U10, V10), wave direction (MWD), wave period (MWP), and significant wave height (SWH), all of which can directly influence the movement of carcasses and debris in coastal waters. Additionally, variables that could indirectly affect turtle presence, such as sea surface temperature (SST), or somehow affect indirectly the sea state, such as sea level height (ZOS), mean sea level pressure (MSL) were included. These factors may influence habitat conditions or the likelihood of strandings by altering turtle behavior or transport mechanisms. Two grid points within the study area were averaged to capture environmental patterns. Subsequently, weekly averages and standard deviations of these variables were calculated to reflect trends and variability in the region, facilitating comparison with weekly stranding data.

2.3. Statistical analysis

Initially, exploratory analyses were performed to investigate the temporal patterns of strandings and identify potential monthly, seasonal, and annual variations. Stranding records (counts) were grouped by year, month, and season, and statistical tests were conducted to compare the components of each group. The Kruskal-Wallis test (1952) was used for overall comparison, followed by Dunn's multiple comparison test (Dunn, 1964) for post hoc analysis.

Spatio-temporal variability maps were created to visualize the locations with the highest concentration of strandings in the region at seasonal and annual scales using Kernel density estimation to estimate the probability density function. The Kernel maps were created in ArcGIS® 10.3 software, utilizing an influence radius of 1 km, calculated as Rizzatti et al. (2020) proposed to better represent local dispersion.

Generalized additive models (GAM; Hastie and Tibshirani, 1986) were employed to investigate potential correlations between weekly stranding patterns and weekly averaged meteoceanographic conditions, following the approach proposed by Warlick et al. (2022) (Eqs. 1–2):

$$y_i \sim Tweedie(\mu_i, \phi_i \quad \mu_i^{\rho}) \tag{1}$$

$$y_i = \beta_{0s} + f_1(Year_i) + f_2(x_i) \tag{2}$$

where y is the number of strandings in a week i, being a function of the intercept β_0 and smooth functions f for year and for environmental covariates x. For the model, it was assumed that the response variable (strandings count) follows a Tweedie distribution, with μ representing the mean of weekly strandings, ϕ being the dispersion parameter, and ρ being the power parameter controlling the probability distribution, with ρ=1.01.

The GAM model was adjusted using a thin plate spline as a smoother for all predictor variables. The model fitting was conducted using the restricted maximum likelihood (REML) method, implemented through the mgcv package (Wood, 2011) in the R statistical environment (R Core Team, 2022). Given the interrelation between meteoceanographic variables, they were selected for the model based on the collinearity values. Collinearity occurs when predictor variables are highly correlated, making it difficult for the model to distinguish their individual effects. Addressing it improves model stability and accuracy by removing or adjusting closely related variables. Wood (2006) classifies collinearity as values ranging from 0 to 1, where 0 indicates no collinearity problems and 1 a complete inability to differentiate between variables. Within the mgcv package for GAMs, collinearity values are categorized into three scenarios: worst, observed, and estimated. To ensure stable estimates, we excluded variables with collinearity values exceeding 0.8 in the worst-case scenario.

The choice of GAMs was motivated by their ability to capture the complex, nonlinear relationships between strandings and environmental variables (Warlick et al., 2022). This flexibility is particularly advantageous in ecological studies, where interactions between biological and environmental factors are often nonlinear and challenging to predict.

2.3.1. Model evaluation

To evaluate and select the best model, we tested all possible combinations of non-correlated environmental variables as predictors of stranding counts. The optimal model was identified by minimizing the Akaike information criterion (AIC; Akaike, 1998), a metric that balances model fit and complexity by penalizing models for the number of parameters, thereby helping to prevent overfitting. By focusing on the model with the lowest AIC value, we ensure that we prioritize models that provide the highest explanatory power for the response variable while using fewer predictor variables. This approach enhances statistical support while maintaining interpretability and applicability in real-world scenarios.

A null model was developed and compared to the final model using AIC to evaluate whether the selected parameters provide greater explanatory power for stranding counts than the data alone. The null model serves as a baseline, including only the intercept, which allows us to assess the added value of the environmental variables in the final model. Comparing AIC values helps confirm the relevance of these parameters in explaining variations in stranding counts.

To assess the model's predictive capability, we calculated the number of strandings in response to environmental variables, generating predicted stranding values. We then conducted a correlation analysis between the predicted and observed data. Finally, we compared the total annual stranding values to evaluate the model's performance.

3. Results

Between 2016 and 2021, 485 strandings of *Chelonia mydas* were documented. Among these, 1 % were identified as young individuals (n=7), 95 % as juveniles (n=464), 1 % as adults (n=4), and 2 % were labeled as undetermined (n=10). Curved carapace lengths (CCL) ranged from 28 cm to 102 cm, with an average of 40.3±8.2 cm. Even those specimens classified as "young" were very close to the "juvenile" category, as none had CCL less than 28 cm. Also, even though there was a single specimen with 102 cm, other adults had an average CCL of 56.2 ±12.0 cm.

Regarding the condition of the carcasses, the most prevalent records were of individuals in an advanced state of decomposition (code 4 = 90.1 %), followed by moderate decomposition (code 3 = 4.9 %), mummified carcasses or skeleton remains (code 5 = 4.3 %), and carcasses in good condition (code 2 = 0.6 %). Due to their decomposition and action of scavengers, most specimens (n=417) could not be sexed. Thus, analyses were performed without separating by sex.

3.1. Spatial and temporal distribution

Throughout the study period, the distribution of stranding records remained consistent, although the number of individuals varied across months and seasons (Table 1; Fig. 2). No significant differences in the total number of strandings were observed across seasons (Table 2), despite seasonal variations in their spatial distribution (see below). However, interannual fluctuations were evident (Table 1; Fig. 2), with significant differences noted (Table 2). Peak values were recorded in 2017 (n = 132), which were markedly higher than those in 2019 (n = 41) and 2021 (n = 54) (Table 3).

The green turtle stranding events did not show a uniform distribution throughout the study area (Fig. 3; Fig. 4). Instead, distinct areas of higher carcass accumulation were identified, which varied spatially and temporally, particularly at the extremes of the study area. A noticeable spatial trend was observed, indicating lower frequencies of events in regions closer to the central parts of the beaches and fluctuations in the locations with a higher density of strandings, alternating between the northern and southern extremities of these environments. While green turtle strandings were observed throughout the monitored area, noticeable shifts in the locations of higher accumulation were detected across different seasons. Higher frequencies were recorded in the northern regions during autumn and winter, whereas in spring and summer, they were more prevalent in the southern areas.

Furthermore, some interannual differences in the locations of higher accumulation were also identified. Higher strandings occurred in the south during 2018 and 2021, while the peak frequency of events in the north was observed in 2019. 2016, 2017, and 2020 followed a similar trend, with higher concentrations in northern and southern regions and lower densities in the central regions.

3.2. Meteoceanographic conditions

To examine the effects of meteoceanographic conditions on green turtle strandings, a total of 32,770 GAMs were explored, representing all possible combinations of the selected variables. To achieve this, environmental data was transformed into weekly means and their corresponding standard deviations (Table 3). This approach ensured the preservation of temporal variations in the processes under consideration. Concurrently, the stranding numbers were modeled using weekly sums.

The best-fitted model (Table 4) was carefully chosen by eliminating correlated variables and focusing on the lowest AIC values, providing a higher explanatory power level (Table 5). The selected model encompassed the effects of the following factors: the effects of year (edf= 4.3; p= 0.000004), MSL mean (edf= 3.26; p= 0.13), SST standard deviation (edf= 5.9; p= 0.000002), SWH mean (edf= 3.06; p= 0.0001), SWH standard deviation (edf= 1; p= 0.002), U10 mean (edf= 1; p= 0.015), U10 standard deviation (edf= 1; p= 0.0006), and ZOS standard deviation (edf= 4.62; p= 0.02). The findings are visually represented in Fig. 5.

This model revealed a discernible trend of decreasing annual stranding numbers throughout the study period, influenced by the zonal component of the wind (u10; wind direction towards the sea) and its lower standard deviation (u10_std). Similarly, this downward trend was observed with increased dispersion of significant wave height (swh_std) and with extreme values of sea level variation (zos_std), both in the lower and higher ranges. Conversely, an increase in stranding numbers was associated with the influence of the meridional component of the wind (v10; wind direction towards land) and with extreme values of atmospheric pressure (msl), again in both lower and higher ranges (however, with a non-significant effect). This pattern persisted with rising significant wave height, reduced variation in its values, and lower variation in sea surface temperature. The overall explained deviation amounted to 31.5 %, suggesting that the model possesses a moderate but meaningful level of explanatory capability.

3.3. Model predictive capacity evaluation

Using the best-fitted model, predictions of stranding numbers were made based on the selected meteoceanographic variables, returning predicted values for the entire time series. The correlation between the predicted and observed data resulted in a correlation coefficient of r=0.65. The moderate positive correlation coefficient is likely sensitive to extreme stranding events.

The annual values of both observed and predicted data, along with their upper and lower 95 % confidence intervals (Table 6), illustrate the accuracy of the model when considering solely meteoceanographic processes as predictors. This accuracy level underscores the best-fitted model's efficacy in explaining the observed patterns.

4. Discussion

The analysis of green turtles, *Chelonia mydas*, strandings from 2016–2021 revealed that 95 % of the individuals were juveniles, most of which were found in advanced stages of decomposition. No discernible seasonal pattern was detected, though interannual fluctuations and spatial variability were evident, with strandings concentrated at the northernmost and southernmost regions of the beaches. These findings suggest that juvenile green turtles utilize the waters around Itajaí and

Table 1
Monthly Number of Chelonia mydas Strandings, 2016 - 2021.

Season	Summer			Fall			Winter			Spring			Total
Month/Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016	14	4	7	1	13	0	8	3	10	7	4	13	84
2017	8	5	6	13	22	16	9	6	12	9	15	11	132
2018	7	19	12	6	2	11	7	5	4	5	7	10	95
2019	3	3	0	2	2	8	4	5	2	2	6	4	41
2020	4	5	12	7	10	10	5	2	2	11	1	10	79
2021	4	10	4	2	3	5	2	4	1	5	4	10	54
Total	40	46	41	31	52	50	35	25	31	39	37	58	485

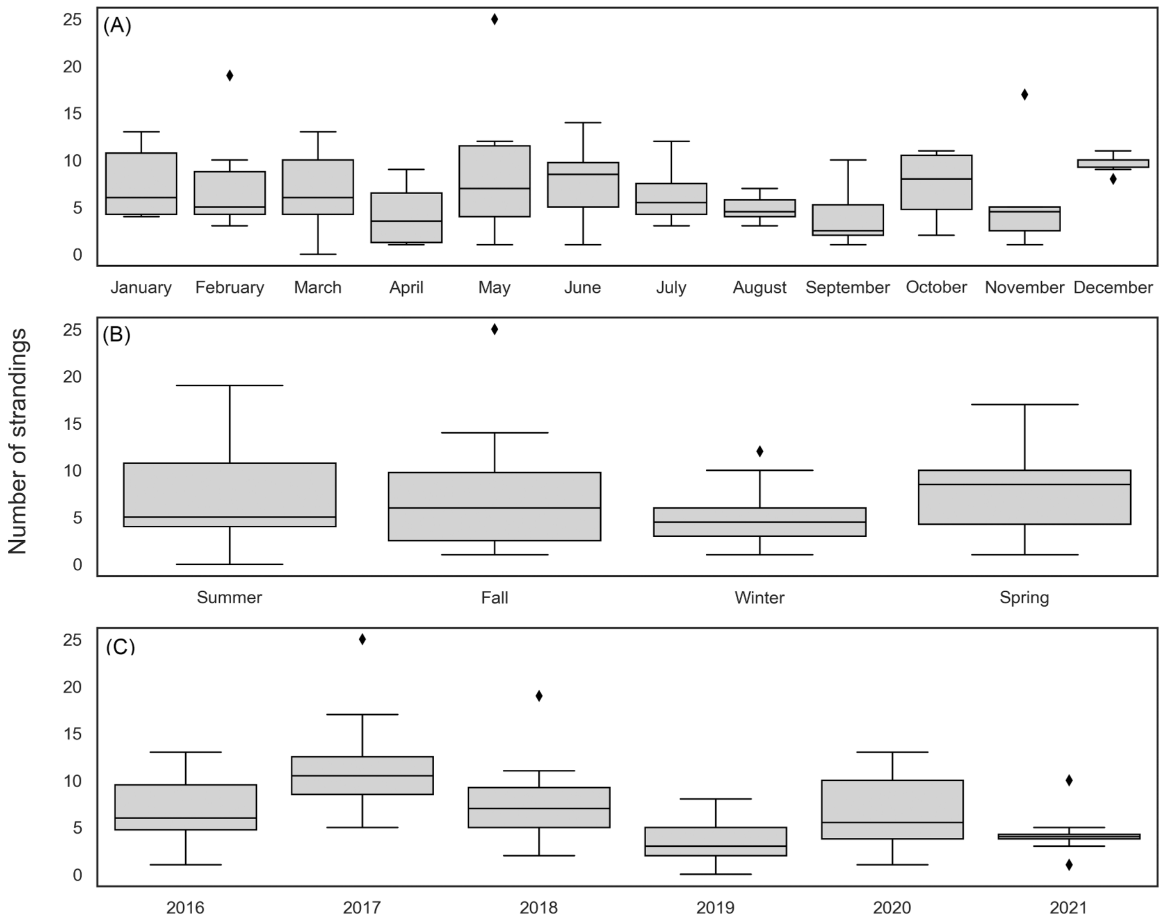

Fig. 2. Temporal variability (median, quartiles, range and outliers) of Chelonia mydas strandings in different scales: (A) monthly, (B) seasonal, and (C) yearly.

Table 2
Results of the Kruskal-Wallis test (df: degrees of freedom; p-value) for the comparison of the number of strandings among the groups: months, seasons, and years.

Kruskal-Wallis	df	p-value
Strandings ~ Month	11	0,3373
Strandings ~ Season	3	0,3079
Strandings ~ Year	5	0,0005749 *

Navegantes throughout the year, likely for foraging activities, as observed in nearby regions (Gallo et al., 2006; Guebert-Bartholo et al., 2011; Reisser et al., 2013; da Silva Valente et al., 2022). Most green turtles that use the Southwest Atlantic as feeding grounds come from the rookeries in Ascension Island (Naro-Maciel et al., 2012; de Almeida et al., 2021). Given that the minimum female CCL is 100 cm in Ascension Island rookeries (Weber et al., 2014) and other locations (Godley et al., 2001), changes in occurrence are unlikely to be related to reproductive migrations, as nearly all specimens in the study area were well below this size.

The interannual fluctuations in stranding numbers could be linked to variations in reproductive success and survival rates of smaller juveniles,

Table 3
Annual mean and standard deviation (std) of the wind components (U10, V10; m/s), sea-level atmospheric pressure (MSL; Pa), mean wave direction (MWD; °T), mean wave period (MWP; s), sea surface temperature (SST; °C), wave height (SWH; m), surface current components (UO, VO; m/s), and sea level (ZOS; m) are presented for the years 2016–2021.

Year		U10 (m/s)	V10 (m/s)	MSL (Pa)	MWD (°T)	MWP (s)	SST (°C)	SWH (m)	VO (m/s)	UO (m/s)	ZOS (m)
2016	Mean.	−0647	0258	101636,7	115,721	7259	21,973	1264	0031	0011	0024
	std	1293	1515	388,077	22,582	0663	3723	0196	0082	0014	0065
2017	Mean.	−1177	−0429	101646,3	104,916	7227	22,881	1361	0025	0009	0026
	std	1024	1494	441,421	14,679	0784	2707	0284	0084	0017	0077
2018	Mean.	−0850	0007	101629,4	112,685	7253	22,487	1271	0031	0011	0101
	std	1267	1467	379,477	16,493	0843	3193	0257	0091	0018	0070
2019	Mean.	−0934	0209	101653,3	111,287	7208	22,867	1313	0050	0008	0094
	std	1032	1619	355,195	14,474	0724	3198	0217	0100	0019	0072
2020	Mean.	−0958	0164	101661,1	112,809	7050	22,531	1261	0014	0002	0103
	std	1372	1605	355,662	19,084	0662	2795	0208	0100	0019	0091
2021	Mean.	−1089	0430	101667,1	113,137	6987	22,374	1254	0013	0000	0091
	std	1505	1444	426,786	18,595	0557	3208	0188	0082	0016	0076

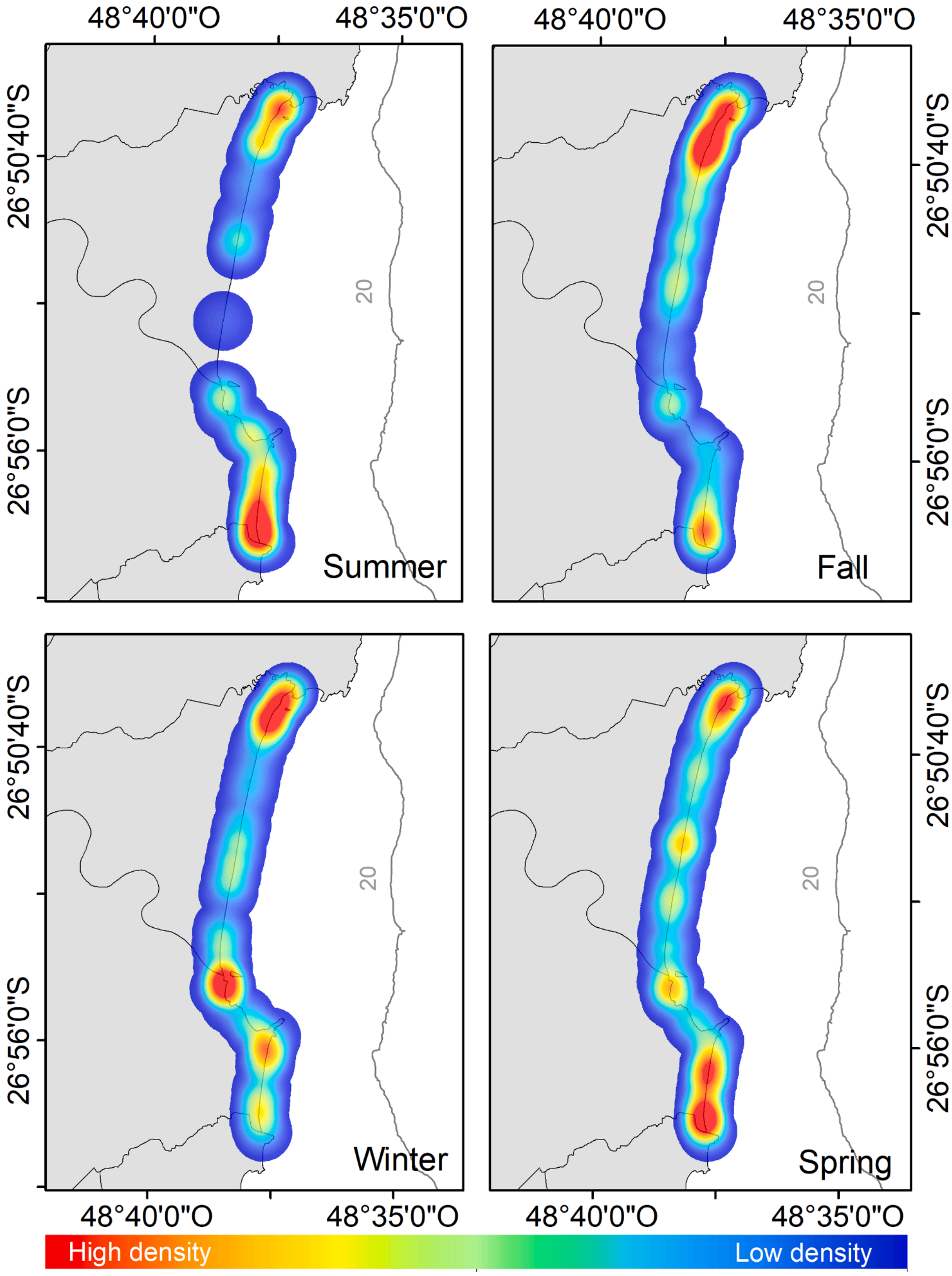

Fig. 3. Spatial distribution analysis of Chelonia mydas strandings in the study area encompassing Itajaí and Navegantes throughout the seasons from 2016 to 2021. Density is represented using kernel density analysis with a 1 km bandwidth, and the 20-meter depth isobath is delineated by a gray line.

thereby influencing the overall stranding patterns. Factors such as species distribution and abundance in the area, adverse environmental conditions outsize of the study area, and increased exposure to anthropogenic influences (e.g. fishing gear, watercrafts, direct human injuries, plastic, and other pollutants) might also contribute to these observed fluctuations (NRC, 1990; Crowder et al. 1995; Epperly et al. 1996; Lewison et al. 2003; Moore et al. 2020; Guimarães et al., 2021). While the present study did not delve into this aspect, it is noteworthy that interactions with fishing activities could increase the number of strandings. Incidental capture in fishing nets is a significant source of mortality for green turtles along the Brazilian coast (Gallo et al., 2006; López-Barrera et al., 2012; Domiciano et al., 2017).

Although the sampling effort experienced a slight reduction for a brief period (March-2020) due to Covid-19 related restrictions, it appears to have had minimal impact on the overall analyses as 2020 showed an increase in strandings compared to 2019 and 2021. Nevertheless, future investigations should explore the causal factors that were not explored in this work, such as human activities, that may be underlying annual differences in stranding numbers.

4.1. *Spatial variability*

The spatial distribution of strandings presented distinct accumulation patterns that varied over time. Notably, a spatial trend emerged, revealing lower stranding densities in regions closer to the center of the study area. In contrast, the highest stranding densities were typically observed in the northernmost and southernmost regions of each beach. Interestingly, the locations with the highest strandings densities exhibited seasonal variability. During autumn and winter, the northern areas tended to display more frequent instances of high densities. In

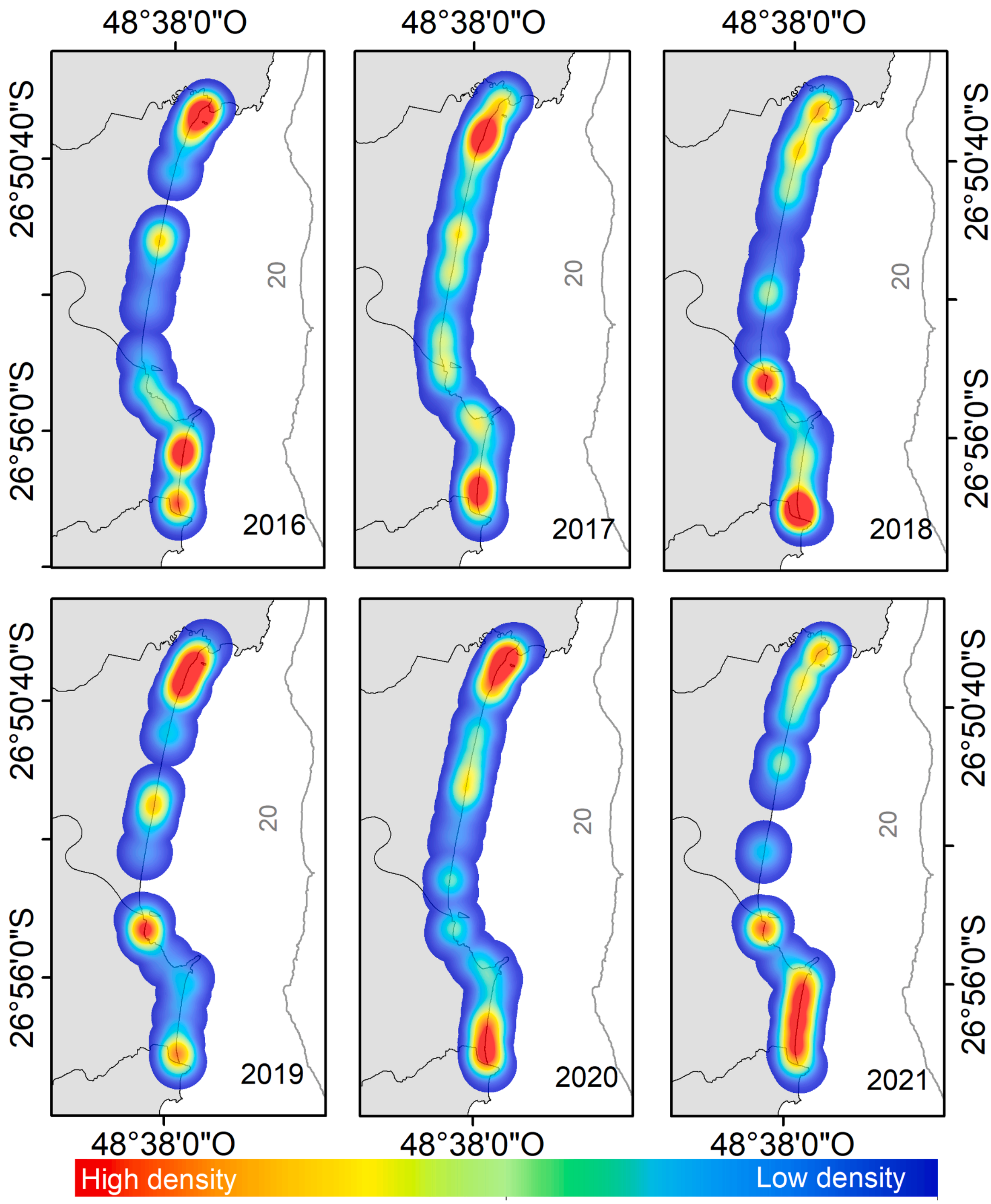

Fig. 4. Spatial distribution of Chelonia mydas strandings within the study area covering Itajaí and Navegantes from 2016 to 2021. Density is represented using kernel density analysis with a 1 km bandwidth, and the 20-meter depth isobath is delineated by a gray line.

Table 4
Best-fitted model for the number of weekly strandings between the years 2016 and 2021 is compared with the null model, including the degrees of freedom (df), Akaike Information Criterion (AIC) values, and explained deviance values (Dev. expl).

Model	AIC	df	Dev. expl.
~ 1 (null)	645,692	3	-
~ s(year) + s(u10_s) + s(u10_std) + s(msl_s) + s(sst_std) + s(swh_s) + s(swh_std) + s(zos_std)	527,213	31,431	31,50 %

Table 5
Results of the Dunn's multiple comparison test are presented, indicating the p-value for the comparison among the years.

	2016	2017	2018	2019	2020	2021
2016	1,0000					
2017	0,3963	1,0000				
2018	1,0000	0,7153	1,0000			
2019	0,3777	0,000543 *	0,1313	1,0000		
2020	0,7951	0,2760	1,0000	0,5065	1,0000	
2021	0,8264	0,00487 *	0,4352	1,0000	0,9623	1,0000

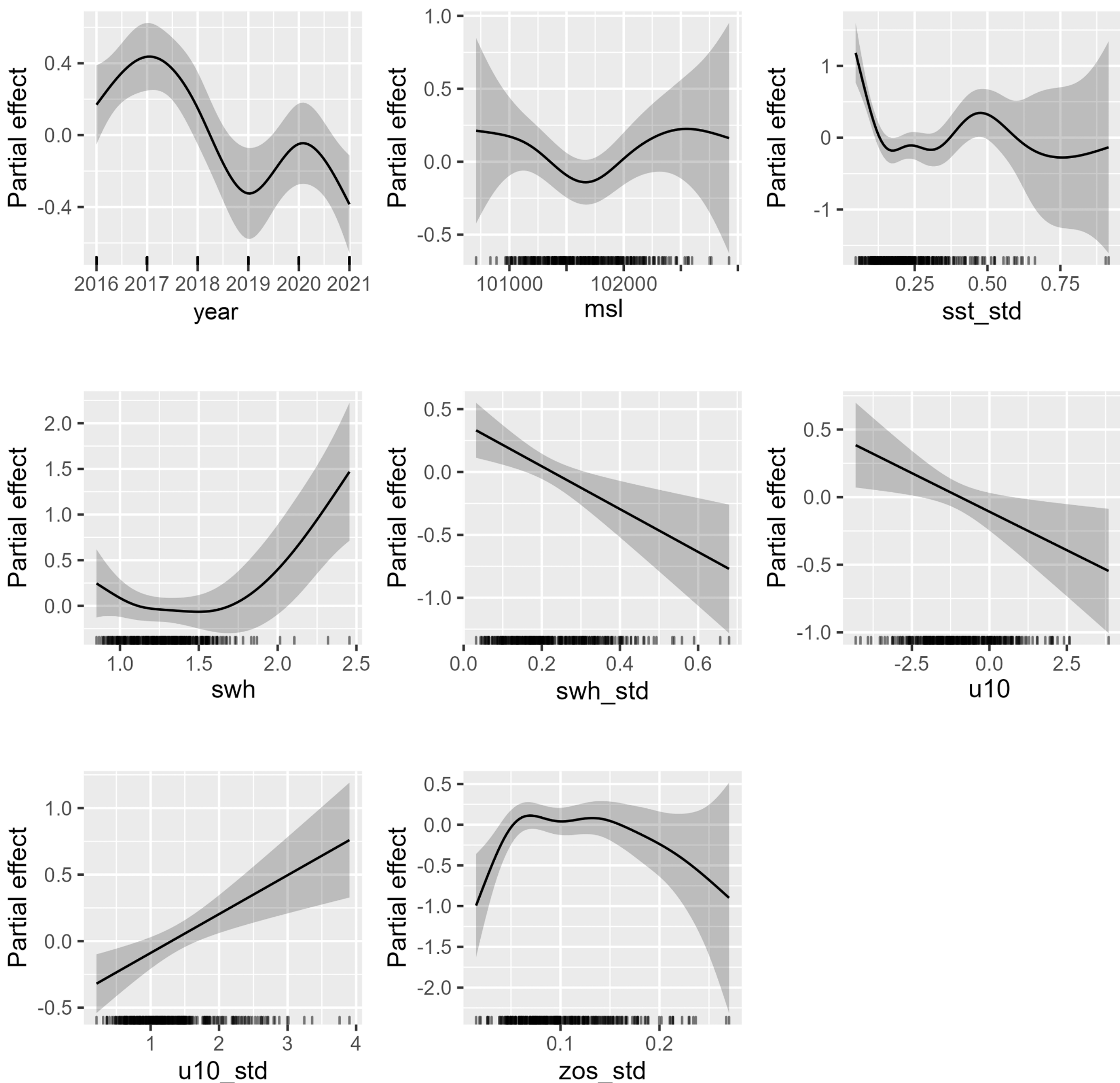

Fig. 5. GAM results (smoothed partial effects and confidence intervals) of meteoceanographic variables fitted to the weekly strandings of Chelonia mydas between years 2016 and 2021. The variables under investigation include Year, Average Sea-Level Atmospheric Pressure mean (MSL) and standard deviation (sst_std), Significant Wave Height mean (swh), and standard deviation (swh_std), 10-meter Surface Ocean Wind in Zonal Component mean (U10), 10-meter Surface Ocean Wind in Zonal Component (u10_std), and Standard Deviation of Significant Height of the Sea Surface Above the Geoid (zos_std).

Table 6
Observed and predicted values by the adjusted model for weekly strandings of Chelonia mydas and the environmental variables, with 95 % confidence intervals lower and upper bounds.

Year	Observed	Predicted	Lower Limit	Upper Limit
2016	84	85	47	123
2017	132	131	77	184
2018	95	92	54	130
2019	41	48	26	69
2020	79	73	41	105
2021	54	56	29	82

contrast, summer and spring witnessed a higher frequency of high-density stranding events in the southern areas.

The higher occurrence in beach extremities may be explained by the green turtles' feeding habits, based on macroalgae (Reisser et al., 2013; Gama et al., 2016). The beaches in the area feature rocky shores at their extremities, where macroalgae species that green turtle feed on usually grow on rocks or other consolidated substrates. These areas near to the beach extremities likely provide better foraging opportunities for the turtles. However, since these areas remain consistent over time, other factors must contribute to the temporal variability observed.

Interannual stranding densities maintained the trend of higher occurrences in the study area's extreme southern and northern regions, while central regions exhibited lower frequencies. Nevertheless, interannual variations were evident, with occasional inversions between years. For instance, higher densities occurred in the southern area during 2018 and 2021 and in the northern area during 2019. These fluctuations can likely be attributed to the seasonal patterns of oceanographic and climatic processes, which exert significant influence on the annual distribution of strandings. However, it is evident that this trend is not consistently uniform across all years in the sample series. This observation suggests the possible dominance of specific climatic events in different years, alongside years when the usual regional regime prevails and engenders similar distributions.

Throughout all temporal intervals of the sample series, the environments exhibiting the highest stranding densities coincide with those most impacted by south and southeast waves, which are prevalent in the region (Araújo et al., 2003; da Silva et al., 2012). Brava Beach to the south of the study area and Gravatá Beach to the north (Klein and Menezes, 2001; de Menezes et al., 2003) stand out as significant locations where these influences are particularly pronounced.

4.2. Meteoceanographic conditions

The results obtained from the GAM model indicated a notable relationship between oceanographic variables (such as wave height and its variation, sea surface temperature oscillation and sea level oscillation) as well as climatic variables (including wind variability and direction and atmospheric pressure) with respect to elucidating the variability observed in weekly stranding quantities. These findings underscore the significance of these factors in influencing and explaining the fluctuations observed in the number of strandings on a weekly basis.

The direct relationship between wind and strandings in the study area was verified due to an increase in strandings with the predominance of stronger winds blowing from the east (towards land) and a decrease under the dominance of stronger winds from the west (towards the sea) These findings are consistent with observations in Rio Grande do Sul (Monteiro et al., 2016). Furthermore, it was found that the effect of wind was positive, with an increase in strandings during periods of greater variation in wind direction. This may be associated with abrupt changes caused by the passage of weather systems. Conversely, the effect of wind was negative with the trend of mean wind values. According to Hart et al. (2006), wind plays a pivotal role in determining the likelihood of marine turtle strandings due to the substantial surface area of these animals, which makes them susceptible to direct wind impact. Epperly et al. (1995) also noted that specific wind regimes can initiate offshore flow, consequently reducing the number of carcasses reaching the beach. A similar process of flow is observed in the study region, influenced by a high-pressure system from the South Atlantic that leads to persistent dominance of north-quadrant winds (Andrade et al., 2016). Under the influence of wind friction, surface waters in the southern hemisphere tend to move to the left, 90° from the wind direction, generating the Ekman transport, a result of balance between the Coriolis and turbulent drag forces (Garrison, 2010; Castello and Krug, 2015). Monteiro et al. (2016) also reported that this transport of surface waters, under persistent dominance of southwest winds, can increase the abundance of jellyfish in coastal waters, thus increasing the presence of marine turtles in the region and, consequently, the probability of strandings.

The effect of significant wave height on carcasses was observed, with an increase in the number of strandings coinciding with the highest wave heights in the time series. Cantor et al. (2020) corroborates with this, emphasizing that waves play a vital role in the mass transport of organisms on the ocean surface. Extreme wave heights exceeding the region's average can significantly influence the transportation of organisms to coastal areas. Furthermore, it was observed that smaller standard deviations of significant wave height were associated with an increase in strandings, while larger variations led to a decline in the number of strandings. The physical processes engendered by the passage of weather systems can cause alterations in wave height, resulting in the generation of waves larger than the average (Davis and Fitzgerald, 2009). Under such conditions of heightened wave activity, the transportation of carcasses toward the coast is favored, leading to a higher frequency of strandings (Cantor et al., 2020). This transportation process intensifies near the coast, where interactions with the seabed modify parameters like wavelength, wave height, and velocity. As carcasses reach the surf zone, wave energy dissipation, manifested as turbulent kinetic energy, produces a longshore current. This current generates an energy vector directing its movement, transporting carcasses to various emergent regions depending on the angle of incidence and wave height (Longuet-Higgins, 1970; Davis and Fitzgerald, 2009).The positive effect of a lower variation in significant wave height on the increase in stranded animals can be attributed to the presence of more energetic swells characterized by well-defined directions and larger waves, thereby contributing to a more uniform average wave height. Conversely, on days without energetic swells, the swell tends to exhibit bimodal directions and irregular wave heights, leading to an increased variation in the average wave height without a concurrent enhancement in the energy of transport. Consequently, the number of strandings tends to decrease under such conditions.

The oscillation in sea surface temperature exhibited a significant association with higher occurrences of strandings in the study area when values were close to the mean. However, this relationship became nonsignificant as greater variations in temperature occurred. This behavior suggests that the trend of strandings related to temperature is closely linked to the mean sea surface temperature values and that greater variability in temperature leads to an attenuation of stranding records in the region, while the direct causal effect of temperature on the transport of carcasses towards the coast is not evident, other hypotheses offer possible explanations for their relationship with strandings. Among these, the literature frequently addresses the connection between sea surface temperature, carcass decomposition rates and species distribution. Carcass decomposition rates are notably influenced by sea surface temperature, with higher temperatures resulting in a more rapid decomposition process (Cook et al., 2021). Additionally, individuals in advanced stages of decomposition tend to float more, which could facilitate their drift over longer distances (Santos et al., 2018).

While the atmospheric pressure variable constitutes the best-fitted model for the species, its partial effect on strandings was not deemed significant. This can be attributed to the low occurrence frequency of atmospheric pressure values that exhibit some effect on stranding events. Consequently, the partial effect values on strandings present wider confidence intervals, and the small effects on the increase in the number of strandings did not reach statistical significance. However, it is noteworthy that these extreme atmospheric pressure values are indicative of high and low-pressure atmospheric systems influenced by the dynamics of extratropical cyclones and anticyclones that affect the southern region of the South Atlantic (Oliveira et al., 2019). These atmospheric systems impact the direction and intensity of winds and waves, as well as temperature, depending on the prevailing meteorological feature controlled by the movement of the Maritime Polar Mass or the Maritime Tropical Mass of the South Atlantic Ocean (Nimer, 1989). Berini et al. (2015) similarly observed a positive correlation between atmospheric pressure and the number of strandings of a particular species, confirming the effects of these atmospheric changes on stranding occurrences. The alterations in the region's dynamic characteristics not only influence wind direction and intensity but also sea level height (Davis and Fitzgerald, 2009). In the context of sea level variation, the effects on stranding occurrences demonstrate a substantial decrease in the number of strandings as sea level values tend towards the average. This trend suggests that smaller sea level variations result in fewer stranding events, underscoring the influence of sea level dynamics on the likelihood of marine turtle strandings in the studied region.

The sea level regularly varies in short periods due to astronomical tides (Pugh, 1987). However, when cold fronts accompanied by winds from the south quadrant occur, they cause a rise in sea level above the expected astronomical tide, giving rise to what is known as meteorological tides (Truccolo, 1996; Marone and Camargo, 1994). This low-frequency phenomenon results from surface ocean currents directed towards the coast, a consequence of the Ekman transport (Garrison, 2010; Castello and Krug, 2015). Similarly, coastal movement and transport along the coast are significantly influenced by the intensification of extreme sea level events, which arise from the combined effects of astronomical and meteorological forcing, thereby altering the hydrodynamics of coastal regions (Andrade et al., 2018; 2021). In this context, Wilson and Adamec (2001) established a connection between sea surface height and strong currents, which can bring individuals, including marine turtles, closer to the coast.

The results of this study highlight the complex interaction between environmental factors and the dynamics of *Chelonia mydas* strandings and the importance of continuous and detailed monitoring of environmental conditions and human activities to better understand stranding patterns and, consequently, contribute to the conservation of green turtles along the Brazilian coast.

5. Conclusion

This study identified spatial and temporal patterns of *Chelonia mydas* strandings along the beaches of Itajaí and Navegantes in Santa Catarina, Brazil. The main oceanographic and climatic processes associated with strandings during the study period were identified and analyzed. The findings shed light on the factors influencing the occurrence of strandings in this specific region, contributing to our understanding of the dynamics of marine turtle strandings in coastal areas.

The adjusted GAM model proved effective in predicting the general trend of annual fluctuations in stranding numbers over the study period, utilizing environmental variables as predictors of stranding events in the region. The model's capability to forecast possible fluctuations in stranding numbers in subsequent years using the selected environmental variables holds promise for future applications. Although oceanographic and climatic processes do not encompass all the factors responsible for green turtle strandings in the study area, they emerged as significant explanatory variables for strandings. Notably, the environmental variables displayed robust predictive power, even during events with stranding numbers far exceeding the average. Furthermore, the influence of oceanographic and climatic processes suggests that areas with higher densities of strandings are correlated with greater exposure of specific beaches to these processes. Additionally, the densities of strandings correspond with the alternating prevalence of specific processes during different periods. It is essential to recognize that other factors may contribute to inter-annual fluctuations in the number of strandings, including the occurrence, abundance, and/or mortality rates of the species in the region, which may not remain constant over time.

Indeed, the established patterns for the studied species, although applicable only to the local scenario, hold significant value in the absence of region-specific studies. The research conducted in this study can serve as a crucial source of information for informing future conservation and management actions in the area. Moreover, the utilization of a relatively small study area to examine possible correlations between strandings provides a more detailed and localized perspective of regional effects. Despite the relatively short time series in comparison to the species' lifespan, the data gathered in this study has the potential to contribute to future research endeavors related to stranding patterns. Continuously monitoring these patterns can offer insights into various biological and ecological factors affecting marine turtles in the area. Moreover, such monitoring efforts can play a critical role in detecting and assessing environmental impacts that may impact individuals or species.

CRediT authorship contribution statement

Ricardo Utzig Nardi: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mauro Michelena Andrade:** Writing – review & editing, Supervision. **André Silva Barreto:** Writing – review & editing. **Rodrigo Sant'Ana:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2024.103939.

Data availability

All data sets used in this study are publicly avaiable.

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