Coral Reefs
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RESEARCH

Coral bleaching and mortality across a 24° latitudinal range in the Southwestern Atlantic during the fourth global bleaching event

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Abstract Anthropogenic climate change combined with the 2023–24 El Niño-Southern Oscillation triggered the fourth global bleaching event, affecting coral reefs worldwide. However, the extent of its impacts on the unique and extensive reef environments in the Southwestern Atlantic remained unquantified. Here, we report results from the first large-scale, standardized bleaching monitoring effort in the Southwestern Atlantic, encompassing 18 reef sites across a broad latitudinal range (3°-27°S). The intensity and duration of the thermal stress experienced were evaluated using the Degree Heating Week metric, obtained through remote-sensing data. Bleaching and coral cover loss were monitored through photoquadrat surveys conducted before, during, and after the event. Our results revealed widespread thermal anomalies that often exceeded 20 °C-weeks and lasted

Miguel Mies and Giovanna Destri have contributed equally to this work.

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3–5 months. Bleaching incidence reached 96% in Maragogi, 84% in Porto de Galinhas, and > 70% in nearby sites on the northern coast (~ 3°–9°S). In contrast, southern sites (~ 22°–27°S) such as Alcatrazes Archipelago and Arraial do Cabo experienced < 5% bleaching. Coral mortality was highest in Maragogi (88%) and São José da Coroa Grande (53%), both within the largest nearshore Brazilian marine protected area. The species *Millepora alcicornis* and *Mussismilia harttii* experienced the highest declines, repeating patterns observed during the 2019–20 bleaching event. As key providers of structural complexity, their continued degradation threatens overall biodiversity. These results highlight the increasing impacts of global warming in a region that is generally neglected in global bleaching assessments, and underscore the urgency of sustained, standardized monitoring to track change and support effective climate conservation efforts across the Southwestern Atlantic.

Keywords Brazil · Climate change · El Niño · Global warming · Marginal · Thermal stress

Introduction

Since the Industrial Revolution, the atmospheric CO_2 concentration has risen ~ 140 ppm, contributing to an increase in Earth's temperature by 1.4 °C (IPCC 2021). With the continuous increase in CO_2 and temperature across the planet, record-breaking thermal anomalies have been registered in the ocean, making recent years the warmest on record (Hoegh-Guldberg et al. 2023; Blunden and Boyer 2024; Rodrigues et al. 2025a). As such, many climate-driven tipping points—when critical thresholds are crossed and cause systemic shifts—have been identified in marine systems, including the collapse of polar ice sheets, the thawing of permafrost, disruptions in thermohaline circulation, and the widespread loss of coral reef ecosystems (Barnard et al. 2021; Heinze et al. 2021; Wunderling et al. 2024). In 2023–24, anthropogenic global warming and the warm phase of the most recent El Niño-Southern Oscillation (ENSO) cycle produced multiple marine heatwaves across the globe (Cheng et al. 2025). This triggered widespread coral bleaching, a stress response driven by the thermally-induced loss of symbiotic dinoflagellates, leading to energetic deficit and increased risk of mortality for the coral hosts (Glynn 1993; Brown 1997; Rädecker et al. 2021; Helgoe et al. 2024). This latest large-scale bleaching event has exacerbated the ongoing global loss of more than 50% of coral cover over the past four decades (Gardner et al. 2003; Dietzel et al. 2020; Tebbett et al. 2023).

As global warming advances, mass coral bleaching episodes have become more frequent and intense, occurring on larger spatial scales and affecting a broader array of species (Hughes et al. 2018). Large-scale events, known as "Global Bleaching Events" (GBE), affect extensive regions of the Atlantic, Pacific, and Indian Oceans and are typically associated with the ENSO warm phase (Oliver et al. 2018; Skirving et al. 2019). In recent decades, three GBE were

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documented in 1997–98, 2009–10, and 2014–17 (Hughes et al. 2017; 2018; Oliver et al. 2018), alongside numerous regional-scale bleaching events in between them (Kleypas et al. 2008; Le Nohaïc et al. 2017; Sully et al. 2019). More recently, in 2023–24, coral reefs worldwide underwent yet another GBE, also associated with the ENSO warm phase (Reimer et al. 2024). Although still in its early stages of documentation, the fourth GBE has already produced severe effects, including the bleaching of 88% of the Great Barrier Reef (Cantin et al. 2024) and mass mortality at reef sites along the Tropical Eastern Pacific and Caribbean (Goreau and Hayes 2024; López-Pérez et al. 2024).

In the South Atlantic Ocean, however, the severity and extent of the impacts caused by the fourth GBE remained unassessed. Reports of bleaching in the region are limited, and are frequently overlooked in global comparisons (Banha 2025). The reef environments in the South Atlantic are primarily located along the Brazilian coast (Southwestern Atlantic) and span approximately 3,000 km in latitude (~ 30°). These reefs are separated from the Caribbean by the Amazon-Orinoco plume and the northward-flowing North Brazil Current, which combine to act as a major biogeographic filter (Geyer et al. 1996; Floeter et al. 2008; Tosetto et al. 2022). The Brazilian continental shelf is under the influence of the Brazil and North Brazil currents (Rocha et al. 2014), which bring warmer waters that support the development of reef environments (Leão and Kikuchi 2001) including true coral reefs, coralline algal reefs, sandstone reefs, and rocky reefs (Mies et al. 2025a). However, both Holocene sea-level regression along the Brazilian coast and the discharge of several large rivers onto portions of the inner continental shelf are key drivers of elevated turbidity and nutrient concentrations (Dominguez 2004; Costa et al. 2006; Silva et al. 2013; Leão et al. 2016; Santana et al. 2023; Mies et al. 2025a). This creates a marginal environment that is generally challenging for the development of typical reef communities (Leão et al. 2003; Soares et al. 2021; Schoepf et al. 2023). Within this unique oceanographic context, a robust coral fauna with low diversity and high endemism emerged (Leão et al. 2003; 2016; Bleuel et al. 2024), predominantly composed of massive species with an enhanced ability to feed heterotrophically (Mies et al. 2017, 2018, 2024; Marangoni et al. 2019; Godoy et al. 2021).

Severe bleaching was first documented in the Southwestern Atlantic in 1998 during the first GBE, although relevant mortality was documented only in the northernmost portion of the Brazilian state of Bahia (Leão et al. 2010; Kelmo and Attrill 2013). During the second GBE (2009–10), bleaching was recorded at only a few locations and coral mortality was generally minimal (Ferreira et al. 2013; Miranda et al. 2013; Soares et al. 2019). The third GBE in 2016 caused extensive bleaching but still relatively low mortality (Teixeira et al. 2019). However, the 2019–20 regional-scale heatwave marked the most intense and prolonged bleaching event ever documented in the Southwestern Atlantic, with thermal anomalies exceeding 20 °C-weeks and persisting for almost five months (Banha et al. 2020; Ferreira et al. 2021; Gaspar et al. 2021; Braz et al. 2022; Pereira et al. 2022; Rodrigues et al. 2025b). Such anomalies caused extensive coral mortality, especially for the endemic and threatened scleractinian coral *Mussismilia hartii*, as well as for the hydrocorals *Millepora braziliensis* (also endemic) and *Millepora alcicornis*, the only branching species found in the South Atlantic (Duarte et al. 2020; Ferreira et al. 2021; Pereira et al. 2022; Corazza et al. 2024). Therefore, bleaching severity and associated mortality are clearly rising

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in Southwestern Atlantic reefs due to the increasing thermal stress in the last decades (Destri et al. 2025).

Despite the escalating impacts of global warming on Southwestern Atlantic reefs, no organized, standardized, and large-scale monitoring effort was conducted during any of the previous bleaching events. Thus, within the context of the 2023–24 ENSO, we performed a coordinated effort to document (i) the intensity and duration of thermal stress, (ii) bleaching incidence, and (iii) coral mortality during the fourth GBE across a broad latitudinal range (3° to 27° S) encompassing nearly the entire tropical Southwestern Atlantic.

Materials and methods

In response to the growing impacts of global warming on Southwestern Atlantic reefs, the Integrated National Program for Bleaching Monitoring was established in 2021. Led by the Coral Vivo Institute, the program is supported by the Brazilian Ministry of Environment and Climate Change (MMA) and Chico Mendes Institute for Biodiversity Conservation (ICMBio—the federal agency for protected areas), with the contribution of researchers from 20 institutions, including 15 Brazilian universities (Universidade de São Paulo, Universidade Federal da Bahia, Universidade Federal de Alagoas, Universidade Federal de Pernambuco, Universidade Federal de Santa Catarina, Universidade Federal de São Carlos, Universidade Federal de Sergipe, Universidade Federal do Ceará, Universidade Federal do Rio de Janeiro, Universidade Federal do Rio Grande, Universidade Federal do Rio Grande do Norte, Universidade Federal do Sul da Bahia, Universidade Federal Fluminense, Universidade Federal Rural de Pernambuco, and Universidade Federal de São Paulo), one French university (Université de Bordeaux), three non-governmental organizations (Coral Vivo Institute, Conservação Recifal Project, and Vida no Oceano Institute), and the ICMBio.

Bleaching monitoring was performed at 18 reef sites (Table 1) distributed in nine different Brazilian states across a broad latitudinal gradient ranging from Caucaia (Ceará State, ~ 3° S) to Galé Island (Santa Catarina State, ~ 27° S) and including two oceanic islands (Rocas Atoll and Fernando de Noronha Archipelago, located 250 and 350 km from the coast, respectively). An additional site at the northernmost Parcel do Manuel Luís State Park (~ 1° S) was considered, but a lack of logistical support and infrastructure prevented any assessments. Fifteen of the investigated sites are located within marine protected areas that are part of the Brazilian SNUC (National System of Nature Conservation Units) (Table 1). SNUC encompasses federal, state, and municipal protected areas

Table 1 The 18 reef sites assessed by the Integrated National Program for Bleaching Monitoring during the 2023–24 global bleaching event, spanning approximately 24° of latitude. Information is shown for their location, Marine Protected Area (MPA) category within the Brazilian SNUC system, reef type (based on Mies et al. 2025a), and geographical coordinates. All sites are coastal, except for the oceanic islands of Rocas Atoll and Fernando de Noronha Archipelago. Some of the reef sites remain unassesed regarding their geomorphological type

#	Reef site	State	MPA category	Reef type	Latitude	Longitude
1	Caucaia	Ceará	none	Sandstone reef	−3.6861	−38.6102
2	Fernando de Noronha Archipelago	Pernambuco	National Park	Rocky reef	−3.8378	−32.4275
3	Rocas Atoll	Rio Grande do Norte	Biological Reserve	Algal reef	−3.8644	−33.8047
4	Rio do Fogo	Rio Grande do Norte	Environmental Protection Area	sandstone reef	−5.2229	−35.3392
5	Porto de Galinhas	Pernambuco	none	Sandstone reef	−8.5125	−35.0003
6	São José da Coroa Grande (Costa dos Corais)	Pernambuco	Environmental Protection Area	Sandstone reef	−8.9025	−35.1358
7	Maragogi (Costa dos Corais)	Alagoas	Environmental Protection Area	Sandstone reef	−9.0307	−35.1937
8	Pedra do Abaís	Sergipe	none	Unassessed	−11.3703	−37.1715
9	Itaparica Island (Todos os Santos Bay)	Bahia	Environmental Protection Area	True coral reef	−13.1205	−38.7247
10	Recife de Fora	Bahia	Municipal Park	Unassessed	−16.4040	−38.9600
11	Corumbau	Bahia	Extractive Reserve	Unassessed	−17.0044	−39.1200
12	Abrolhos Archipelago	Bahia	National Park	True coral reef	−17.9586	−38.7125
13	Tartaruga Beach (Armação dos Búzios)	Rio de Janeiro	Municipal Park	Rocky reef	−22.7558	−41.9044
14	Forno Beach (Arraial do Cabo)	Rio de Janeiro	Extractive Reserve	Rocky reef	−22.9658	−42.0100
15	Anchieta Island	São Paulo	State Park	Rocky reef	−23.5308	−45.0844
16	Alcatrazes Archipelago	São Paulo	Wildlife Refuge	Rocky reef	−24.0910	−46.1811
17	Laje de Santos	São Paulo	State Park	Rocky reef	−24.3214	−45.6925
18	Galé Island (Arvoredo)	Santa Catarina	Biological Reserve	Rocky reef	−27.1810	−48.4100

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(Brasil 2002; Schiavetti et al. 2013) and includes multiple protection categories, reflecting the wide variation in ecosystems, biodiversity, and human uses across the country. Overall, the monitoring program spans approximately 24° of latitude, covering around 2,700 km in a straight north–south line and more than 4,000 km of coastline.

Field surveys

A simple, standardized, and comparable protocol was applied at each reef site by a small team of three or four divers. At each site, three 20-m fixed transects were established haphazardly, generally spaced around 50 m apart, although exact distances varied slightly. A 50 × 50-cm PVC pipe frame was positioned alongside the transect, with a Coral Health Chart attached to it. This chart uses a color-coded palette to track changes in coral pigmentation, which is directly linked to the concentration of symbiotic dinoflagellates present on the coral tissue (see Siebeck et al. 2006). The PVC frame containing the chart was photographed along each transect using a digital camera, resulting in 40 images per transect. All transects were located at 3 to 7 m of depth, except at the Pedra do Abaís site in Sergipe, where a deeper, previously unexplored and submerged reef was surveyed at 20 m. Surveys were carried out at three key phases of the GBE at each site—before (August to December 2023), during (April to June 2024), and after (September to December 2024) the thermal stress period induced by the fourth GBE in the Southwestern Atlantic. Surveys were performed under the authorization of SISBIO license #96,895–2.

Image analysis

A total of 6,360 images were generated, and benthic cover was quantified using the PhotoQuad® software (Trygonis and Sini 2012). The perimeter of each benthic feature was determined for all images, and its area was then calculated by the PhotoQuad® algorithm, with the 50 × 50-cm PVC frame serving as a metric reference. Benthic cover features identified were divided into eight categories: live coral (including all photosymbiotic corals identified at the species level), bleached coral, zoantharians, turf algae, frondose algae, crustose coralline algae, other benthic invertebrates, bare substrate, and unidentified. Coral bleaching incidence was determined as the percentage of bleached coral cover relative to the total live coral cover. A coral colony (or a portion of it) was considered bleached if its pigmentation decreased by at least one category on the Coral Health Chart (except when it was reduced from category 6 to 5) or if it matched categories 1 or 2. Coral mortality was calculated for each site and species based on reductions in relative live coral cover between the before and after survey periods.

Thermal stress intensity and duration

The intensity and duration of the thermal stress across the 18 reef sites in the Southwestern Atlantic were evaluated using the Degree Heating Week (DHW) metric developed by the U.S. National Oceanic and Atmospheric Administration Coral Reef Watch program (NOAA CRW). DHW, one of the most used metrics for evaluating cumulative thermal stress, quantifies the accumulation of thermal anomalies exceeding the maximum monthly mean sea surface temperature for a given site over the past 12 weeks (Liu et al. 2014; Skirving et al. 2017). Another metric used was HotSpot, a measure of how much the current sea surface temperature exceeds the maximum monthly mean for a given location (Liu et al. 2014). A + 1 °C HotSpot threshold is used for thermal stress accumulation in DHW (NOAA Coral Reef Watch 2018). Daily DHW and HotSpot data at a 5-km resolution were obtained for each reef site, based on their latitude and longitude (see Table 1), from NOAA CRW's FTP server (NOAA Coral Reef Watch 2018) for the period between January 1st and December 12th, 2024. Thermal stress intensity was assessed by obtaining the maximum DHW value recorded for each of the 18 surveyed reef sites. The duration of thermal stress for each site was determined by counting the number of days with DHW ≥ 0.1 °C-weeks and HotSpot ≥ 1.0 °C—*i.e.*, whenever thermal anomalies were present.

Exploratory data analyses

The distribution of benthic cover data was evaluated to define the most adequate modeling technique to apply to our data. Initial data exploration showed that total site cover data was always greater than zero and never reached 1 or 100%, thus our observed data $y_k \epsilon (0,1)$ (Fig. S1). Nonetheless, some individual species could be completely absent at some sites, but none of them alone ever covered an entire area, thus data of individual species was in the interval $y_k \epsilon [0,1)$ (Fig. S2). Overall, these data distributions show that Beta regression and Zero-Inflated (ZI) Beta regression, fully described below, are suitable considering our data (Ferrari and Cribari-Neto 2004; Douma and Weedon 2019).

Beyond identifying the distribution of cover data, the exploratory analyses indicated some plausible model structures to be compared. For instance, the average (Fig. S1) and standard deviation (SD) of total cover varied between periods ($SD_{before} = 0.136$, $SD_{after} = 0.152$). Variability was caused by the increase in the frequency of values near to zero after the bleaching event. As such, it seems reasonable to compare Beta regressions where the precision ϕ and the probability of zero observations ψ are either constant or vary across periods (Table S3). Since variability in coral cover within sites (among replicated transects) was detected (Fig.

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S4), we compared Beta regression models either accounting (transect ID as a random intercept in the model of the response average μ) or not for the effect of the transects (Table S3). We also identified site-specific variation in total coral cover between periods (Fig. S2). Because species varied in cover between periods, it seemed reasonable to evaluate models where period and site interact to determine total coral cover and the cover of individual species/functional groups (Table S3).

Beta regression analysis

Beta regression is a modeling technique designed to handle proportional data (Ferrari and Cribari-Neto 2004; Douma and Weedon 2019) such as the benthic cover data. The usual parameterization of the Beta regression includes the average μ and precision ϕ parameters (Douma and Weedon 2019). The response average μ given a set of covariates $\mathbf{X}$ is assumed to be linear on the logit-transformed scale (as in a logistic regression), as shown in Eqs. 1–3:

$$\mathbf{y}_k \sim \text{Beta}(\mu, \phi) \tag{1}$$

$$\log it\,(\mu) = \log\,(\mu\,/\,1 - \mu) = \eta = \boldsymbol{X'\beta} \tag{2}$$

$$\log\,(\phi) = \zeta = \mathbf{Z'\gamma} \tag{3}$$

where $\boldsymbol{y}_k$ is a vector of $k = 1, \ldots, K$ observations. The parameters η and ζ are the linear predictors of the average and precision models, respectively. $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ are vectors of regression coefficients (intercept and slopes) to be estimated, and $\boldsymbol{X}$ and $\boldsymbol{Z}$ are the design matrices of covariates (Douma and Weedon 2019). In our case, $\boldsymbol{X}$ had the factors period, site, period x site interaction for total cover analyses, and period, species/functional group, period x species/functional group interaction for analyses at the species/functional group level (see Table S3 for a list of model structures and covariates per model). $\boldsymbol{Z}$ included period in models where we allow precision to vary between periods. Estimates from these two models can be interpreted in the proper response interval by back transforming the linear predictors using the inverse of link functions of the linear predictors—*i.e.*, $\text{logit}^{-1}(\eta)$ and $\exp(\zeta)$.

In comparison to the Beta regression presented in Eqs. 1 to 3, there is one additional parameter in the ZI Beta regression, ψ, which is the probability that one observation is zero or not. As μ and ϕ, the ψ can be constant (*e.g.*, $\psi \sim 1$, where only the intercept—the average—is estimated) or vary in function of covariates (in our case period) in a logistic regression such as Eq. 2. The function $\text{logit}^{-1}(\psi)$ provides an estimate of the proportion of zeroes in the data set. The ZI Beta regression was fitted to data of 15 individual species/functional groups observed in at least eight different sites across all periods (corals: *Agaricia humilis*, *Favia gravida*, *Madracis decactis*, *Millepora alcicornis*, *Montastraea cavernosa*, *Mussismilia braziliensis*, *Mussismilia harttii*, *Mussismilia hispida*, *Porites astreoides*, *Siderastrea* sp.; zoantharians: *Palythoa caribaeorum*, *Zoanthus* sp.; algae: crustose coralline algae, frondose macroalgae, turf algae).

Posterior-predictive checks were done to analyze model predictive performance to new data, using the Leaving-One-Out cross-validation method—LOO-CV. Models were compared using the Leaving-One-Out cross-validation criterion (Vehtari et al. 2017). An absolute difference of 4 ELPD (expected log pointwise predictive density) units was used to elect the single or multiple models with highest predictive performance and fit to data. Models were fitted to data and parameters estimated in a Bayesian framework, thus enabling to calculate the probability associated to each result being produced or hypothesis being tested. All these analyses were done using the 'brms' (Bürkner 2017) and 'loo' (Vehtari, et al. 2017) packages in the R Programming Environment (R Core Team 2024). Parameters were estimated using the Hamiltonian Monte Carlo (HMC) with No-U-Turn-Sampling, run with 10,000 interactions in four independent chains, warm-up of 5,000 iterations and a thinning each ten iterations, yielding 2,000 posterior distribution draws of each parameter. The HMC control parameter 'adapt_delta' was set to 0.99, enabling successful model convergence. Models were initialized using weakly informative or flat priors for parameters ($Normal(\mu = 0, \sigma = 1)$ for regression slopes, $student - t(3, 0, 2.5)$ for intercepts and standard deviation of μ model, $Logistic(0, 1)$ for ψ intercept and improper flat priors for ψ coefficients, and improper flat priors for ϕ intercept and slopes).

From the best-ranked model we extracted posterior distribution draws to plot, and calculated statistics summarizing the 2,000 posterior distribution draws of each parameter, using the 'emmeans' package of R (Lenth 2024). Using 'emmeans' we could estimate the isolated effect of period and site or period and species/functional group while accounting for interactions (period x site or period x species/functional group). We used histograms and density plots to visualize the distribution of posterior samples, highlighting the median value across all draws. These tools were used to illustrate the difference between before and after the bleaching event in total coral cover regionally, per site, and species/functional group (while considering the interactions). We used boxplots to illustrate the total coral cover per site and period, along with 1st, median, 3rd quantiles of the 2,000 posterior distribution draws. The probability of before-after bleaching cover differences being different from zero was calculated as the number of draws above or below zero relative to the total of 2,000 posterior draws. A complete workflow of the analyses is described in Supporting Information Figure S5.

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Results

Thermal stress

Along the entire Brazilian coast, thermal stress anomalies persisted for approximately five months, from early January to mid-June 2024 (Figs. 1, S6). However, their intensity and duration varied along the coast, with some sites experiencing higher thermal stress than others. Thermal stress was more intense to the north of Itaparica Island (Todos os Santos Bay, Bahia State), where all reef sites recorded DHW values of approximately 16 °C-weeks or higher (Figs. 1 and 2; Table 2). The highest levels were observed at Caucaia (21.3 °C-weeks), Rio do Fogo (20.9 °C-weeks), Maragogi (20.6 °C-weeks), and São José da Coroa Grande (20.2 °C-weeks), indicating that the northern portion of the coast was the most affected. The reef sites that experienced the lowest thermal stress intensity were Tartaruga Beach (Armação dos Búzios) and Forno Beach (Arraial do Cabo), both of which were subjected to less than 4.0 °C-weeks. Three clearly distinct patterns are evident in Fig. 1: southern sites experienced shorter and earlier thermal stress

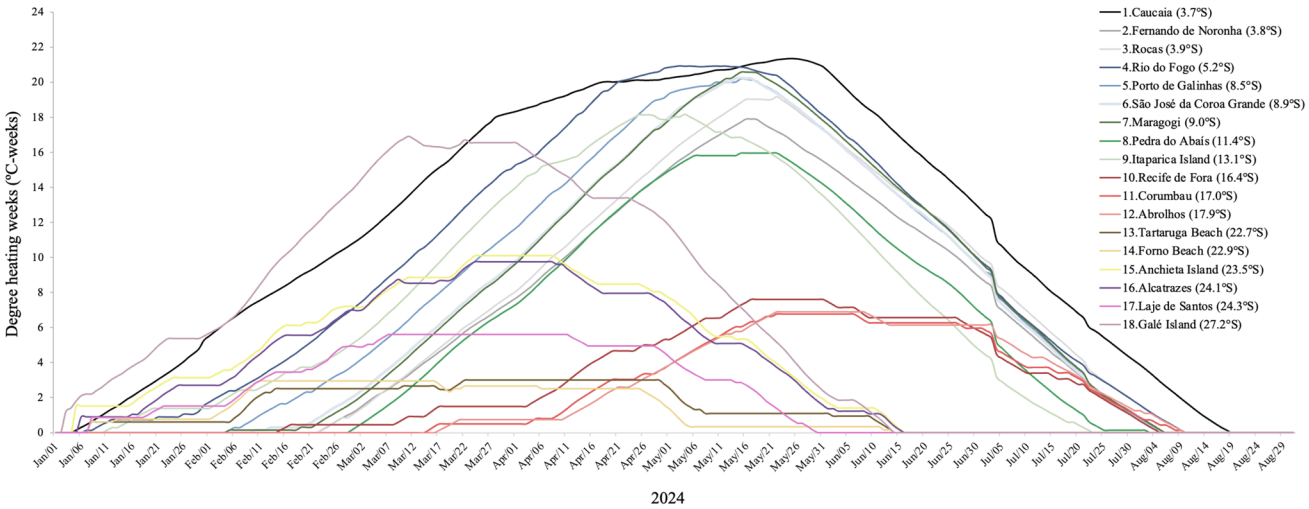


Fig. 1 The temporal progression of cumulative thermal stress (Degree Heating Weeks) in 18 Southwestern Atlantic reef sites during the fourth global bleaching event in 2024. Sites and corresponding latitudes are listed on the right panel.The sites are Caucaia, Fernando de Noronha Archipelago, Rocas Atoll, Rio do Fogo, Porto de Galinhas, São José da Coroa Grande (Costa dos Corais), Maragogi (Costa dos Corais), Pedra do Abaís, Itaparica Island (Todos os Santos Bay), Recife de Fora, Corumbau, Abrolhos Archipelago, Tartaruga Beach (Armação dos Búzios), Forno Beach (Arraial do Cabo), Anchieta Island, Alcatrazes Archipelago, Laje de Santos, Galé Island (Arvoredo)

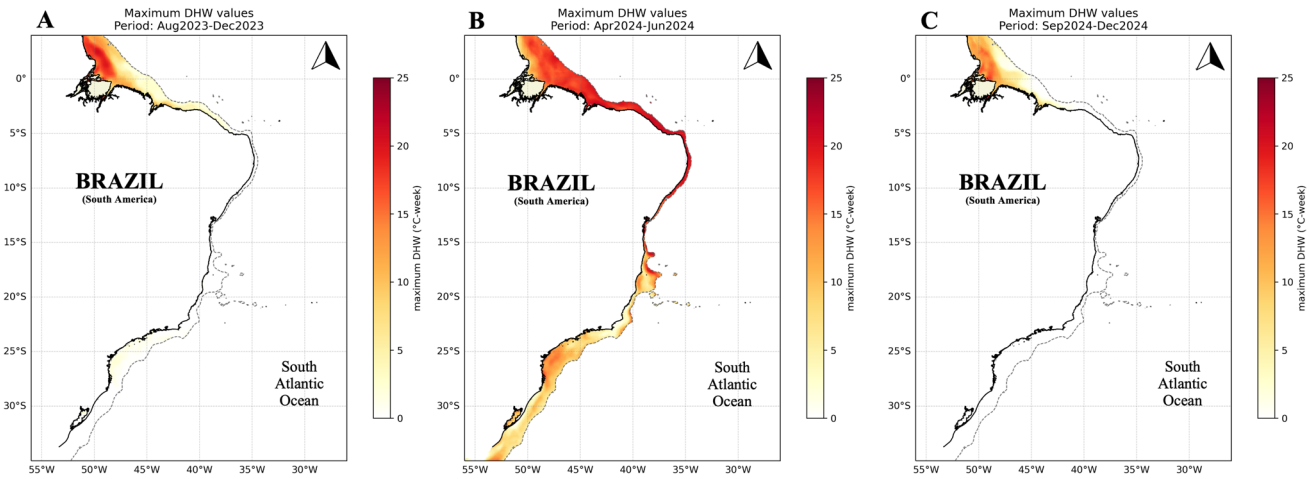


Fig. 2 Maximum Degree Heating Weeks (DHW) values for the periods before (**A**, August to December 2023), during (**B**, April to June 2024), and after (**C**, September to December 2024) thermal stress in the Southwestern Atlantic coast during the fourth global bleaching event in 2024

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Table 2 Descriptive summary of the thermal stress experienced by the 18 Southwestern Atlantic reef sites, monitored for bleaching incidence and coral mortality during the fourth global bleaching event. Thermal stress intensity, measured by the maximum Degree Heating Week (DHW) value recorded; thermal stress duration, determined by the number of days spent under moderate and severe thermal stress ($0 < DHW < 8$ °C-weeks and $DHW \geq 8$ °C-weeks, respectively, with $HotSpot \geq 1$ °C); and the total number of days under thermal stress. Data cover the period from January 1st to December 12th, 2024

#	Reef site	Maximum DHW value	Days under $0 < DHW < 8$	Days under $DHW \geq 8$	Total days under thermal stress
1	Caucaia	21.35	39	108	147
2	Fernando de Noronha Archipelago	17.89	40	46	86
3	Rocas Atoll	19.17	38	52	90
4	Rio do Fogo	20.91	56	80	136
5	Porto de Galinhas	20.18	42	62	104
6	São José da Coroa Grande (Costa dos Corais)	20.24	44	54	98
7	Maragogi (Costa dos Corais)	20.58	49	55	104
8	Pedra do Abaís	15.97	35	42	77
9	Itaparica Island (Todos os Santos Bay)	18.16	60	54	114
10	Recife de Fora	7.61	93	0	93
11	Corumbau	6.76	69	0	69
12	Abrolhos Archipelago	6.90	67	0	67
13	Tartaruga Beach (Armação dos Búzios)	3.00	74	0	74
14	Forno Beach (Arraial do Cabo)	2.95	34	0	34
15	Anchieta Island	10.10	61	18	79
16	Alcatrazes Archipelago	9.77	59	19	78
17	Laje de Santos	5.60	59	0	59
18	Galé Island (Arvoredo)	16.92	37	42	79

compared to northern sites, whereas central sites experienced thermal stress that was both later and less intense.

On average, the 18 monitored reef sites experienced 88.2 ± 6.3 (mean ± standard error) days of thermal stress, equivalent to roughly three consecutive months under anomalous temperatures. Caucaia (147 days), Rio do Fogo (136 days), Itaparica Island (114 days), Maragogi (104 days), and Porto de Galinhas (104 days), all located on the northern coast, are among the sites that experienced longer-lasting thermal stress (Table 2). Once again, some southern sites experienced a shorter duration of thermal stress, with 34 days recorded for Forno Beach (Arraial do Cabo) and 59 for Laje de Santos. Therefore, thermal stress was considerably more intense and prolonged in the northern portion of the Southwestern Atlantic coast. The central coast of Brazil experienced milder levels, and the southern coast exhibited the lowest intensity and shortest duration of thermal stress.

Bleaching incidence

Bleaching was first detected in Forno Beach (Arraial do Cabo) in February 2024 before progressing northwards along the coast. Thirty-six percent of the whole area surveyed along the Brazilian coast displayed signs of coral bleaching during the fourth global bleaching event (Table 3). The most affected sites were located on the northern coast: Maragogi (96% of coral cover bleached), Porto de Galinhas (84%), Rio do Fogo (72%), and São José da Coroa Grande (71%). The least affected sites, however, were located further south, including Anchieta Island, Alcatrazes Archipelago, and Forno beach (Arraial do Cabo), all of which experienced bleaching incidence of less than 5%.

Twenty-three photosymbiotic cnidarian species were detected in our surveys (15 scleractinians, 3 milleporid hydrocorals, 3 alcyonaceans, and 2 zoantharians). Across all sites, the most frequently observed species with signs of bleaching were *S. wellsii* (78%), *M. braziliensis* (54%), *A. humilis* (53%), *M. harttii* (52%), *Siderastrea* sp. (46%), and *M. alcicornis* (43%) (Table 4). Other massive species such as *M. hispida*, *M. cavernosa*, and *Siderastrea* sp. also experienced bleaching at the northern sites (Fig. 3). The species that faced little to no bleaching were *M. decactis*, *Mussismilia leptophylla*, *Porites branneri*, *Phyllogorgia dilatata*, *Plexaurella grandiflora*, and *Zoanthus* sp. The last three are either alcyonaceans (soft corals) or zoantharians, and, in the case of *P. branneri*, bleaching was challenging to detect given its naturally white-colored coenosarc.

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Table 3 Relative bleaching incidence (proportion of bleached coral cover) and live coral cover data for 18 Southwestern Atlantic reef sites before, during, and after the thermal stress associated with the fourth global bleaching event in 2024. Relative change indicates the variation in mean coral cover between the periods before and after thermal stress (except for Pedra do Abaís, for which it was considered the difference between the periods during and after thermal stress). Data are expressed as mean ± standard error. "n/a" = data not available

#	Reef site	BLEACHING INCIDENCE			LIVE CORAL COVER			
		Before thermal stress	During thermal stress	After thermal stress	Before thermal stress	During thermal stress	After thermal stress	Relative change
1	Caucaia	0.01 ± 0.00	**0.43 ± 0.05**	0.00 ± 0.00	0.25 ± 0.05	0.24 ± 0.03	0.25 ± 0.04	=
2	Fernando de Noronha Archipelago	0.09 ± 0.04	**0.65 ± 0.11**	0.02 ± 0.02	0.23 ± 0.05	0.25 ± 0.04	0.23 ± 0.05	=
3	Rocas Atoll	0.09 ± 0.02	**0.45 ± 0.05**	0.19 ± 0.04	0.15 ± 0.01	0.13 ± 0.01	0.15 ± 0.05	=
4	Rio do Fogo	0.17 ± 0.05	**0.72 ± 0.08**	0.15 ± 0.05	0.13 ± 0.02	0.12 ± 0.00	0.08 ± 0.00	↓ **38%**
5	Porto de Galinhas	0.09 ± 0.07	**0.84 ± 0.15**	0.17 ± 0.08	0.18 ± 0.01	0.19 ± 0.02	0.13 ± 0.02	↓ **28%**
6	São José da Coroa Grande (Costa dos Corais)	0.01 ± 0.01	**0.71 ± 0.11**	0.16 ± 0.04	0.36 ± 0.06	0.40 ± 0.02	0.17 ± 0.01	↓ **53%**
7	Maragogi (Costa dos Corais)	0.05 ± 0.05	**0.96 ± 0.02**	0.16 ± 0.10	0.18 ± 0.01	0.18 ± 0.02	0.02 ± 0.00	↓ **88%**
8	Pedra do Abaís	n/a	**0.70 ± 0.13**	0.26 ± 0.05	n/a	0.46 ± 0.07	0.43 ± 0.08	↓ **6%**
9	Itaparica Island (Todos os Santos Bay)	0.03 ± 0.02	**0.22 ± 0.06**	0.05 ± 0.02	0.18 ± 0.02	0.16 ± 0.03	0.17 ± 0.03	↓ **4%**
10	Recife de Fora	0.04 ± 0.01	**0.13 ± 0.05**	0.02 ± 0.01	0.47 ± 0.10	0.44 ± 0.14	0.45 ± 0.06	↓ **3%**
11	Corumbau	0.01 ± 0.01	**0.18 ± 0.06**	0.05 ± 0.03	0.33 ± 0.05	0.34 ± 0.05	0.35 ± 0.09	↑ **3%**
12	Abrolhos Archipelago	0.03 ± 0.02	**0.13 ± 0.03**	0.08 ± 0.05	0.34 ± 0.09	0.36 ± 0.03	0.35 ± 0.08	↑ **2%**
13	Tartaruga Beach (Armação dos Búzios)	0.00 ± 0.00	**0.14 ± 0.10**	0.06 ± 0.06	0.19 ± 0.03	0.19 ± 0.04	0.19 ± 0.05	=
14	Forno Beach (Arraial do Cabo)	0.00 ± 0.00	**0.04 ± 0.03**	0.07 ± 0.03	0.17 ± 0.01	0.18 ± 0.03	0.17 ± 0.04	↑ **1%**
15	Anchieta Island	0.03 ± 0.03	**0.01 ± 0.01**	0.08 ± 0.06	0.15 ± 0.04	0.21 ± 0.05	0.15 ± 0.03	↑ **1%**
16	Alcatrazes Archipelago	0.03 ± 0.02	**0.03 ± 0.01**	0.00 ± 0.00	0.12 ± 0.02	0.13 ± 0.2	0.12 ± 0.02	=
17	Laje de Santos	0.04 ± 0.01	**0.07 ± 0.06**	0.07 ± 0.04	0.25 ± 0.05	0.28 ± 0.02	0.26 ± 0.04	↑ **3%**
18	Galé Island (Arvoredo)	0.01 ± 0.00	**0.05 ± 0.03**	0.02 ± 0.01	0.36 ± 0.04	0.32 ± 0.07	0.37 ± 0.04	↑ **1%**
-	OVERALL (all sites)	0.04 ± 0.01	**0.36 ± 0.05**	0.09 ± 0.01	0.21 ± 0.03	0.23 ± 0.03	0.19 ± 0.02	↓ **5%**

Relative coral cover change

The relative loss in coral cover, calculated as the ratio of after- to before-thermal stress cover, was about 5% across the 18 sites combined (Table 3). However, mirroring the geographic pattern of bleaching incidence, most northern sites experienced greater losses in coral cover, while sites along the central and southern coasts showed minimal to no decline (Fig. 4; Table 3). Seven sites underwent reduction in live coral cover, with Maragogi (88% relative loss), São José da Coroa Grande (53% relative loss), Rio do Fogo (38% relative loss), and Porto de Galinhas (28% relative loss) being the most affected (Fig. 5).

Seven species underwent benthic cover decline (Table 4), with *S. wellsii* (66% reduction), *M. alcicornis* (54%), and *M. harttii* (28%) being the most affected. The high mortality

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Table 4 Relative bleaching incidence (proportion of bleached coral cover) and live benthic cover for all photosymbiotic cnidarian species observed across all fixed transects combined at 18 Southwestern Atlantic reef sites before, during, and after the fourth global bleaching event in 2024. Data for other benthic functional groups are also included. Relative change compares the variation in mean benthic cover between the before and after thermal stress periods. Data are expressed as mean ± standard error. "-'' = not applicable

Taxon or functional group	Bleaching Incidence	Benthic Cover		Benthic Cover			
	Before thermal stress	During thermal stress	After thermal stress	Before thermal stress	During thermal stress	After thermal stress	Relative change
Scleractinia							
Agaricia fragilis	0.00 ± 0.00	**0.00 ± 0.00**	0.00 ± 0.00	< 0.0001	< 0.0001	< 0.0001	=
Agaricia humilis	0.03 ± 0.01	**0.53 ± 0.09**	0.07 ± 0.03	0.0053 ± 0.0020	0.0057 ± 0.0019	0.0058 ± 0.0021	↑ **9%**
Favia gravida	0.01 ± 0.00	**0.17 ± 0.07**	0.01 ± 0.00	0.0010 ± 0.0005	0.0014 ± 0.0007	0.0010 ± 0.0003	=
Madracis decactis	0.00 ± 0.00	**0.01 ± 0.00**	0.00 ± 0.00	0.0227 ± 0.0116	0.0204 ± 0.0107	0.0229 ± 0.0117	=
Meandrina brasiliensis	0.17 ± 0.13	**0.50 ± 0.22**	0.00 ± 0.00	< 0.0001	< 0.0001	< 0.0001	=
Montastraea cavernosa	0.01 ± 0.00	**0.37 ± 0.08**	0.04 ± 0.02	0.0219 ± 0.0057	0.0228 ± 0.0058	0.0211 ± 0.0048	↓ **3%**
Mussismilia braziliensis	0.00 ± 0.00	**0.06 ± 0.03**	0.02 ± 0.02	0.0071 ± 0.0029	0.0087 ± 0.0035	0.0068 ± 0.0028	↓ **4%**
Mussismilia harttii	0.09 ± 0.05	**0.52 ± 0.09**	0.03 ± 0.01	0.0177 ± 0.0049	0.0198 ± 0.0059	0.0128 ± 0.0054	↓ **28%**
Mussismilia hispida	0.01 ± 0.00	**0.20 ± 0.05**	0.04 ± 0.01	0.0287 ± 0.0084	0.0272 ± 0.0081	0.0271 ± 0.0088	=
Mussismilia leptophylla	0.00 ± 0.00	**0.00 ± 0.00**	0.00 ± 0.00	< 0.0001	< 0.0001	< 0.0001	=
Porites astreoides	0.02 ± 0.02	**0.26 ± 0.09**	0.02 ± 0.00	0.0025 ± 0.0012	0.0024 ± 0.0008	0.0023 ± 0.0008	↓ **8%**
Porites branneri	0.00 ± 0.00	**0.00 ± 0.00**	0.00 ± 0.00	< 0.0001	< 0.0001	< 0.0001	=
Scolymia wellsii	0.00 ± 0.00	**0.78 ± 0.28**	0.01 ± 0.00	0.0003 ± 0.0001	0.0003 ± 0.0001	0.0001 ± 0.0000	↓ **66%**
Siderastrea sp.	0.04 ± 0.01	**0.46 ± 0.06**	0.09 ± 0.02	0.0864 ± 0.0160	0.0827 ± 0.0157	0.0892 ± 0.0164	↑ **3%**
Stephanocoenia intersepta	0.00 ± 0.00	**0.00 ± 0.00**	0.00 ± 0.00	< 0.0001	< 0.0001	< 0.0001	=
Milleporidae							
Millepora alcicornis	0.01 ± 0.00	**0.43 ± 0.09**	0.01 ± 0.00	0.0242 ± 0.0058	0.0256 ± 0.0056	0.0111 ± 0.0041	↓ **54%**
Millepora braziliensis	0.00 ± 0.00	**0.54 ± 0.27**	0.00 ± 0.00	< 0.0001	< 0.0001	< 0.0001	=
Millepora nitida	0.00 ± 0.00	**0.13 ± 0.05**	0.03 ± 0.02	0.0006 ± 0.0003	0.0008 ± 0.0005	0.0006 ± 0.0004	=
Octocorallia							
Muriceopsis sulphurea	0.00 ± 0.00	**0.09 ± 0.05**	0.02 ± 0.01	0.0022 ± 0.0013	0.0035 ± 0.0019	0.0025 ± 0.0015	↑ **13%**
Phyllogorgia dilatata	0.00 ± 0.00	**0.00 ± 0.00**	0.00 ± 0.00	0.0040 ± 0.0018	0.0039 ± 0.0019	0.0037 ± 0.0010	↓ **7%**
Plexaurella grandiflora	0.00 ± 0.00	**0.00 ± 0.00**	0.00 ± 0.00	< 0.0001	< 0.0001	< 0.0001	=
Zoantharia							
Palythoa *caribaeorum*	0.08 ± 0.02	**0.30 ± 0.07**	0.12 ± 0.02	0.0438 ± 0.0112	0.0575 ± 0.0139	0.0444 ± 0.0125	↑ **1%**
Zoanthus sp.	0.00 ± 0.00	**0.00 ± 0.00**	0.00 ± 0.00	< 0.0001	< 0.0001	< 0.0001	=
Others							
Turf algae	–	–	–	0.5694 ± 0.0276	0.5613 ± 0.0273	0.5871 ± 0.0234	↑ **3%**
Frondose algae	–	–	–	0.0147 ± 0.0064	0.0062 ± 0.0025	0.0101 ± 0.0026	↓ **31%**
Crustose coralline algae	–	–	–	0.0107 ± 0.0019	0.0095 ± 0.0030	0.0131 ± 0.0033	↑ **22%**
Other benthic invertebrates	–	–	–	0.0166 ± 0.0038	0.0093 ± 0.0018	0.0133 ± 0.0017	↓ **20%**
Bare rock or sand	–	–	–	0.0956 ± 0.0192	0.0922 ± 0.0211	0.0790 ± 0.0157	↓ **17%**
Unidentified	–	–	–	0.0329 ± 0.0044	0.0369 ± 0.0056	0.0348 ± 0.0049	↑ **5%**

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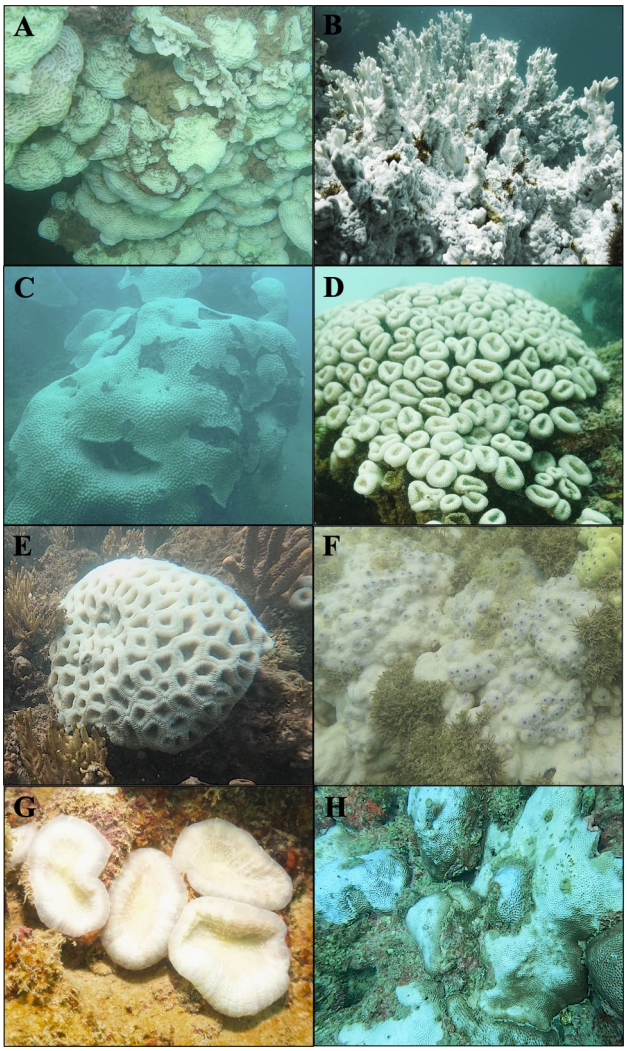


Fig. 3 Multiple coral species experiencing bleaching in Southwestern Atlantic reefs during the fourth global bleaching event in 2024: *Agaricia humilis* (**A**), *Millepora alcicornis* (**B**), *Montastraea cavernosa* (**C**), *Mussismilia harttii* (**D**), *Mussismilia hispida* (**E**), *Porites astreoides* (**F**), *Scolymia wellsii* (**G**), and *Siderastrea* sp. (**H**). Photographs by Ricardo Miranda at Maragogi (**A**, **F**), Pedro Henrique Pereira at São José da Coroa Grande (**B**, **C**, **D**, **G**), Carlos Henrique Lacerda at Recife de Fora (**E**), and Priscilla Campos at Pedra do Abaís (**H**)

recorded for *S. wellsii* was confined to São José da Coroa Grande, the only site where it occurred in relevant numbers along the surveyed transects. Among other benthic groups, turf algae cover remained relatively stable at 55–60%, while frondose algae declined by 31%. In contrast, crustose coralline algae increased by 22%, primarily colonizing the dead skeletons of scleractinian and milleporid corals. A summary of the changes in benthic cover for each species at each site is presented in Table S7.

Data analysis for absolute coral cover change

The LOO criterion indicated that the Beta regression model with a constant ϕ and a transect-level random effect had the strongest support from the total coral cover data, yet there was similar fit among the first three models (ELPD difference < 4) (Table S3). The third model showed an ELPD difference of 3.2 and a very large SE, so it is reasonable to leave it out of further analyses. Density plots of posterior predictive checks also showed that all models being compared had a good predictive performance (they overall fitted well to the data and could predict well new data according to the LOO method) (Fig. S1). For inference on total coral cover change between periods, we used the model with random intercept and constant ϕ which showed a subtle better predictive performance than the other models (Fig. S8).

We estimated that the total coral cover before the bleaching event was 25.4% (lower and upper 95% High Probability Density (HDI) interval: 14.6%, 39.4%), decreasing to 22.9% (95% HDI: 12.6%, 35.1%) after the bleaching event. The absolute loss (calculated as the difference between coral cover before and after thermal stress) of coral cover was -2.53% (95% HDI: -5.18%, 0%) (Fig. S9), with a 97.5% probability that this decline differs from zero. Among the sites, São José da Coroa Grande (-17.1% absolute coral cover, HDI: -28.4, -6.62%), Maragogi (-14.5%, HDI: -25, -5.37%), Porto de Galinhas (-5.02%, HDI: -15, 3.22%) and Rio do Fogo (-4.85%, HDI: -13.3, 2.46) were those showing the most intense losses of coral cover (*i.e.*, those whose estimated loss was different from zero loss with probability > 88%) (Fig. S9). The standard deviation of the random intercept (*i.e.*, variation in cover caused by replicated transects) was 0.42 (95% HDI: 0.002, 1.19). The precision of the Beta distribution was $\widehat{\phi} = 39.4$ (95% HDI: 27.26.84, 52.38.19). We did not find convergence issues in this model (Rhat < 1.1 for all parameters).

Considering species-level models (ZI Beta regressions), we found that all models had similar support and predictive performance (ELPD difference < 4 with small SE) (Table S3, Figs. S4, S10-11). Therefore, we did inference with the best-ranked and most parsimonious model (Table S3). This model showed that the average absolute cover across all species/functional groups before the bleaching event was 9.6% (HDI: 8.9, 10.45%), and it reduced to an average of 8.75% after the event (HDI: 8.1, 9.5%) (Fig. S12). The average absolute difference in species/functional group cover across species/functional group was -0.88% (95% HDI: -1.84, 0.032%) (Fig. S13), with 96.45% probability of this loss be lower than zero loss. The species/functional groups showing cover loss with ≥ 80% probability were *M. alcicornis* (difference between periods: -2.74% absolute coral cover, HDI: -6.11, 0.8%), *M. harttii* (-2%, HDI: -5.8, 1.7%), and *Palythoa caribaeorum* (-1.85%, HDI: -5.27, 1.63%). The cover of turf

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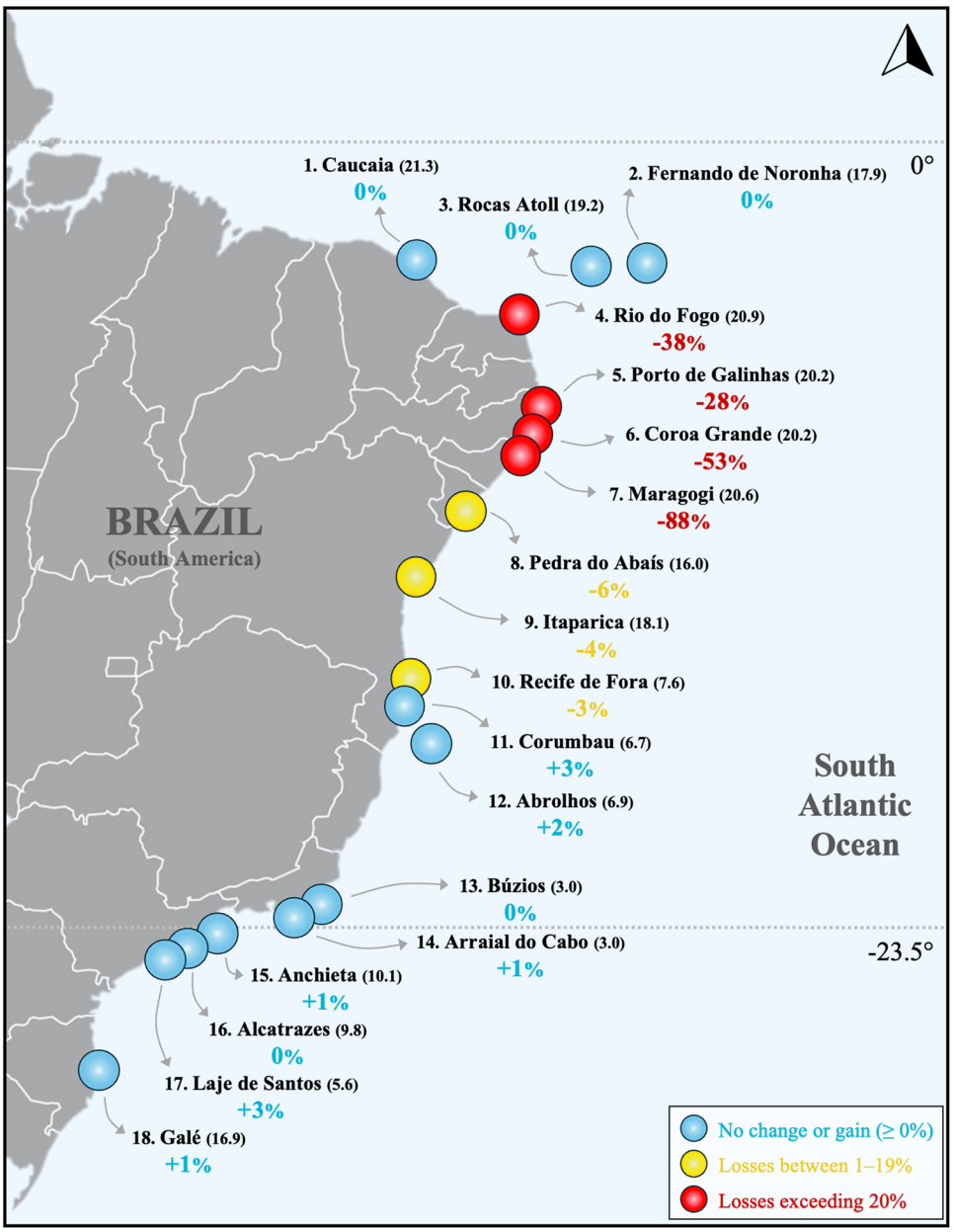


Fig. 4 Relative coral cover change for each of the 18 Southwestern Atlantic reef sites monitored during the fourth global bleaching event in 2024. Sites with stable or increased cover are shown in blue; those with relative losses of 1–19% are shown in yellow; and those with losses exceeding 20% are shown in red. Numbers within parentheses indicate the maximum Degree Heating Weeks value (°C-weeks) experienced by the reef site. The sites (numbered latitudinally from #1 to #18) are Caucaia, Fernando de Noronha Archipelago, Rocas Atoll, Rio do Fogo, Porto de Galinhas, São José da Coroa Grande (Costa dos Corais), Maragogi (Costa dos Corais), Pedra do Abaís, Itaparica Island (Todos os Santos Bay), Recife de Fora, Corumbau, Abrolhos Archipelago, Tartaruga Beach (Armação dos Búzios), Forno Beach (Arraial do Cabo), Anchieta Island, Alcatrazes Archipelago, Laje de Santos, Galé Island (Arvoredo)

algae showed a consistent increase of 1.83% of cover (HDI: -3.56, 7.55) between periods, with 74% probability of an increase higher than zero. The precision of this model was $\hat{\phi} = 9.35$ (95% HDI: 8.19, 10.49), and the zero-inflation term was hat $\hat{\psi} = 0.59$ (HDI: 0.56, 0.61) (*i.e.*, 59% of the data were zeroes). We did not find convergence issues in this model (Rhat < 1.1 for all parameters).

Discussion

This work reports the results of the largest coordinated bleaching monitoring effort ever conducted in Brazil and the Southwestern Atlantic, carried out during the fourth global bleaching event in 2024. We demonstrate that thermal stress was both intense and prolonged, with sites experiencing up to 21 °C-weeks and three to five months of elevated temperatures. Bleaching affected 36% of the surveyed area combined for the 18 sites, and while mean coral cover loss across all sites was low (5%), some northern reefs experienced relative losses exceeding 50% and up to 88%. Overall, the effects on coral assemblages were spatially heterogeneous: the northern coast (mainly Rio Grande do Norte, Pernambuco, and Alagoas states) was severely impacted, a transitional zone with substantially less impacts was observed along the central coast, and reefs in the southern sector underwent no coral mortality despite being exposed to moderate to high levels of thermal stress. This geographic variation in

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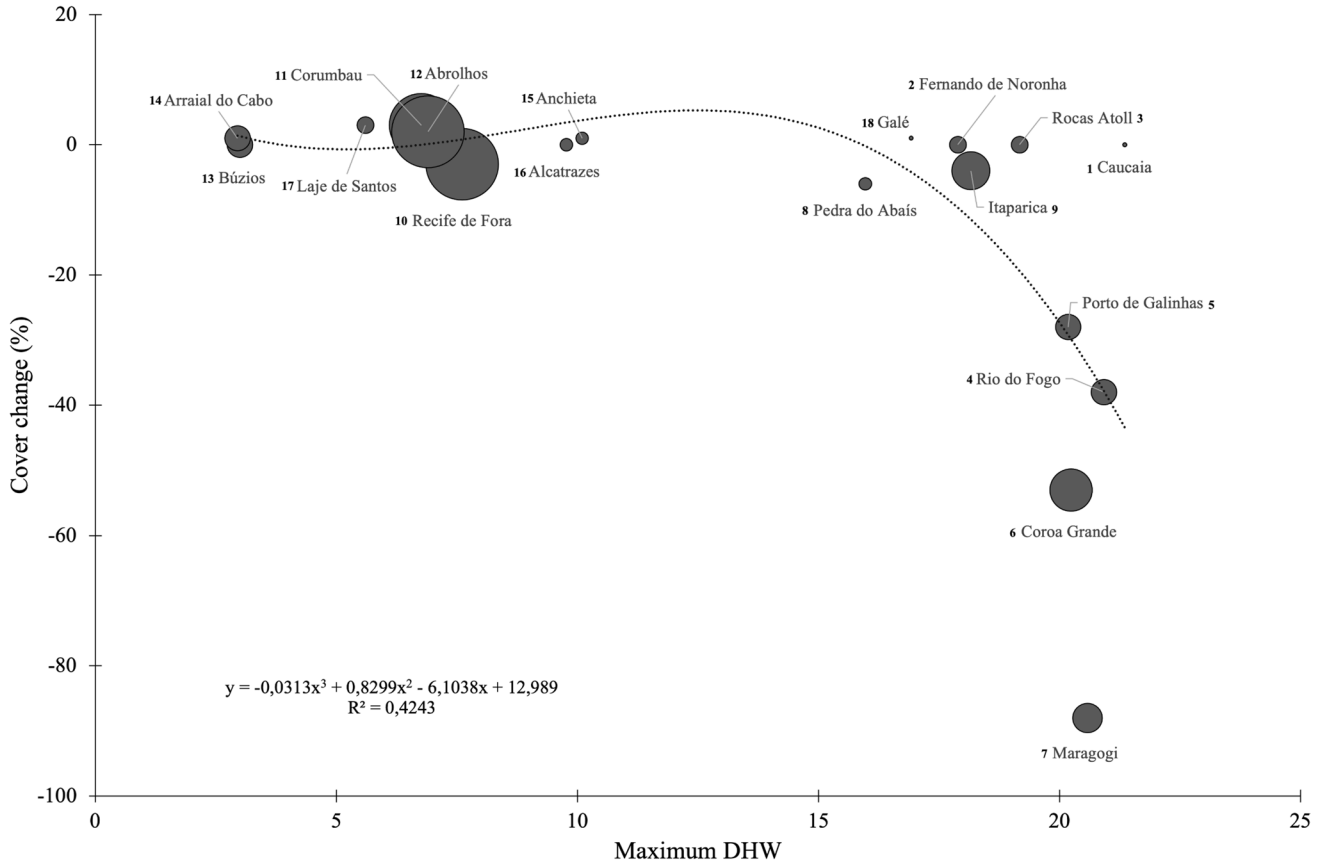


Fig. 5 Bubble plot with a fitted curve displaying the relative live coral cover change for 18 Southwestern Atlantic reef sites after the fourth global bleaching event in 2024. Bubble size accounts for the number of photosymbiotic cnidarian species observed for each site (numbered latitudinally from #1 to #18). The sites are Caucaia, Fernando de Noronha Archipelago, Rocas Atoll, Rio do Fogo, Porto de Galinhas, São José da Coroa Grande (Costa dos Corais), Maragogi (Costa dos Corais), Pedra do Abaís, Itaparica Island (Todos os Santos Bay), Recife de Fora, Corumbau, Abrolhos Archipelago, Tartaruga Beach (Armação dos Búzios), Forno Beach (Arraial do Cabo), Anchieta Island, Alcatrazes Archipelago, Laje de Santos, Galé Island (Arvoredo)

responses likely reflects not only differences in cumulative thermal stress across reef sites but also distinct coral species composition at each location.

The mechanisms underlying the greater heat accumulation in the northern areas of the Southwestern Atlantic during the fourth global bleaching event remain unclear from a meteo-oceanographic perspective. Still, it is well-documented that the northern region has higher vulnerability to warming and thermal stress than the south. First, the Brazil and North Brazil Currents and their many rings transport warm equatorial waters mainly along the northern Brazil coast (Silveira et al. 1994; Bueno et al. 2022; Fernández et al. 2024). Additionally, the continental shelf north of the Abrolhos Bank (< 15°S) is considerably narrow—often only a few dozen kilometers wide—resulting in a smaller water volume over the shelf that warms more rapidly (Vital et al. 2010; Dominguez et al. 2013; Amaya et al. 2023). Furthermore, the lower latitudes on the northern coast are also subject to higher solar irradiance and low cloud coverage, further intensifying surface heating (Lean 2010; Rodrigues et al. 2025b). In contrast, the southern coast experiences mitigating processes, such as higher turbidity, the prevalence of upwelling zones in the Rio de Janeiro region and the seasonal subsurface intrusion of the colder South Atlantic Central Water (SACW) during spring and summer (Castelao and Barth 2006; Castro 2014; Sasaki et al. 2024). In general, these oceanographic features may explain why the northern coast underwent higher thermal stress and, consequently, higher coral bleaching and mortality compared with the southern coast.

Although most of the northern sites were heavily affected, the northernmost site, Caucaia, suffered no coral mortality despite experiencing the highest thermal stress intensity and duration. The reasons for this resilience remain uninvestigated, however the enclosed reefs in Caucaia experience tidal dynamics similar to those of tide pools, which may promote higher thermal tolerance in local corals (Schoepf et al. 2015). In addition, there is a monotypic dominance

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of *Siderastrea* sp., a generally stress-tolerant massive coral species (Leão et al. 2003; Barros et al. 2021; Gaspar et al. 2021). Maragogi and São José da Coroa Grande, the two sites located within the Costa dos Corais Marine Protected Area (MPA), the largest coastal MPA in Brazil, experienced the highest levels of coral mortality. This is particularly concerning, as this nearshore area was also heavily affected during the 2019–20 bleaching event (Pereira et al. 2022). Endemic and threatened species in the region, such as *Millepora braziliensis*, are now facing an increased risk of extinction (Silva et al. submitted). This species has not been detected in belt transects at Maragogi and São José da Coroa Grande after suffering nearly 100% of mortality in the 2019–20 bleaching event (Pereira et al. 2022). However, it has been shown that effective local zoning processes in the area may promote coral recovery (Pereira et al. 2024). The reefs at Pedra do Abaís, only recently described in Sergipe State (Campos 2025) and found near the upper edge of mesophotic depths, exhibited minimal mortality despite experiencing 70% bleaching. This could also be explained by the dominance of stress-tolerant massive species such as *Siderastrea* sp. and *M. cavernosa*, along with the higher depth and turbidity in the region (Martello et al. 2024; Campos 2025).

In addition to the coastal reefs, the two oceanic islands of Rocas Atoll and Fernando de Noronha Archipelago provide important insight into regional bleaching dynamics. Despite their clearer waters and geographic proximity to heavily impacted northern sites, both exhibited moderate bleaching incidence and minimal coral mortality. Rocas Atoll supports unique benthic assemblages that have shown resilience to thermal anomalies (Gaspar et al. 2021). Likewise, Fernando de Noronha Archipelago, although exhibiting 65% bleaching, showed no significant decline in coral cover, reinforcing the relative stability in coral health even during the 2019–20 event (Vieira and Longo 2025). In both cases, low mortality likely results from dominance of a few massive, stress-tolerant species. In the central part of the Southwestern Atlantic coast, reefs in Bahia State (Itaparica Island, Recife de Fora, Corumbau, and the Abrolhos Archipelago) showed little change in coral cover during the fourth global bleaching event. Despite suffering significant coral cover losses during the 2019–20 bleaching event (Duarte et al. 2020; Ferreira et al. 2021; Corazza et al. 2024), they were generally subjected to lower-intensity and shorter-duration thermal stress in the latest event. This likely mitigated mortality in these highly diverse reef systems, which are considered the richest in the Southwestern Atlantic (Castro and Pires 2001; Dutra et al. 2006; 2025; Bleuel et al. 2024).

Southern reefs were mostly spared during the fourth global bleaching event. Reef assemblages in this region are emerging as some of the most tolerant along the Brazilian coast due to a combination of oceanographic conditions and biological traits. For example, Tartaruga Beach (Armação dos Búzios) and Forno Beach (Arraial do Cabo) benefit from an upwelling system that prevents heat accumulation (Castelao and Barth 2006; Ribeiro et al. 2011). In São Paulo State, reefs such as those at Anchieta Island, Alcatrazes Archipelago, and Laje de Santos are dominated by the massive, stress-tolerant *M. hispida*, which exhibited minimal mortality despite facing over 20 °C-weeks during the 2019–20 bleaching event (Banha et al. 2020; Roos et al. 2024). Additionally, the high turbidity of the region offers further protection for corals, as suspended sediment particles absorb part of the irradiance and heat (Mies et al. 2018; Sully and van Woesik 2020). Despite the advances of global warming and tropicalization, the low-diversity rocky reefs in São Paulo will likely remain suitable habitats for coral survival in the coming decades due to the tropicalization effect—when subtropical communities become more dominated by species with tropical affinity (Vergés et al. 2014; Bleuel et al. 2021; Príncipe et al. 2021; Martello et al. 2024).

The geographic pattern observed suggests that the 2023–24 bleaching event in the Southwestern Atlantic, although severe, was not as impactful as the 2019–20 episode. In 2019–20, thermal stress was more uniformly distributed along the Southwestern Atlantic coast, leading to widespread bleaching and significant coral mortality, particularly in the northern and central portions of the Brazilian coast, with even some mortality observed in southern sites (Banha et al. 2020; Duarte et al. 2020; Ferreira et al. 2021; Gaspar et al. 2021; Pereira et al. 2022; Corazza et al. 2024; Rodrigues et al. 2025b). In contrast, the 2023–24 event was marked by more heterogeneous impacts in terms of spatial distribution, thermal stress intensity, and associated coral mortality, all of which were more intense in the northern part of the Southwestern Atlantic coast. The less widespread and more varied nature of the impacts in 2023–24, when compared to the prior major heatwave, could suggest an element of acquired environmental memory within some coral communities following the 2019–20 episode, potentially modulating their physiological responses or resilience to the subsequent thermal stress (Hackerott et al. 2021). Nonetheless, the 2023–24 bleaching event marks the second major and geographically extensive mass bleaching episode ever documented in the Southwestern Atlantic, occurring just five years after the first one.

Concerning species-level damage, the 2023–24 bleaching episode compounded the damage caused by the 2019–20 event, with both *M. alcicornis* and *M. harttii* among the species experiencing the greatest declines in benthic cover (see Duarte et al. 2020; Ferreira et al. 2021; Pereira et al. 2022). Branching scleractinians, which play the key role of increasing habitat complexity because of their three-dimensional morphology (Graham and Nash 2013; Darling et al. 2017), are absent from shallow and

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mesophotic reefs in the South Atlantic Ocean (Leão et al. 2016; Mies et al. 2020). In the Southwestern Atlantic, this role is almost exclusively fulfilled by *M. alcicornis*, a widespread branching and calcifying hydrozoan (Coni et al. 2013; Leal et al. 2012; Luza et al. 2023; Bleuel et al. 2024). However, this species suffered declines of 50–90% at multiple sites during the 2019–20 bleaching event (Duarte et al. 2020; Ferreira et al. 2021; Corazza et al. 2024; Vidal et al. 2025). *M. harttii*, an endemic and threatened species with a limited geographic distribution, showed the second-greatest decline during the 2019–20 event (Braz et al. 2022; Pereira et al. 2022; Corazza et al. 2024). Although not a branching species, its phaceloid morphology is characterized by wide spaces between corallites that offer habitat for a diverse invertebrate community (Nogueira et al. 2015; 2021). As a result, the two primary coral species responsible for promoting habitat complexity have experienced increased mortality within a short time span. This places the functional role of structural complexity provision on Southwestern Atlantic reefs at risk, jeopardizing their entire structure and functioning (see Luza et al. 2024). Furthermore, a notable difference from the 2019–20 event is that the 2023–24 bleaching episode caused severe mortality of *S. wellsii*, a solitary scleractinian species. Although its presence was largely restricted to São José da Coroa Grande within the surveyed transects, mortality reached 66%, with dozens of individuals lost along the transects and likely hundreds (if not more) throughout the Costa dos Corais MPA. This species is now found in extremely low numbers in the area, with a strong risk of local extinction. Thus, after the mortality produced by the fourth global bleaching event, the conservation status of some Southwestern Atlantic species may require revision.

Although Southwestern Atlantic reefs and species may display several resilience features (Mies et al. 2020), thermal stress in the region is increasing in intensity, duration, and frequency (Destri et al. 2025; Rodrigues et al. 2025b; Silva et al. 2025). The increasing proximity of severe bleaching events is diminishing the capacity of Southwestern Atlantic reefs to recover, exacerbated by the slow growth rates of most coral species, which are typically massive and grow only millimeters per year (Barros and Pires 2006; Kikuchi et al. 2013; Pinheiro et al. 2017; Silva et al. 2019). Evidence for this is the absence of coral cover recovery in Bahia reefs in the period between the 2019–20 and 2023–24 bleaching events (Corazza et al. 2024). However, this vulnerability to global warming is likely amplified by chronic local anthropogenic stressors. These include overfishing, which has altered fish community structures and depleted key stocks along the Brazilian coast, and pollution from various sources, such as land-based runoff containing metals and organic matter, contamination from maritime activities, and the pervasive issue of plastic debris, largely originating from fishing activities (Pinheiro et al. 2023; Eggertsen et al. 2024; Mello et al. 2025). Within this context, the ability to withstand and recover from future bleaching events is quite likely to be spatially heterogeneous, given the unique oceanographic and biological features across distinct reefs within the Southwestern Atlantic. Therefore, the conservation strategies and efforts must not only address the overarching threat of climate change but also be tailored to mitigate compounding local stressors effectively at each site.

Conclusions

This study documented the widespread impacts of the 2023–24 ENSO-related bleaching event on Southwestern Atlantic reefs, revealing a heterogeneous pattern of responses along the coast. While some regions showed signs of resilience, others experienced elevated coral mortality, particularly among species with key functional roles such as *M. alcicornis* and *M. harttii*. These findings highlight the crucial importance of sustained and standardized monitoring efforts, not only to enable meaningful comparisons across regions and timeframes, both within and beyond the Southwestern Atlantic, but also to support effective, evidence-based conservation actions (see Magris et al. 2021; Mies et al. 2025b). Given the accelerating degradation of this unique reef system and its role in providing essential ecosystem services (Giglio et al. 2024), understanding its regional responses is critical. Our findings also underscore the urgent need for climate resilience strategies and conservation efforts in areas across the northern portion of the coast (*e.g.*, Rio Grande do Norte, Pernambuco, and Alagoas states, including Costa dos Corais, the largest nearshore Brazilian MPA), which were the most severely impacted in the last two major bleaching events.

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Data availability The complete dataset generated during this investigation is available in the Supplementary Information.

Declarations

Conflict of interest The authors declare no competing interests.

References

Amaya DJ, Jacox MG, Alexander MA, Scott JD, Deser C, Capotondi A, Phillips AS (2023) Bottom marine heatwaves along the continental shelves of North America. Nat Commun 14:1038

Banha T (2025) Finding inspiration in frustration: lessons from reef science. Nat Rev Biodivers. https://doi.org/10.1038/s44358-025-00027-y

Banha TNS, Capel KCC, Kitahara MV, Francini-Filho RB, Francini CLB, Sumida PYG, Mies M (2020) Low coral mortality during the most intense bleaching event ever recorded in subtropical Southwestern Atlantic reefs. Coral Reefs 39:515–521

Barnard PL, Dugan JE, Page HM, Wood NJ, Hart JA, Cayan DR, Erikson LH, Hubbard DM, Myers MR, Melack JM, Iacobellis SF (2021) Multiple climate change-driven tipping points for coastal systems. Sci Rep 11:15560

Barros Y, Lucas CC, Soares MO (2021) An urban intertidal reef is dominated by fleshy macroalgae, sediment, and bleaching of a resilient coral (*Siderastrea stellata*). Mar Pollut Bull 173:112967

Barros MM, Pires DO (2006) Aspects of the life history of *Siderastrea stellata* in the tropical Western Atlantic, Brazil. Invertebr Reprod Dev 49:237–244

Bleuel J, Pennino MG, Longo GO (2021) Coral distribution and bleaching vulnerability areas in Southwestern Atlantic under ocean warming. Sci Rep 11:12833

Bleuel J, Waechter L, Bender M, Longo GO (2024) Taxonomic and functional diversity of zooxanthellate corals and hydrocorals in Southwestern Atlantic reefs. Front Ecol Evol 12:1322751

Blunden J, Boyer T (2024) State of the climate in 2023. Bull Am Meteorol Soc 105:S1–S484

Brasil (2002) Decreto N° 4.340, DE 22 de agosto de 2002. Regulamenta artigos da Lei n° 9.985, de 18 de julho de 2000, que dispõe sobre o Sistema Nacional de Unidades de Conservação da Natureza—SNUC, e dá outras providências

Braz GB, Lacerda CH, Evangelista H, Güth AZ, Rumbelsperger AM, Capel KC, Mies M (2022) Unprecedented erosion of *Mussismilia harttii*, a major reef-building species in the Southwestern Atlantic, after the 2019 bleaching event. Coral Reefs 41:1537–1548

Brown BE (1997) Coral bleaching: causes and consequences. Coral Reefs 16:S129–S138

Bueno LF, Costa VS, Mill GN, Paiva AM (2022) Volume and heat transports by North Brazil Current rings. Front Mar Sci 9:831098

Bürkner PC (2017) Brms: an R package for Bayesian multilevel models using Stan. J Stat Softw 1:1–28

Campos PT (2025) Eles existem! Há recifes de coral em Sergipe! Criação Publishing, Aracaju, Sergipe, p 93

Cantin N, James N, Stella J (2024) Aerial surveys of the 2024 mass coral bleaching event on the Great Barrier Reef. Australian Institute of Marine Science, Townsville, 2024:2024-04

Castelao RM, Barth JA (2006) Upwelling around Cabo Frio, Brazil: the importance of wind stress curl. Geophys Res Lett 33:L03602

Castro BM (2014) Summer/winter stratification variability in the central part of the South Brazil Bight. Cont Shelf Res 89:15–23

Castro CB, Pires DO (2001) Brazilian coral reefs: what we already know and what is still missing. Bull Mar Sci 69:357–371

Cheng L, Abraham J, Trenberth KE, Reagan J, Zhang HM, Storto A, Von Schuckmann K, Pan Y, Zhu Y, Mann ME, Zhu J et al (2025) Record high temperatures in the ocean in 2024. Adv Atmos Sci 42:1092–1109

Coni EO, Ferreira CM, Moura RL, Meirelles PM, Kaufman L, Francini-Filho RB (2013) An evaluation of the use of branching fire-corals (*Millepora* spp.) as refuge by reef fish in the Abrolhos Bank, eastern Brazil. Environ Biol Fishes 96:45–55

Corazza BM, Lacerda CHF, Güth AZ, Marcançoli RKM, Bianchini A, Calderon EN, Capel KCC, Conceição E, Faria SC, Francini-Filho RB, Garrido AG, Guebert FM, Kitahara MV, Longo GO, Lotufo TMC, Salvi KP, Segal B, Sumida PYG, Zilberberg C, Mies M (2024) No coral recovery three years after a major bleaching event in reefs in the Southwestern Atlantic refugium. Mar Biol 171:114

Costa OS Jr, Attrill MJ, Nimmo M (2006) Seasonal and spatial controls on the delivery of excess nutrients to nearshore and offshore coral reefs of Brazil. J Marine Syst 60:63–74

Darling ES, Graham NA, Januchowski-Hartley FA, Nash KL, Pratchett MS, Wilson SK (2017) Relationships between structural complexity, coral traits, and reef fish assemblages. Coral Reefs 36:561–575

Destri G, Güth AZ, Luza AL, Ibanhez JY, Dottori M, Silveira IC, Braz GB, De La Cour JL, Manzello DP, Skirving WJ, Mies M (2025) The thermal stress history of South Atlantic reefs reveals increasing intensity, duration, frequency, and likely undocumented bleaching episodes. Glob Change Biol 31:e70162

Dietzel A, Bode M, Connolly SR, Hughes TP (2020) Long-term shifts in the colony size structure of coral populations along the Great Barrier Reef. Proc R Soc Lond B Biol Sci 287:20201432

Dominguez JML (2004) The coastal zone of Brazil: an overview. J Coast Res SI39:16–20

Dominguez JML, Silva RP, Nunes AS, Freire AF (2013) The narrow, shallow, low-accommodation shelf of central Brazil: sedimentology, evolution, and human uses. Geomorphology 203:46–59

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Douma JC, Weedon JT (2019) Analysing continuous proportions in ecology and evolution: a practical introduction to beta and Dirichlet regression. Methods Ecol Evol 10:1412–1430
Duarte GA, Villela HD, Deocleciano M, Silva D, Barno A, Cardoso PM, Peixoto RS (2020) Heat waves are a major threat to turbid coral reefs in Brazil. Front Mar Sci 7:179
Dutra GF, Allen GR, Werner T, McKenna SA (2006) A rapid marine biodiversity assessment of the Abrolhos Bank, Bahia, Brazil. RAP Bulletin of Biological Assessment 38. Conservation International, Washington, DC, USA
Dutra GF, Santos LP, Coutinho BH, Saliba A, Martinez MIG, Mies M, Camargo E, Teixeira JB, Bianchini A, Guebert FM, Lacerda CHF, Negrão F, Francini-Filho RB (2025) Marine biodiversity hotspots in the Abrolhos Region and Vitória-Trindade Seamount Chain, Brazil, with implications for conservation. Ocean Coast Res 73:e25019
Eggertsen L, Luza AL, Cordeiro CAMM, Dambros C, Ferreira CEL, Floeter SR, Francini-Filho RB, Freire KMF, Gasalla MA, Giglio VJ, Giarrizzo T, Hanazaki N, Longo GO, Lopes PFM, Luiz OJ, Magris RA, Mendes TC, Pinheiro HT, Quimbayo JP, Reis-Filho JA, Vila-Nova DA, Bender MG (2024) Complexities of reef fisheries in Brazil: a retrospective and functional approach. Rev Fish Biol Fish 34:9826
Fernández P, Speich S, Bellenger H, Lange Vega D, Karstensen J, Zhang D, Rocha CB (2024) On the mechanisms driving latent heat flux variations in the Northwest Tropical Atlantic. J Geophys Res Oceans 129:e2023JC020658
Ferrari SLP, Cribari-Neto F (2004) Beta regression for modelling rates and proportions. J Appl Stat 31:799–815
Ferreira BP, Costa MB, Coxey MS, Gaspar AL, Veleda D, Araújo M (2013) The effects of sea surface temperature anomalies on oceanic coral reef systems in the southwestern tropical Atlantic. Coral Reefs 32:441–454
Ferreira LCL, Grillo AC, Repinaldo Filho FPM, Souza FNR, Longo GO (2021) Different responses of massive and branching corals to a major heatwave at the largest and richest reef complex in South Atlantic. Mar Biol 168:54
Floeter SR, Rocha LA, Robertson DR, Joyeux JC, Smith-Vaniz WF, Wirtz P, Edwards AJ, Barreiros JP, Ferreira CEL, Gasparini JL, Brito A, Falcón JM, Bowen BW, Bernardi G (2008) Atlantic reef fish biogeography and evolution. J Biogeogr 35:22–47
Gardner TA, Côté IM, Gill JA, Grant A, Watkinson AR (2003) Long-term region-wide declines in Caribbean corals. Science 301:958–960
Gaspar TL, Quimbayo JP, Ozekoski R, Nunes LT, Aued AW, Mendes TC, Garrido AG, Segal B (2021) Severe coral bleaching of *Siderastrea stellata* at the only atoll in the South Atlantic driven by sequential marine heatwaves. Biota Neotrop 21:e20201131
Geyer WR, Beardsley RC, Lentz SJ, Candela J, Limeburner R, Johns WE, Soares ID (1996) Physical oceanography of the Amazon shelf. Cont Shelf Res 16:575–616
Giglio VJ, Aued AW, Cordeiro CA, Eggertsen L, Ferrari DS, Gonçalves LR, Bender MG (2024) A global systematic literature review of ecosystem services in reef environments. Environ Manage 73:634–645
Glynn PW (1993) Coral reef bleaching: ecological perspectives. Coral Reefs 12:1–17
Godoy L, Mies M, Zilberberg C, Pastrana Y, Amaral A, Cruz N, Pereira CM, Garrido AG, Paris A, Santos LF, Pires DO (2021) Southwestern Atlantic reef-building corals *Mussismilia* spp. are able to spawn while fully bleached. Mar Biol 168:1–8
Goreau TJ, Hayes RL (2024) 2023 record marine heat waves: coral reef bleaching HotSpot maps reveal global sea surface temperature extremes, coral mortality, and ocean circulation changes. Oxford Open Clim Change 4:kgae005
Graham NA, Nash KL (2013) The importance of structural complexity in coral reef ecosystems. Coral Reefs 32:315–326
Hackerott S, Martell HA, Eirin-Lopez JM (2021) Coral environmental memory: causes, mechanisms, and consequences for future reefs. Trends Ecol Evol 36:1011–1023
Heinze C, Blenckner T, Martins H, Rusiecka D, Döscher R, Gehlen M, Gruber N, Holland E, Hov Ø, Joos F, Matthews JB et al (2021) The quiet crossing of Ocean tipping points. Proc Natl Acad Sci U S A 118:e2008478118
Helgoe J, Davy SK, Weis VM, Rodriguez-Lanetty M (2024) Triggers, cascades, and endpoints: connecting the dots of coral bleaching mechanisms. Biol Rev 99:715–752
Hoegh-Guldberg O, Skirving W, Dove SG, Spady BL, Norrie A, Geiger EF, Liu G, De La Cour JL, Manzello DP (2023) Coral reefs in peril in a record-breaking year. Science 382:1238–1240
Hughes TP, Anderson KD, Connolly SR, Heron SF, Kerry JT, Lough JM, Wilson SK (2018) Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359:80–83
Hughes TP, Kerry JT, Álvarez-Noriega M, Álvarez-Romero JG, Anderson KD, Baird AH, Babcock RC, Beger M, Bellwood DR, Berkelmans R, Bridge TC (2017) Global warming and recurrent mass bleaching of corals. Nature 543:373–377
IPCC (2021) Climate Change 2021: The Physical Science Basis. In: Masson-Delmotte V, Zhai P, Pirani A, et al (eds) Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press
Kelmo F, Attrill MJ (2013) Severe impact and subsequent recovery of a coral assemblage following the 1997–8 El Niño event: a 17-year study from Bahia, Brazil. PLoS ONE 8:e65073
Kikuchi RKP, Oliveira MD, Leão ZMAN (2013) Density banding pattern of the south western Atlantic coral *Mussismilia braziliensis*. J Exp Mar Biol Ecol 449:207–214
Kleypas JA, Danabasoglu G, Lough JM (2008) Potential role of the ocean thermostat in determining regional differences in coral reef bleaching events. Geophys Res Lett 35:L03613
Leal ICS, Pereira PHC, De Araujo ME (2012) Coral reef fish association and behaviour on the fire coral *Millepora* spp. in north-east Brazil. J Mar Biol Assoc UK 93:1703–1711
Lean JL (2010) Cycles and trends in solar irradiance and climate. Wiley Interdiscip Rev Clim Change 1:111–122
Leão ZMAN, Kikuchi RKP (2001) The Abrolhos reefs of Brazil. Coastal marine ecosystems of Latin America. Springer, Berlin Heidelberg, Berlin, pp 83–96
Leão ZMAN, Kikuchi RKP, Ferreira BP, Neves EG, Sovierzoski HH, Oliveira MD, Maida M, Correia MD, Johnsson R (2016) Brazilian coral reefs in a period of global change: a synthesis. Braz J Oceanogr 64:97–116
Leão ZM, Kikuchi RKP, Oliveira MDM, Vasconcellos V (2010) Status of Eastern Brazilian coral reefs in time of climate changes. Pan-Am J Aquat Sci 5:224–235
Leão ZMAN, Kikuchi RKP, Testa V (2003) Corals and coral reefs of Brazil. In: Cortés J (ed) Latin American Coral Reefs. Elsevier, Amsterdam, pp 9–52
Le Nohaïc M, Ross CL, Cornwall CE, Comeau S, Lowe R, McCulloch MT, Schoepf V (2017) Marine heatwave causes unprecedented regional mass bleaching of thermally resistant corals in northwestern Australia. Sci Rep 7:14999
Lenth R (2024) emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.10.5. https://CRAN.R-project.org/package=emmeans
Liu G, Heron SF, Eakin CM, Muller-Karger FE, Vega-Rodriguez M, Guild LS, Lynds S (2014) Reef-scale thermal stress monitoring of coral ecosystems: new 5-km global products from NOAA coral reef watch. Remote Sens 6:11579–11606
López-Pérez A, Granja-Fernández R, Ramírez-Chávez E, Valencia-Méndez O, Rodríguez-Zaragoza FA, González-Mendoza T,

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Martínez-Castro A (2024) Widespread coral bleaching and mass mortality of reef-building corals in southern Mexican Pacific reefs due to 2023 El Niño warming. Oceans 5:196–209

Luza AL, Aued AW, Barneche DR, Dias MS, Ferreira CE, Floeter SR, Francini-Filho RB, Longo GO, Quimbayo JP, Bender MG (2023) Functional diversity patterns of reef fish, corals and algae in the Brazilian biogeographical province. J Biogeogr 50:1163–1176

Luza AL, Bender MG, Ferreira CE, Floeter SR, Francini-Filho RB, Longo GO, Pinheiro HT, Quimbayo JP, Bastazini VA et al (2024) Coping with collapse: functional robustness of coral-reef fish network to simulated cascade extinction. Glob Change Biol 30:e17513

Magris RA, Costa MD, Ferreira CE, Vilar CC, Joyeux JC, Creed JC, Copertino MS, Horta PA, Sumida PY, Francini-Filho RB, Floeter SR et al (2021) A blueprint for securing Brazil's marine biodiversity and supporting the achievement of global conservation goals. Divers Distrib 27:198–215

Marangoni LF, Mies M, Güth AZ, Banha TN, Inague A, Fonseca JD, Dalmolin C, Faria SC, Ferrier-Pagès C, Bianchini A (2019) Peroxynitrite generation and increased heterotrophic capacity are linked to the disruption of the coral–dinoflagellate symbiosis in a scleractinian and hydrocoral species. Microorganisms 7:426

Martello MF, Bleuel J, Pennino MG, Longo GO (2024) Projected climate-driven shifts in coral distribution indicate tropicalisation of Southwestern Atlantic reefs. Divers Distrib 30:e13851

Mello TJ, Longhini CM, Wanderley BM, Silva CA, Lehrback BD, Bom FC, Neto RR, Sá F, Vieira EA, Costa VE, Longo GO (2025) Pollution affects even oceanic marine protected areas in Southwestern Atlantic. Environ Pollut 366:125485

Mies M, Chaves-Filho AB, Miyamoto S, Güth AZ, Tenório AA, Castro CB, Pires DO, Calderon EN, Sumida PYG (2017) Production of three symbiosis-related fatty acids by *Symbiodinium* types in clades A-F associated with marine invertebrate larvae. Coral Reefs 36:1319–1328

Mies M, Güth AZ, Tenório AA, Banha TNS, Waters LG, Polito PS, Taniguchi S, Bícego MC, Sumida PYG (2018) In situ shifts of predominance between autotrophic and heterotrophic feeding in the reef-building coral *Mussismilia hispida*: an approach using fatty acid trophic markers. Coral Reefs 37:677–689

Mies M, Francini-Filho RB, Zilberberg C, Garrido AG, Longo GO, Laurentino E, Güth AZ, Sumida PYG, Banha TNS (2020) South Atlantic coral reefs are major global warming refugia and less susceptible to bleaching. Front Mar Sci 7:514

Mies M, Banha TNS, Castro CB, Cordeiro RTS, Lotufo TMC, Bianchini A (2024) Biology of Brazilian benthic reef builders and dwellers. In: Kikuchi RKP, Leão ZMAN, Araújo ME, Lotufo TMC (eds) Brazilian coral reefs: a multidisciplinary approach. Springer-Verlag, pp 81–112

Mies M, Banha TNS, Francini-Filho RB, Garrido AG, Santos LFA, Güth AZ, Dottori M, Longo GO, Zilberberg C (2025a) Reef Ecosystems in the Brazilian Continental Shelf. In: Oceanography, Biodiversity, Fisheries and Conservation of Brazilian Continental Shelf Habitats (eds PYG Sumida, M Mies), pp 115–172, Springer-Verlag.

Mies M, Longo GO, Bianchini A, Calderon EN, Castro CB, Faria SC, Francini-Filho RB, Guebert FM, Kitahara MV, Lacerda CHF, Lotufo TMC, Marangoni LFB, Pires DO, Cordeiro RTS (2025b) Challenges for coral restoration in Southwestern Atlantic reefs: guidelines for ethical and sustainable practices. Biodivers Conserv 17:1–27

Miranda RJ, Cruz ICS, Leão ZMAN (2013) Coral bleaching in the Caramuanas reef (Todos os Santos Bay, Brazil) during the 2010 El Niño event. Lat Am J Aquat Res 41:351–360

NOAA Coral Reef Watch (2018) NOAA Coral Reef Watch Version 3.1 Daily Global 5km Satellite Coral Bleaching Degree Heating Week Product, Jan. 1, 2024–Dec. 12, 2024. NOAA Coral Reef Watch, College Park, Maryland, USA. Accessed 2020-09-01 at ftp://ftp.star.nesdis.noaa.gov/pub/sod/mecb/crw/data/5km/v3.1/nc/v1.0/daily/dhw/

Nogueira MM, Neves E, Johnsson R (2021) Effects of habitat structure on the mollusc assemblage in *Mussismilia* corals: evaluation of the influence of different coral growth morphology. J Mar Biol Assoc U K 101:61–69

Nogueira MM, Neves E, Johnsson R (2015) Effects of habitat structure on the epifaunal community in *Mussismilia* corals: does coral morphology influence the richness and abundance of associated crustacean fauna? Helgol Mar Res 69:221–229

Oliver JK, Berkelmans R, Eakin CM (2018) Coral bleaching in space and time. In: van Oppen MJH, Lough JM (eds) Coral Bleaching: Patterns, Processes, Causes and Consequences. Springer, Berlin, pp 27–49

Pereira PHC, Lima GV, Pontes AV, Côrtes LG, Gomes E, Sampaio CL, Seoane JCS (2022) Unprecedented coral mortality on Southwestern Atlantic coral reefs following major thermal stress. Front Mar Sci 9:725778

Pereira PHC, Lima GV, Silva EG, Pontes AVF, Côrtes LG, Sampaio CL, Pinto TK, Belluci MSP, Cardoso ATC, Normande IC (2024) Spatial distribution, management zoning and depth effects on reef biodiversity and productivity at the largest Brazilian coastal marine protected area. Coral Reefs 43:1271–1283

Pinheiro HT, MacDonald C, Santos RG, Ali R, Bobat A, Cresswell BJ, Francini-Filho RB, Freitas R, Galbraith GF, Musembi P, Phelps TA, Quimbayo JP, Quiros TEAL, Shepherd B, Stefanoudis PV, Talma S, Teixeira JB, Woodall LC, Rocha LA (2023) Plastic pollution on the world's coral reefs. Nature 619:311–316

Pinheiro BR, Pereira NS, Agostinho PG, Montes MJ (2017) Population dynamics of *Siderastrea stellata* Verrill, 1868 from Rocas Atoll, RN: implications for predicted climate change impacts at the only South Atlantic atoll. An Acad Bras Cienc 89:873–884

Príncipe SC, Acosta AL, Andrade JE, Lotufo TMC (2021) Predicted shifts in the distributions of Atlantic reef-building corals in the face of climate change. Front Mar Sci 8:673086

R Core Team (2024) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>

Rädecker N, Pogoreutz C, Gegner HM, Cárdenas A, Roth F, Bougoure J, Guagliardo P, Wild C, Pernice M, Raina JB, Meibom A, Voolstra CR (2021) Heat stress destabilizes symbiotic nutrient cycling in corals. Proc Natl Acad Sci U S A 118(5):e2022653118

Reimer JD, Peixoto RS, Davies SW, Traylor-Knowles N, Short ML, Cabral-Tena RA, Burt JA, Pessoa I, Banaszak AT, Winters RS, Moore T (2024) The fourth global coral bleaching event: where do we go from here? Coral Reefs. https://doi.org/10.1007/s00338-024-02504-w

Ribeiro FN, Soares J, de Oliveira AP (2011) A coupled numerical model to investigate the air–sea interaction at the coastal upwelling area of Cabo Frio, Brazil. Environ Fluid Mech 11:551–572

Rocha CB, Silveira ICA, Castro BM, Lima JA (2014) Vertical structure, energetics, and dynamics of the Brazil Current System at 22 S–28 S. J Geophys Res Oceans 119(1):52–69

Rodrigues RR, Artana C, Neto AG, Frölicher TL, Keenlyside N, Hobday AJ, Burger FA, Bernardo PS, Araújo J (2025a) Extreme compound events in the equatorial and South Atlantic. Nat Commun 16:3183

Rodrigues RR, Gonçalves Neto AH, Vieira EA, Longo GO (2025b) The severe 2020 coral bleaching event in the tropical Atlantic linked to marine heatwaves. Commun Earth Environ 6(1):208

Roos NC, Longo PA, Ilieva JR, Motta FS, Pereira-Filho GH (2024) Scleractinian corals at their subtropical Southwestern Atlantic limit: post-2019 mass bleaching event analysis. Aquat Conserv Mar Freshw Ecosyst 34(12):e70031

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Santana EF, Mies M, Longo GO, Menezes R, Aued AW, Luza AL, Francini-Filho RB (2023) Turbidity shapes shallow Southwestern Atlantic benthic reef communities. Mar Environ Res 183:105807

Sasaki DK, Silva D, Del Giovannino Júnior SR, Almeida da Silveira IC, Belo WC, Martins RP, Dottori M (2024) Hydrographic climatology of the South Brazil Bight continental shelf and slope. Theor Appl Climatol 155(10):9407–9425

Schiavetti A, Manz J, dos Santos CZ, Magro TC, Pagani MI (2013) Marine protected areas in Brazil: an ecological approach regarding the large marine ecosystems. Ocean Coast Manag 76:96–104

Schoepf V, Baumann JH, Barshis DJ, Browne NK, Camp EF, Comeau S, Cornwall CE, Guzmán HM, Riegl B, Rodolfo-Metalpa R, Sommer B (2023) Corals at the edge of environmental limits: a new conceptual framework to re-define marginal and extreme coral communities. Sci Total Environ 884:163688

Schoepf V, Stat M, Falter JL, McCulloch MT (2015) Limits to the thermal tolerance of corals adapted to a highly fluctuating, naturally extreme temperature environment. Sci Rep 5:17639

Siebeck UE, Marshall NJ, Klüter A, Hoegh-Guldberg O (2006) Monitoring coral bleaching using a colour reference card. Coral Reefs 25:453–460

Silva AS, Leão ZM, Kikuchi RK, Costa AB, Souza JR (2013) Sedimentation in the coastal reefs of Abrolhos over the last decades. Cont Shelf Res 70:159–167

Silva GL, Kampel M, Nakamura T (2025) Thirty years of coral bleaching in the Southwestern Atlantic Ocean: a historical assessment based on Degree Heating Week indices. Coral Reefs 1–5

Silva IC, Liparini A, Pereira NS, Braga BL, Sial AN, Liu SC, Shen CC, Kikuchi RKP (2019) Assessing the growth rate of the South Atlantic coral species *Mussismilia hispida* (Verrill, 1902) using carbon and oxygen stable isotopes. J South Am Earth Sci 96:102346

Silva TRS, Marangoni LFB, Lacerda CHF, Güth AZ, Longo GO, Bianchini A, Mies M, Cordeiro RTS (submitted) A fragile branch: the silent decline of neglected Brazilian milleporids amid the fourth global bleaching event

Silveira ICA, de Miranda LB, Brown WS (1994) On the origins of the North Brazil Current. J Geophys Res Oceans 99(C11):22501–22512

Skirving W, Enríquez S, Hedley JD, Dove S, Eakin CM, Mason RA, Iglesias-Prieto R (2017) Remote sensing of coral bleaching using temperature and light: progress towards an operational algorithm. Remote Sens 10:18

Skirving WJ, Heron SF, Marsh BL, Liu G, De La Cour JL, Geiger EF, Eakin CM (2019) The relentless march of mass coral bleaching: a global perspective of changing heat stress. Coral Reefs 38:547–557

Soares MO, Rossi S, Gurgel AR, Lucas CC, Tavares TCL, Diniz B, Alvarez-Filip L (2021) Impacts of a changing environment on marginal coral reefs in the Tropical Southwestern Atlantic. Ocean Coastal Manage 210:105692

Soares MO, Teixeira CE, Ferreira SM, Gurgel AL, Paiva BP, Menezes MO, Davis M, Tavares TC (2019) Thermal stress and tropical reefs: mass coral bleaching in a stable temperature environment? Mar Biodivers 49:2921–2929

Sully S, van Woesik R (2020) Turbid reefs moderate coral bleaching under climate-related temperature stress. Glob Change Biol 26(3):1367–1373

Sully S, Burkepile DE, Donovan MK, Hodgson G, Van Woesik R (2019) A global analysis of coral bleaching over the past two decades. Nat Commun 10:1264

Tebbett SB, Connolly SR, Bellwood DR (2023) Benthic composition changes on coral reefs at global scales. Nat Ecol Evol 7:71–81

Teixeira CD, Leitão RL, Ribeiro FV, Moraes FC, Neves LM, Bastos AC, Moura RL (2019) Sustained mass coral bleaching (2016–2017) in Brazilian turbid-zone reefs: taxonomic, cross-shelf and habitat-related trends. Coral Reefs 38:801–813

Tosetto EG, Bertrand A, Neumann-Leitão S, Nogueira Júnior M (2022) The Amazon River plume, a barrier to animal dispersal in the Western Tropical Atlantic. Sci Rep 12(1):537

Trygonis V, Sini M (2012) Photoquad: a dedicated seabed image processing software, and a comparative error analysis of four photoquadrat methods. J Exp Mar Biol Ecol 424:99–108

Vehtari A, Gelman A, Gabry J (2017) Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. Stat Comput 27:1413–1432

Vergés A, Steinberg PD, Hay ME, Poore AG, Campbell AH, Ballesteros E, Heck KL Jr, Booth DJ, Coleman MA, Feary DA, Figueira W et al (2014) The tropicalization of temperate marine ecosystems: climate-mediated changes in herbivory and community phase shifts. Proc R Soc Lond B Biol Sci 281:20140846

Vidal TJ, de Almeida GN, Müller MN, da Silveira CB, Maida M, Ferreira BP (2025) Mortality patterns and recovery challenges in *Millepora alcicornis* after mass bleaching event on Northeast Brazilian reefs. Mar Environ Res 204:106864

Vieira EA, Longo GO (2025) Interannual health status stability of the reef-building coral *Montastraea cavernosa* in a southwestern Atlantic marginal reef. Mar Environ Res 208:107104

Vital H, Gomes MP, Tabosa WF, Frazão EP, Santos CL, Plácido Júnior JS (2010) Characterization of the Brazilian continental shelf adjacent to Rio Grande do Norte State, NE Brazil. Braz J Oceanogr 58:43–54

Wunderling N, von der Heydt AS, Aksenov Y, Barker S, Bastiaansen R, Brovkin V, Brunetti M, Couplet V, Kleinen T, Lear CH, Lohmann J et al (2024) Climate tipping point interactions and cascades: a review. Earth Syst Dyn 15(1):41–74

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