

Unveiling thermal responses on macroalgae assemblages after a 10 years' time span in a subtropical rocky shore from Southwestern Atlantic Ocean

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Abstract

Biotic thermal stress caused by sea surface temperature (SST) anomalies and marine heatwaves (MHW), driven by ongoing ocean-atmosphere exchanges and the climate change, can severely alter macroalgae community composition. Macroalgae provide vital ecosystem services and serve as key bioindicators. Understanding their dynamic supports impact mitigation in inhabited coastal areas and enhances socio-environmental resilience. We comparatively evaluated changes in richness and composition of seaweed assemblages after a 10-years' timespan on a rocky shore in southern Brazil. Seasonal biological data from a 2014 baseline checklist were compared to a 2024 resurvey conducted along the same intertidal transects and analyzed alongside local SST and MHW intensity and frequency data retrieved from global databases for the preceding decades. Over this ten-years interval was observed a seasonal inversion on Rhodophyta and Phaeophyceae species richness, being higher during austral winter 2024, contrasting to the higher summer richness observed in 2014. Ulvophyceae was the exception, displaying lower overall richness and biomass-dominance of few opportunistic taxa across both seasons. This intriguing seasonal pattern inversion was strongly related to thermal stress, suggesting that assemblages are shifting toward thermally more suitable seasons, while demonstrating local resilience mechanisms and adaptive capacity. Given the scarcity of ecological studies on macroalgal communities in the SWAO, these biotic shifts enhance our understanding of thermal stressors. Furthermore, this study updates the regional algal diversity database and reports new records, providing a valuable baseline for future long-term monitoring efforts.

1 Introduction

The Southwestern Atlantic Ocean (SWAO) is pressured from intensive fisheries (Perez et al. 2023) and climate change (Gianelli et al. 2023). These changes include, among other cascade effects, shifts in thermo-haline patterns and increasing frequency and intensity of marine heatwaves (MHW) (synopsis in Pellizzari et al. 2025). Sea surface temperature (SST) modes of climate variability in the SWAO remain a challenging topic (Nogueira et al. 2026). Vasconcelos et al. (2023) compared the warming trends of SWAO SST and the summer's warmest SST's impact on South American climate, concluding that the warmest summers since 1980s–1990s ratified the role of SST intensification. In other instance, MHW events are discrete periods of anomalously elevated ocean temperature, characterized by their duration, intensity, and spatial extent, occurring when regional SST exceed historical average before returning to the baseline conditions (Hobday et al. 2016). MHW events exceed 90% of the local long-term climatology for at least five consecutive days, allowing no more than two days below the threshold (Hobday et al. 2018). Also, according to Goes et al. (2024) showed that basin-scale ocean dynamics influence MHWs in the SWAO and stated that MHW and cold spells are extreme surface temperature events linked to adverse ecosystem impacts.

However, MHW prediction remains challenging due to the short duration on ocean-atmosphere interactions. Anomalously warm events have risen 34–54% in frequency and 17% in duration between 1925 and 2016, with major implications for coastal ecosystems (Straub et al. 2019; Nauer et al. 2022).

Goes et al. (2024) also observed that the circulation transports tropical or subpolar waters into subtropics, modulating MHWs and cold fronts occurrence.

As effects of climate change, SST anomalies and MHWs have been linked to known responses of macroalgae to thermal stress, such as changes in a primary productivity (Gouvea et al. 2017), community composition and seaweed biogeography, affecting ecosystem's functions (Pellizzari et al. 2025, 2026). Changes in thermohaline patterns, whether gradual or abrupt, such in MHW events, may favor opportunistic and stress-tolerant species over sensitive, slow-growing taxa. Loss of component species and shifts in the assemblage composition may result in reduction of ecosystem services (Vergara-Carranza et al. 2024). MHWs, side-effects of broader scale climatic change, are impacting benthic ecosystems; and warmer SST enhance tropical cyclones and intensify global climatic events, further promoting MHW, self-reinforcing events (Choi et al. 2024).

Macroalgal community structure are driven mainly by thermal patterns, besides pH, nutrient availability, herbivory, irradiance, and physical conditions such as substrate, currents and winds (Briggs et al. 2021). Altered physicochemical ocean parameters may constraint macroalgal growth and reproduction, shifting species distribution (Clarke et al. 2012; Pellizzari et al. 2017, 2023). Also, MHWs and or shifts in SST, components of broader climate-driven change, can interact with anthropogenic pressures (e.g., nutrient enrichment and reduced water transparency), generating multiple stressors on populations (Wernberg and Straub 2024). Is known that macroalgae assemblages exhibit adaptive strategies that enable responses to seasonal variability and disturbance gradients within certain limits of resilience. Assemblages can adjust reproductive/biochemical characteristics, growth rates, secondary metabolite production patterns, and distribution in response to environmental conditions (Horinouchi et al. 2024), with the seawater temperatures as key driver. However, these responses may fail under intense and/or persistent pressures (Airoldi & Beck 2007), including shifts in sea surface temperature (SST) patterns (Ishida et al. 2023) and MHWs events (Pellizzari et al. 2025). Besides, severe thermal stress may also drive local extinctions and phenotypic change, even at molecular level (Ortiz et al. 2020).

Seaweeds are being target studied for their roles in climate mitigation, besides applied uses in food, colloids, nutraceutical industries, and bioactive compounds sources for pharmaco-cosmetical applications (Segaran et al. 2023). Ecologically, these primary producers support marine food web, assimilating nutrients, releasing oxygen, regulating biogeochemical homeostasis and, finally, contributing to the global carbon cycle – functions challenged by climate change (Cotas et al. 2023). Coastal habitats and algal species are threatened by abiotic changes, shifting their contribution to regional and global productivity and ecosystem services (Hanley et al. 2024).

Through physiological sensitivity, seaweeds may serve as bioindicators with slight shifts in abiotic conditions resulting changes in the community (Piñeiro-Corbeira et al. 2018). Meteoceanographic changes (Pellizzari et al. 2026), combined with direct anthropogenic impacts (Gissi et al. 2021), purses a growing threat to macroalgae assemblages (Hanley et al. 2024). Alterations in biogeographic distributions and migration patterns (Duarte et al. 2025; Wernberg et al. 2025; Pellizzari et al. 2023, 2025,

2026) along with changes in ecological interactions (Tavares et al. 2020; Ferreira et al. 2026) may signal the onset of broader ecological changes. Rising temperatures may also shift competitive dynamics in macroalgal communities, favoring invasive over native species. Warmer temperatures modify herbivory patterns, further reshaping macroalgal community structure (Tavares et al. 2020; Gao et al. 2021).

Thus, abiotic changes are redistributing algae assemblages, particularly in temperate and polar regions (see synopsis in Pellizzari et al. 2025, 2026). The tropical and subtropical Brazilian coast hosts over 800 seaweed species (Guiry 2024) with higher richness concentrated in Espírito Santo State, and lower richness in Sergipe, and Paraná states, where according to Pellizzari et al. (2014) ca. of 139 spp. were listed. This lower richness is attributed to the short coastal extent and lower hard substrate availability. On the other hand, lower species richness may facilitate long-term coastal monitoring relevant to conservation and management.

Finally, and compared with polar and temperate zones, studies linking thermal response of seaweed assemblages' changes in warmer zones remain limited, except for laboratory studies (Nauer et al. 2022; Borburema et al. 2025). In this sense, the lack of information from subtropical SWAO justify the present evaluation and temporal dynamics comparison of seaweed assemblages in relation to decadal SST and MHW variability, particularly in the southern Brazil. This study focused on seasonal changes in macroalgal composition and richness in Farol Island, comparing two surveys conducted in 2014 and 2024 within the context of thermal changes, also relating the decadal dataset to project further assemblages' response.

2 Material and Methods

2.1. Studied area

SWAO, where Brazilian coastline is inserted, plays a significant role in international cooperation agreements (Grenno et al. 2023), as it is bordered to the north by the Equator and to the south by Antarctica, the “air conditioner” of the Southern Hemisphere (Pellizzari et al. 2025), and for this reason these integrated meteoceanographic huge systems (Southern Ocean and the Atlantic) exerts a great influence in the climate of the surrounded continents.

The Paraná Coast extends 90 km and is the second shortest stretch of coastline in Brazil. The northern part of this coast includes the largest grain's port in South America, located in the Paranaguá Estuarine Complex. The study site, Farol Island (25°51'S/48°32'W), lies close to the mainland coast, where its sheltered coast faces Guaratuba Bay, with low water transparency and nutrient input rainfall dependent. The ocean-facing coast experiences higher hydrodynamic activity, however, urbanization of the area has resulted in environmental degradation mainly during summer. Farol Island's benthic algae assemblages have been monitored over the past decade enabling the present comparison.

2.2 The use of previous biotic data

Pellizzari et al. (2014) provided a database to support further seasonal monitoring of seaweeds richness and diversity as a fundamental step in detecting environmental impacts that could change seaweed biogeography in urbanized and harbor areas. This work surveyed along the main four coastal Paraná insular areas, including Farol. Isl. Algal samples were collected during the winter and the summer seasons, between 2010 and 2013), along parallel transects on the coast in the intertidal zone. Pellizzari et al. (2014) Paraná coast survey comprised 139 taxa of marine phycoflora (being 90 Rhodophyta, 27 Chlorophyta and 22 Phaeophyceae) at all sampled islands. The previous and the present methodologies and sampling efforts were the same (locations, seasons, transect size, number of samples and field observers). Given also the consistency of the taxonomic resolutions between surveys we assume that the differences observed in results are related to ecological changes in the assemblage.

2.3 Sampling and laboratorial analysis

Sampling surveys were performed during austral winter and summer (December 2023/ August 2024) along parallel transects in the intertidal zone of Farol Island's rocky shores. Macroalgae were sampled along six randomly distributed 100 m transect parallel to the coastline. Macroalgae specimens, preferentially entire and fertile, were collected manually (n = 3 per species and per transect). The collected material was initially sorted, washed and stored in polyethylene flasks containing formalin (4% diluted in seawater). For integrative taxonomy vouchers were also stored in Sigel to enable molecular approaches for cryptic species. The samplings and analytic resolution for samples from 2014 and 2024 were the same.

Macroalgal specimens were analyzed focusing on the morphological features of their vegetative and reproductive regions. Histological sections and/or filaments were used to assess (i) cell size (ii) number, position and shape of chloroplasts, (iii) shape and size of uni- and multi-cellular fertile structures, (iv) organization of branching, (v) type, size and shape of the apical cells, and (vi) exclusive morphological features. The material was analyzed using stereoscopic and optical microscopy with phase contrast and image capture (Motic SMZ-161, Olympus CX31 and CX41). Taxonomic identification and species diagnostic characters were assessed by comparing the specimens obtained with specialized bibliographies of seaweeds taxonomy from SWAO. Nomenclatural updates follow Guiry and Guiry (2026). Specimens representing new records (NR) of macroalgae for the area are in process of deposition in the collection of the Museu Botânico Municipal Herbarium (MBM, Curitiba Botanical Garden, Paraná, Brazil).

The biotic data comparisons of community composition and species richness across seasons and years (summer/winter, 2014/2024) were based on presence–absence data. Beta-diversity metric was calculated based on the Sørensen dissimilarity (β SOR) metric using the equation (range: 0–1): $\beta_{sor} = (b + c) / (2a + b + c)$, where a = number of species common to both samples (shared species), b= number of unique species in sample 1 (absent in sample 2), and c= number of unique species in sample 2 (absent in sample 1). This beta diversity index is 'a broad sense' measure, to detect compositional differences and variability in species composition (Baselga and Leprieur 2015). A dendrogram was generated using the Unweighted Pair-Group Method Average (UPGMA). In order to characterize the occurrence of

species, Dajoz's constancy index (CI) was used where each taxon was classified as "rare" (< 25%), "accessory" (25–50%) or "constant" (> 50%) (Parada et al., 2025).

2.4 Abiotic data retrieval and modeling and statistics

Sea surface temperature (SST) data set over the past decades (January 2004 till 2024) were retrieved from the global database Copernicus (https://data.marine.copernicus.eu/product/SST_GLO_SST_L4_NRT), with the bounding box to the coordinates covering the Paraná coastal shelf region (approximately 25-26°S // 47-48°W) used to generate a long-term (20 years) climatological series for the studied area. The localized time-series trend analysis performed for these daily satellite SST data (source: Level-4 satellite SST data from the Copernicus Marine Data Store), averaging it to annual means, were an Ordinary Least Squares (OLS) linear regression, using bootstrapping or standard error formulas for the 95% confidence interval.

Comparative maps of sea surface temperature were generated using the World Ocean Atlas 2023 (WOA23) climatology database. The baseline gridded data and statistical means were retrieved and visualized via the NOAA-supported web Ocean Data View (ODV) Explore interface (Reagan et al., 2024 / <https://explore.webodv.awi.de/>), where were selected the 2005–2024 climatological normal data of SST to evaluate spatial anomalies in the SWAO along the decades, including our sampling site. Time intervals analyzed throughout the period included: a) approximately decadal intervals; b) at five-year intervals for SST (decadal and seasonal data) and Marine Heatwave (MHW) climatological analysis. A Student's t-test was applied to confirm the statistical significance of differences among the means.

Previous and *in situ* sea surface temperature (SST) and salinity data were also retrieved from Pellizzari et al. (2014), and measured in the studied location, using a digital thermometer (SPER waterproof RTD), and portable refractometer (MSE pro), respectively, as local-coastal reference.

Temporal data over the last decade of MHW frequency, intensity and duration (in days), expressed by lolliplots time-series maps, were obtained from the Marine Heatwaves Tracker (www.marineheatwaves.org). Categories of MHWs were classified following Hobday et al. (2018). MHW and Cold Waves were presented in lolliplots with colors classification. In order to present comparative illustrations of the relationships between macroalgal species richness on Farol Island, the frequency, intensity and duration of MHWs events over the past decade, the comparison was plotted in five-years intervals. The SST anomaly considered here as MHW were the temperatures exceeding the 90th percentile of historical records in periods lasting more than five days, following Hobday et al. (2016). Their duration may be considered as: SHORT (5–15 days), MEDIUM (16 to 30 days), and LONG (more than a month).

SST and MHW analyses were conducted using the R programming language (R Development Core Team 2024) using the packages "ncdf4" (Pierce 2019), and "fields" (Nychka et al. 2017). A t test has been applied to assess the statistical differences of SST seasonal (summer and winter months). The mean intensity, duration, and total number (frequency) of MHWs were analyzed over a 20-years timespan in 5-

year intervals using a one-way analysis of variance (ANOVA). For MHW calculation and plotting, we used “heatwaveR” (Schlegel and Smit, 2018) and “ggplot2” (Wickham 2016), respectively.

3 Results

3.1 Biotic data

A total of 92 macroalgae species were recorded on Farol Island, comprising 20 species Ulvophyceae, 13 Phaeophyceae and 59 Rhodophyta (Fig. 1, Table 1). Seasonal species richness shifted over time, with higher summer richness in 2014, and higher winter richness in 2024 (Fig. 1). The seasonal inversion in richness observed between 2014 and 2024 was mainly driven from shifts in Rhodophyta and Phaeophyceae, groups that showed higher richness in winter of 2024. For Rhodophyta, winter of 2024 showed more than twice richness compared to winter 2014 (Fig. 1). Ulvophyceae maintained the pattern of higher richness during summer but showed reduction in species number for both seasons during 2024 (followed by an observed predominance of higher biomass of fewer opportunistic taxa). The stronger winter representation of red algae in 2024 indicates that this group responded and contributed most to the temporal shift in community composition.

Table 1

Seasonal variation on the diversity of macroalgae along a decade at Ilha do Farol, Southwestern Atlantic Ocean (SWAO). Where **X** is for taxa presence, and - (minus) for absence. **NR** = new record for the Paraná Coast. Dajoz Constancy Index is indicated by letters on the right of the species name (**C** = constant, **A** = Accessory and **R** = rare)

BENTHIC MARINE MACROALGAE	2014	2014	2024	2024
TAXA LIST	Farol Island, Paraná, South Brazil			
	Summer	Winter	Summer	Winter
CHLOROPHYTA - ULVOPHYCEAE				
Bryopsidales				
Bryopsidaceae				
<i>Bryopsis pennata</i> J.V. Lamouroux (A)	X	-	X	-
Caulerpaceae				
<i>Caulerpa fastigiata</i> Montagne (C)	X	X	X	X
<i>Caulerpa</i> sp. (R)	X	-	-	-
Codiaceae				
<i>Codium decorticatum</i> (Woodward) M.A. Howe (A)	X	X	-	-
<i>Codium taylorii</i> P.C. Silva (C)	X	X	-	X
Udoteaceae				
<i>Boodleopsis pusilla</i> (F.S. Collins) W.R. Taylor, A.B. Joly & Bernatowicz (A)	X	X	-	-
Cladophorales				
Boodleaceae				
<i>Cladophoropsis membranacea</i> (Hofman Bang ex C. Agardh) Børgesen (R)	-	X	-	-
Cladophoraceae				
<i>Chaetomorpha antennina</i> (Bory de Saint-Vincent) Kützinger (C)	X	X	-	X
<i>Chaetomorpha brachygona</i> Harvey (R)	-	-	-	X
<i>Cladophora montagneana</i> Kützinger (R)	-	X	-	-
<i>Cladophora prolifera</i> (Roth)Kützinger (R)	-	X	-	-
<i>Cladophora vagabunda</i> (Linnaeus) Hoek (C)	X	X	X	X
<i>Pseudorhizoclonium africanum</i> (Kützinger) Boedeker (A)	-	X	X	-

BENTHIC MARINE MACROALGAE	2014	2014	2024	2024
<i>Rhizoclonium riparium</i> (Roth) Harvey (C)	X	X	-	X
Ulotrichales				
Gayraliaceae				
<i>Gayralia brasiliensis</i> Pellizzari, M.C. Oliveira et N.S. Yokoya (C)	X	X	-	X
Ulvales				
Ulvaceae				
<i>Ulva clathrata</i> (Roth) C. Agardh (R)	X	-	-	-
<i>Ulva flexuosa</i> Wulfen (C)	X	X	-	X
<i>Ulva lactuca</i> Linnaeus, formerly as <i>U. fasciata</i> (C)	X	X	X	X
<i>Ulva linza</i> Linnaeus (R)	-	X	-	-
<i>Ulva</i> sp. (R)	-	-	X	-
Total 20	13	15	6	9
HETEROKONTOPHYTA/ PHAEOPHYCEAE				
Dictyotales				
Dictyotaceae				
<i>Canistrocarpus cervicornis</i> (Kützinger) De Paula & De Clerck 2006 (R)	-	-	-	X
<i>Lobophora variegata</i> (Lamouroux) Womersley ex Oliveira (R)	X	-	-	-
<i>Padina antillarum</i> (Kützinger) Piccone (R)	X	-	-	-
<i>Padina gymnospora</i> (Kützinger) Sonder (C)	X	X	X	X
<i>Spatoglossum schroederi</i> (C.Agardh) Kützinger 1859 (R)	-	-	X	-
Ectocarpales				
Scytosiphonaceae				
<i>Chnoospora minima</i> (K. Hering) Papenfuss (A)	X	-	X	-
<i>Petalonia fascia</i> (O.F. Müller) Kuntze(A)	-	X	-	X
Fucales				
Sargassaceae				

BENTHIC MARINE MACROALGAE	2014	2014	2024	2024
<i>Sargassum cymosum</i> C. Agardh (C)	X	X	-	X
<i>Sargassum cymosum</i> var. <i>nanum</i> E. de Paula & E. C. Oliveira (C)	X	-	X	X
<i>Sargassum stenophyllum</i> Martius (C)	X	X	-	X
<i>Sargassum vulgare</i> C. Agardh (R)	X	-	-	-
Ralfsiales				
Neoralfsiaceae				
<i>Neoralfsia expansa</i> (J.Agardh) P.E.Lim & H.Kawai 2012 (R)	-	-	X	-
Scytothamnales				
Bachelotiaceae				
<i>Bachelotia antillarum</i> (Grunow) Gerloff (R)	-	X	-	-
Total 13	8	5	5	6
RHODOPHYTA				
Acrochaetiales				
Acrochaetiaceae				
Acrochaetium crassipes (Børgesen) Børgesen 1915 NR* (R)	-	-	-	X
Bangiales				
Bangiaceae				
Bangia fuscopurpurea (Dillwyn) Lyngbye NR* (A)	-	-	X	X
<i>Pyropia acanthophora</i> (E.C.Oliveira & Coll) M.C.Oliveira, D.Milstein & E.C.Oliveira (A)	X	-	-	X
<i>Phycocalidia acanthophora</i> var. <i>brasiliensis</i> (E.C.Oliveira & Coll) Santiañez (A)	-	X	-	X
<i>Pyropia spiralis</i> (E.C.Oliveira & Coll) M.C.Oliveira, D.Milstein & E.C.Oliveira (A)	-	X	-	X
<i>Pyropia suborbiculata</i> (Kjellman) J.E.Sutherland, H.G.Choi, M.S. Hwang & W.A.Nelson (C)	X	X	-	X
Ceramiales				
Callithamniaceae				

BENTHIC MARINE MACROALGAE	2014	2014	2024	2024
Callithamnion tetragonum (Stackhouse) S.F.Gray 1821 NR*	-	-	X	-
<i>Spyridia hypnoides (Bory) Papenfuss (R)</i>	-	-	-	X
Spyridia clavata Kützinger NR*	-	-	-	X
Ceramiaceae				
<i>Aglaothamnion felliponei</i> (M. Howe) N. Aponte, D. L. Ballant. & J. N.Norris (C)	X	-	X	X
<i>Aglaothamnion uruguayense</i> (W. R. Taylor) N. Aponte, D. L. Ballant (C)	X	X	X	X
<i>Centroceras gasparrinii (Meneghini) Kützinger (formerly as C. clavulatum) (C)</i>	X	X	X	X
<i>Ceramium brasiliense</i> A. B. Joly (R)	X	-	-	-
<i>Ceramium dawsonii</i> A. B. Joly (A)	X	-	X	-
<i>Ceramium deslongchampsii Chauvin ex Duby (A)</i>	-	-	X	X
<i>Ceramium sp. (A)</i>	X	-	-	X
Delesseriaceae				
<i>Caloglossa leprieurii</i> (Mont.) G. Martens (R)	X	-	-	-
<i>Hypoglossum hypoglossoides</i> (Stackhouse) F.S. Collins & Hervey (R)	-	X	-	-
Erythropeltales				
Erythrotrichiaceae				
<i>Sahlingia subintegra (Rosenvinge) Kornmann sobre Chaetomorpha (R)</i>	-	-	-	X
Rhodomelaceae				
<i>Acanthophora spicifera</i> (Vahl) Børgesen (A)	X	-	X	-
<i>Bostrychia montagnei</i> Harvey (A)	X	X	-	-
<i>Bostrychia moritziana</i> (Sonder ex Kützinger) J.Agardh (R)	-	-	-	X
<i>Bostrychia radicans</i> (Mont.) Mont. In Orbigny (C)	X	X	-	X
Bryocladia subtilissima (Montagne) Díaz-Tapia NR* (R)	-	-	X	-
<i>Bryocladia thyrsgera</i> (J. Agardh) F. Shmitz (C)	X	-	X	X
<i>Alsidium seaforthii (Turner) J.Agardh formerly as Bryothamnion (A)</i>	X	-	-	X

BENTHIC MARINE MACROALGAE	2014	2014	2024	2024
<i>Herposiphonia secunda f. tenella</i> (C. Agardh) Ambronn (R)	X	-	-	-
<i>Palisada perforata</i> (Bory) K.W. Nam (A)	X	-	-	X
<i>Polysiphonia howei</i> Hollenberg (R)	-	X	-	-
<i>Polysiphonia</i> sp. (A)	X	-	X	-
<i>Xiphosiphonia pennata</i> (C.Agardh) Savoie & G.W.Saunders (Formerly as <i>Pterosiphonia</i>) (C)	X	X	X	X
<i>Vertebrata foetidissima</i> (Cocks ex Bornet) Díaz-Tapia & <i>Maggs</i> (formerly as <i>Polysiphonia</i>) (R)	-	-	-	X
Wrangeliaceae				
<i>Wrangelia argus</i> (Montagne) Montagne 1856 (R)	-	-	-	X
Corallinales				
Corallinaceae				
<i>Arthrocardia flabellata</i> (Kütz.) Manza (R)	-	X	-	-
<i>Jania pedunculata</i> var. <i>adhaerens</i> (J.V.Lamouroux) A.S.Harvey, Woelkerling & Reviers. (R)	-	-	X	-
<i>Jania rubens</i> (Linnaeus) J.V.Lamouroux (R)	-	-	-	X
<i>Jania capillacea</i> Harvey (A)	-	-	X	X
Lithophyllaceae				
<i>Amphiroa beauvoisii</i> J.V.Lamouroux 1816 (R)	-	-	-	X
<i>Lithophyllum stictiforme</i> (Areschoug) Hauck 1877 (A)	-	-	X	X
Hapalidiaceae				
<i>Lithothamnion</i> Complex	-	-	-	X
Gelidiales				
Gelidiaceae				
<i>Gelidium crinale</i> (Hare ex Turner) Gaillon (R)	-	-	-	X
<i>Gelidium microdenticum</i> W.R.Taylor NR* (R)	-	-	-	X
<i>Gelidium pusillum</i> (Stackh.) Le Jolis (C)	X	X	X	X
<i>Gelidium</i> sp. (A)	X	-	X	-

BENTHIC MARINE MACROALGAE	2014	2014	2024	2024
Pterocladaceae				
<i>Pterocladella capillacea</i> (S. G. Gmel.) Santel. & Hommers. (C)	X	X	-	X
Gigartinales				
Cystocloniaceae				
Hypnea cervicornis J.Agardh 1851 NR* (R)	-	-	X	-
<i>Hypnea pseudomusciformis</i> Nauer, Cassano & M.C.Oliveira (formerly as <i>H. musciformis</i>) (C)	X	X	X	X
<i>Hypnea spinella</i> (C. Agardh) Kütz. (A)	X	-	-	X
Gigartinaceae				
<i>Chondracanthus acicularis</i> (Roth) Fredericq (C)	X	-	X	X
<i>Chondracanthus elegans</i> (Grev. in J. St. Hil.) Guiry (R)	X	-	-	-
Phyllophoraceae				
<i>Gymnogongrus griffithsiae</i> (Turner) Mart. (C)	X	-	X	X
Gracilariales				
Gracilariaceae				
<i>Gracilaria domingensis</i> (Kütz.) Sond. ex Dickie (A)	X	-	-	X
<i>Gracilaria caudata</i> J.Agardh (A)	X	X	-	-
Halymeniales				
Halymeniaceae				
<i>Grateloupia dichotoma</i> J. Agardh (A)	X	X	-	-
<i>Grateloupia doryphora</i> (Montagne) M.A. Howe (R)	X	-	-	-
Halymenia rosea M.Howe & W.R.Taylor NR* (R)	-	-	-	X
Hildenbrandiales				
Hildenbrandiaceae				
<i>Hildenbrandia rubra</i> (Sommerf.) Menegh. (A)	X	-	-	X
Nemaliales				
Galaxauraceae				
<i>Tricleocarpa cylindrica</i> (J. Ellis & Sol.) J. V. Lamour. (R)	X	-	-	-

BENTHIC MARINE MACROALGAE	2014	2014	2024	2024
Rhodymeniales				
Rhodymeniaceae				
<i>Rhodymenia pseudopalmata</i> (J.V.Lamouroux) P.C.Silva (R)	-	-	-	X
Total 59	32	16	21	39

Details of the taxa recorded are presented in Table 1 with the respective authorship of the taxonomical entities listed here. Taxa recorded only in 2014 (exclusive), included 4 brown, 7 green, and 8 red algae are: *Lobophora variegata*, *Padina antillarum*, *Bachellotia antillarum*, *Sargassum vulgare*; *Codium decorticatum*, *Boodleopsis pusilla*, *Cladophoropsis membranaceae*, *Cladophora montagneana*, *C. prolifera*, *Ulva clathrata*, *U. linza*; *Ceramium brasiliense*, *Hypoglossum hypoglossoides*, *Herposiphonia secunda* f. *tenella*, *Polisiphonia howei*, *Arthrocardia flabellata*, *Chondracanthus elegans*, *Grateloupia dichotoma*, and *Tricleocarpa cylindrica*.

In 2024, 3 brown and 15 red algae species were exclusive: *Canistrocarpus cervicornis*, *Spatoglossum schroederi*, *Neoralfsia expansa*; *Spyridia hypnoides*, *Ceramium deslongchampsii*, *Sahlingia subintegra*, *Bostrychia moritziana*, *Bryocladia subtilissima*, *Vertebrata foetidissima*, *Wrangelia argus*, *Jania pedunculata* var. *adhaerens*, *J. rubens*, *J. capillacea*, *Amphiroa beauvoisii*, *Lithophyllum stictiforme*, *Lithothamnion Complex*, *Gelidium crinale*, and *Rhodymenia pseudopalmata*.

Based on the integrative taxonomic analyses of the 2024 data, eight Rhodophyta species represent new records (NR) for Paraná State, including *Acrochaetium crassipes*, *Bangia fuscopurpurea*, *Callithamnion tetragonum*, *Gelidium microdenticum* *Halymenia rosea*, *Hypnea cervicornis*, *Spyridia clavata*, and *Polysiphonia subtilissima*.

Compositional turnover between 2014 and 2024 was evident across all groups, based on the dissimilarity indexes that showed moderate to low overlap among seasons, varying also among algal groups (Table 1, Fig. 2). Ulvophyceae and Phaeophyceae showed more winter stability in composition. However, Phaeophyceae during summer of 2024 were 60–65% distinct from the other sampling periods, while during winter the assemblages among decade were similar (Fig. 2). Considering Ulvophyceae (Chlorophyta), 38–40% of the species were similar during summer (Sorensen 0.38 i.e., were distinct by 60% dissimilarity); and 48% of similarity during winter. The temporal turnover observed among groups was in general higher during summer compared to winter. Particularly for Rhodophyta, data showed lower seasonal homogeneity among years and seasons. The most distinct composition (63–65%) was observed during the winter of 2014 (Fig. 2) for red seaweeds, where only 16 species were recorded, compared to 39 spp. listed during winter 2024. Approximately 50% of Rhodophyta recorded in summer of 2014 were not detected in summer 2024, suggesting an expressive turnover. In general, considering the compiled (2014) and sampled data (2024), only five species of Rhodophyta were common to all seasons and years analyzed, three Ulvophyceae spp. and one sp. of Phaeophyceae.

Dajoz's constancy index (CI) indicated, among Rhodophyta, 12 constant (C) species, 20 accessories (A), and 27 rares (R) (with few records only occurring during winter of 2024, details provided in Table 1). For Ulvophyceae eight species were constant, four were accessories and 8 eight rare ssp. (winter 2024). Considering Phaeophyceae four species were constant, two accessories and seven rare spp. (i.e., deletions in 2024 in relation to winter 2014). Based on the CI and categorization of species by algal group, 24 species were constant, being eight Ulvophyceae, four Phaeophyceae, and 12 Rhodophyta. Thus, a total of 26 species were accessory, being the majority Rhodophyta (20). Rare species prevail (42), with highly representative taxa also within reds (27).

3.2 Abiotic data

The Annual mean sea surface temperature (SST) retrieved from Paraná coastal shelf region from 2004 to 2024 (Fig. 3) showed a clear warming trend of $0.013^{\circ}\text{C year}^{-1}$ corresponding to an increase of 0.3°C between the compared decades (2014 and 2024). The Figs. 3 and 4 shows that the SST pattern increased over a decade during the austral summer and winter months, align the sampling site. Although there was great variation in the interannual means, it is still possible to observe a gradual increase in the SST.

The seasonal spatial patterns of SST along the coastal shelf of SWAO (Fig. 4) where the white dot indicates the sampling site (Paraná State) in the ODV map show between 2005–2014 registered for SST $26.4 \pm 0.02^{\circ}\text{C}$ in summer and $20.8 \pm 0.02^{\circ}\text{C}$ in winter and for the period between 2015–2022; and registered during winter a mean and SD of $21.9 \pm 0.4^{\circ}\text{C}$ and during summer, $24.2 \pm 0.3^{\circ}\text{C}$. Data obtained in the same database between 2023–2024 ranged from 22 and 28°C during winter and summer, respectively. Currently, during summer the SST anomaly is $2 \pm 0.2^{\circ}\text{C}$ higher than in the previous decade along Paraná Coast. Significant differences were observed in the annual averages for the winter months between 2010–2014 and 2020–2024 ($t = -2.61$; $df = 918$; $p = 0.009$).

For more accuracy of the data, we also monitored SST *in situ* during 2013–2014 and 2023–2024 sampling surveys. Along 2013–2014 the values ranged from $20.5 \pm 1.2^{\circ}\text{C}$ to $25.2 \pm 1.1^{\circ}\text{C}$ during winter and summer, respectively; and along 2023–2024, between $23 \pm 0.2^{\circ}\text{C}$ to $27.5 \pm 0.3^{\circ}\text{C}$. The SST mean anomaly measured *in situ* (coastal area adjacent to the rocky shore) was of 2.3°C . The salinity data along Farol Island ranged in both decades from 30 ± 2 during summer to 32 ± 1 psu during winter.

Considering a ten-years span analysis, the cold waves reaching South Brazil showed a lower frequency between 2015 and 2025 (Fig. 5); however, the intensity and frequency of marine heatwaves (MHW) enhanced significantly (Fig. 5a, b). From 2013 onwards, 12 ± 3 MHW events were observed along the southern Brazilian coast (SWAO), representing twice of the average number of events recorded between 2003 and 2012. Furthermore, from 2016 onwards, minimum three severe events were recorded, being one longer in duration of extreme category (Fig. 5b).

The statistical analysis of SST and MHW (frequency, duration, and intensity) time-series data (2005–2025) from the Paraná coast considering average (daily and annual) are presented in Table 2 and Fig. 6

(a, b).

Table 2

Frequency of MHW (F), intensity anomaly means (I_{mean}) and maximum (I_{max}), the average of MHW duration, expressed in days, (D_{mean}) and maximum duration (I_{max}) classified into four categories, and the proportion of time spent (P%) by 5-year period (2005–2025). md: moderate, st: strong, se: severe e ex: extreme

Period	N MHW	I_{mean} (°C)	I_{max} (°C)	D max	D mean	P _{md} (%)	P _{st} (%)	P _{se} (%)	P _{ex} (%)
2005– 2010	18	1,99	3,54	19	14,7	50	50	-	-
2011– 2015	17	2,12	2,78	39	15,5	47	53	-	-
2016– 2020	20	1,84	2,72	53	20	55	40	5	-
2021– 2025	17	1,78	2,34	51	14	82,3	17,7	-	-

Over the past 20 years the areas experienced a mean annual SST increase of $2 \pm 0.2^{\circ}\text{C}$, mainly during summer. A total of 72 MHW events were identified, being 42 classified as “moderate”, 29 as “Strong” and one “severe”. Regarding these last two categories the mean intensity (ANOVA: $df = 26$, $F = 14.93$, $p = 0.00001$), duration (ANOVA: $df = 25$, $F = 4.17$, $p = 0.0158$) were significantly increased along the time. From 2011 to 2025, when we observed the richness seasonal inversion and changes in the composition of the assemblages (dominated by rare species), were recorded 33 events as moderates and 20 as strong. The number (frequency) of moderated events has gradually increased from 8 to 14 in five years. One severe MHW was recorded in 2016, lasting 22 days (April 6–27).

The current seasonal inversion in the seaweed richness patterns, mainly for Rhodophyta and Phaeophyceae (Fig. 1), as well as the shift observed between 2014 and 2024 surveys, coincided with changes in SST during summer (Fig. 3), and mainly with the higher MHW frequency and duration (Fig. 5b). Regarding Phaeophyceae there was a reduction in species richness during summer in 2024, compared to 2014. Autumn and winter events of strong and severe MHWs have become more frequent since 2014 and continue to the present day (Fig. 5c, and 6).

4 Discussion

The present contribution reveals an intriguing seasonal richness pattern inversion of seaweed assemblages in the SWAO, in a decadal time-lapse, suggesting that assemblages are moving to thermally more suitable seasons, besides signaling resilience mechanisms to thermal stress and adaptation ability to the current new patterns of the environmental conditions (SST anomalies, frequent and intense events of MHW). The assemblages of Farol Island in 2014 survey showed a higher richness

in summer compared to the winter. In contrast, 2024 data recorded greater richness during winter, particularly for Rhodophyta and Ulvophyceae. Phaeophyceae, typically associated with cooler conditions and oligotrophy, showed lower richness in the summer of 2024 compared to 2014.

This seasonal inversion is consistent with thermal variability (SST anomalies / MHW events), suggesting these factors as potential drivers for the redistribution observed. Similarly, Chefaoui et al. (2024) investigated the SST related factors (gradual warming, MHW, seasonality) that explain persistence and local deletion of macroalgae taxa using baseline survey and a resurvey of macroalgae.

These richness and compositional patterns, using data generated with comparable taxonomic resolution, as well as the seasonal redistribution of the entire algal assemblage were unprecedentedly reported for Southern Brazil, SWAO. Rhodophyta richness during the winter of 2024 approximately double compared to richness recorded in 2014. The shift and biotic responses seem consistent with thermal changes data compiled here, SST and MHW (Figs. 4 and 5).

Similar patterns have been reported for brown algae at higher latitudes where gradual SST increases have been linked with *Ecklonia radiata* and *Scytothalia dorycarpa* populations shifts in Western Australia (Wernberg et al. 2016), and poleward “migration” in kelp assemblages (Thomsen et al. 2019; Ryder et al. 2026). In comparison, our data showed approximately 30% reduction in Phaeophyceae richness in 2024 summer. Pellizzari et al. (2023, 2025) reported changes in seaweed richness around the Antarctic Peninsula, suggesting that new species records may reflect expansion in distributional ranges linked to abiotic changes, and or introductions, between the Southern Hemisphere and Antarctica, or vice-versa.

Besides new species records can also reflect redistribution of seaweed species among ecoregions, potentially linked to meteoceanographic related effects, such as frequent and intense MHWs (Pellizzari et al. 2025). According to Wernberg et al. (2025) species thermal tolerance generally occurs through their latitudinal distributions, making those narrow ranges of populations near warm distribution limits particularly vulnerable to acute thermal stress.

Our field data suggest that Rhodophyta may be particularly sensitive to thermal variability, mainly considering higher richness of rare taxa. Experimental studies in Brazil conducted by Nauer et al. (2022) have shown that abrupt temperature increases can affect red macroalgae under both laboratory and field-deployed mesocosms conditions. The authors assessed the response on *Hypnea pseudomusciformis* to simulated MHW by exposing populations to temperature increase of + 2, +4, and + 6°C, and observed that populations from different latitudes exhibited distinct physiological responses. Tropical and transitional populations were more affected under higher thermal stress, whereas warm-temperate populations showed greater recovery capacity. These results suggest that tropical and subtropical populations of *H. pseudomusciformis* may be more vulnerable to acute thermal stress.

Borburema et al. (2025) examined the agarophytes *Gracilaria caudata* and *G. birdiae* from northeastern Brazil and reported species- and season-dependent responses facing MHW conditions. Specimens were cultured at 25°C (rainy season conditions), and 28°C (dry season conditions) before exposure to

temperature increases like those used by Nauer et al. (2022). Both species showed reduced growth and effective quantum yield under thermal stress with stronger declines following dry-season conditions, particularly in *G. birdiae*.

Our comparative data, a decade apart, indicates an overall reduction in species richness during summer of 2024 (Fig. 1). Ulvophyceae richness decline in summer and winter, except for *Ulva lactuca* and *Caulerpa fastigiata*, recognized as opportunistic taxa in coastal areas, and dominant in both periods analyzed. Such variation may reflect shift in detectability or seasonal suitability. Experimental projections suggest that *U. lactuca* may benefit from future warming conditions maintaining or enhancing photosynthetic performance under short-term thermal stress (Resende et al. 2025), consistent with its eco-physiological plasticity and green tides intensification.

Macroalgal distribution is influenced by multiple environmental drivers (Schermer et al. 2013). Seasonal and perennial life histories further contribute to variability in richness patterns. Previous studies from southern Brazil also reported higher richness during summer, including Arvoredo Island (Santa Catarina State) and coastal islands in Paraná State (Pascelli et al. 2013; Pellizzari et al. 2014), whereas our 2024 survey recorded greater richness in winter. Richness patterns vary with latitude and season, and these differences reflect environmental conditions at the time of sampling, mainly influenced by thermal stress, besides nutrients, light availability, and herbivory pressure.

Seasonal changes observed in algal composition at Farol Is. indicates different community structure after ten years, with many taxa represented by low-frequency occurrences. Species losses, replacements, and new records (NR) between 2014 and 2024 suggest variability in assemblage composition across sampling periods. Dissimilarity analysis suggests that summer assemblages of Ulvophyceae and Phaeophyceae richness were lower. Rhodophyta composition also differs between winter surveys (2014 and 2024), with higher richness recorded during the summer 2024 (Fig. 2).

Overall macroalgal richness recorded in 2024 along Farol Isl. survey was higher including eight new records. Seasonal differences were evident, with greater richness observed in the winter of 2024 compared to higher summer richness of 2014. These findings expand the regional checklist to approximately 150 taxa and reinforce the ecological relevance of this even urbanized island as a diverse macroalgal habitat.

Coastal urbanization was often associated with macroalgal loss and community shifts in the Atlantic (Schermer et al. 2013). However, differences observed between the 2014 and 2024 surveys at Farol Island may reflect probably thermal variability rather than urban pressure alone. Located near the outer sector of Guaratuba Bay, Farol Isl. macroalgal assemblages are likely influenced by estuarine inputs and nutrient enrichment, suggesting also tolerance to eutrophication.

Field observations are important for detecting ecological changes associated with climate variability, but establishing casual links often requires experimental evidence and broader environmental datasets (Pineiro-Corbeira et al. 2018). These authors suggested thermal sensitivity as the main driver of algal

distributional changes NW Iberian coast. Similar responses have been reported for Brazilian species. Faria & Plastino (2022), reported that *Gracilariopsis tenuifrons* tolerated temperatures between 18–30°C but not 35°C, indicating latitudinal ecotypes associated with thermal conditions. Their results suggested that warming could shift the species' distribution toward higher latitudes. At broader scales, changes in macroalgal communities have been documented along Brazilian coast, including decadal losses of canopy-forming *Sargassum* species in warm-temperate regions (Gorman et al. 2020). Reviews of climate-related seaweed responses frequently highlight taxa such as *Gracilaria* and *Sargassum* as potentially sensitive indicators of environmental change (Segaran et al. 2023), both species are conspicuous along our sampling sites.

Compiled environmental data indicate increased SST, and MHW events more frequent and intense along Paraná coast over the past decade (Figs. 3 and 4). This period also coincides with biotic differences observed between 2014 and 2024 surveys, including seasonal changes in richness, and shifts in species composition, such as new records and species absences (Fig. 1, Table 1).

Relationship of the phycological patterns and MHW frequency and intensity remains challenging because is indirect and may involve delayed responses. The MHW events occurring in spring season may influence summer assemblages rather than immediate seasonal conditions. Our environmental datasets indicate that summer SST anomalies along Paraná coast were up to 2°C higher during 2015 and 2024 compared to the previous decade. Also, intensity and frequency of MHW during this period increased 35–40% in moderate and in extreme events (Fig. 3, 4), besides two severe events combined with reduction in cold-spells events in the analyzed decade.

These patterns are consistent with broader warming trends reported globally (IPCC 2023) and with regional observations from Santos estuarine system in São Paulo (Marochi et al. 2022), and along Paranaguá Estuarine Complex (Bettim et al. 2025), located approximately 35 km from Farol Isl. Bettim et al. (2025) evaluated the effects of strong MHWs on benthic meiofauna in PEC, and reported increases in the intensity, duration, and frequency of MHWs between 1982 and 2023. Approximately 67% of the species examined showed negative responses to these events, and delayed effects, including reduced benthic invertebrates' density in subsequent years. Some responses indicate that even when communities show signs of resilience, shifts in species composition may alter ecosystem functioning.

Interpretations of MHW impacts can be misleading if cumulative effects are not considered (Ishida et al. 2023). Species richness, biomass, or composition may appear stable immediately after heating events, while longer-term monitoring may reveal declines in benthic communities. Ours results suggested a shift in macroalgal community composition and richness comparing the analyzed years, coinciding with enhancing in SST, and more frequent and long lasting strong and severe MHW events detected prior to 2024 (with higher heatwave intensity and mean event duration), compared to 2014 and decade before (Figs. 5 and 6), what is consistent with the evidence that changes in MHW regimes can reorganize macroalgal assemblages over decadal scales (Smith et al. 2024; Pellizzari et al. 2025; Mazzuco et al. 2026). This reorganization may reflect the ecological effects of increasingly thermal stress, which are

known to drive physiological stress, changes in competitive interactions, and differential interspecific / algal group tolerance (Hesse et al. 2025).

This study provides field observation in SWAO, a region where the potential ecological effects of SST and MHW (Figs. 4 and 5) remains less documented compared to temperate and polar regions (Wernberg et al. 2016; Pellizzari et al. 2025). Contributions have reported multiple impacts of MHW on seaweed communities, including in composition, mainly in branched and crustose coralline algae (CCA), kelp forests and turf-forming algae (Straub et al. 2019; Smith et al. 2020; Ryder et al. 2026). In addition, Brijis et al. (2025) studies from warmer regions reports the collapse of herbivorous fish control of invasive *Caulerpa* spp. during MHW event. Straub et al. (2019) reported that turf-forming seaweeds often increased in abundance following MHW events, whereas native canopy-forming typically declined. In comparison, the assemblages recorded at Farol Island in 2014 and 2024 showed the predominance of opportunistic species. Similarly, the species that were listed in 2014, but not in 2024, were composed mainly by representatives from the upper intertidal zone, suggesting potential ecological substitutions as described by Straub et al. (2019). The seaweed species zonation, as well as composition, under thermal stress is a gap to be further investigated.

Wernberg and Straub (2024) highlighted that in addition to increasing MHW, human activities are causing coastal darkening through turbidity, driving interacting-multiple stressors for algae assemblages. In experimental studies on kelps, temperature was the main cause of physiological decline with negative effects observed under intense heatwave conditions (28°C) promoting tissue bleaching, as also observed in calcareous algae from Farol Isl. mainly during summer 2024. The authors also observed that high turbidity amplified the negative effects who's persisted even after temperatures returned to background levels; besides emphasize the importance of considering multiple stressors in MHW evaluations for accurate readings of the impacts on these assemblages. Given that Farol Island experiences tourism pressure during summer, local macroalgal assemblages may also be influenced by multiple stressors, and further investigation is recommended.

The scientific challenge disentangling the major effects from those of co-occurring stressors including changes in ocean circulation, increasing herbivory, changes in nutrient concentration and turbidity, irradiance and desiccation stress along the intertidal zones. With the projected increase of intensity, duration and frequency of MHWs, subtropical seaweed assemblages may experience shifts in community structure in cascade effect, potentially favoring opportunistic taxa such as filamentous and foliaceous green algae over long-lived fleshy or calcareous species reducing habitat complexity. Although relatively few studies have examined impacts of MHWs on seaweed from subtropical coastal areas, our range of compositional and decadal richness changes highlights the need of improved baseline data and continuous monitoring for better understanding seaweed's vulnerability and resilience facing climatic disturbances. More intense or prolonged MHW can favor thermally tolerant taxa while reducing the occurrence of sensitive species (Smith et al. 2024). Consistent findings from other regions including Southern Hemisphere polar assemblages (Pellizzari et al. 2025), and our dataset indicate an increase in MHWs occurrence in the SWAO, particularly in Southern Brazilian coast.

Thus, the present study suggests changes in Paraná algal assemblages that probably will drive another side effects in the entire local marine community structure. We are aware of some limitations of the study that lie in biological analyses were based on species composition and richness, not including the abundance, percent cover and biomass. Consequently, changes in richness may also reflect the appearance or disappearance of some rare taxa rather than substantial shifts in ecosystem functioning. On the other hand, we report several new species records, and a high number of Rhodophyta rare taxa. Also, given the substantial taxonomic revisions that have occurred in many algal groups over the last decade in the Brazilian coast, some component of the observed turnover may reflect improved taxonomic resolution rather than ecological change. Besides, our data considered only the isolated influence of thermal anomalies and MHW. Despite knowing that these are the main driver of changes, considering multiple drivers that may pressure seaweed assemblages nowadays is recommended for greater robustness of the inferences. Thus, the significance of the reported “seasonal inversion” should be interpreted with caution, and continuous monitoring and further data will be necessary to confirm our hypothesis. Also, our analysis was based on a limited number of temporal samples, and results should be interpreted cautiously and primarily as an indication of possible associations between thermal patterns and macroalgal structure rather than causality definitive evidence. Longer time series and broader sampling would be necessary to robustly assess the influence of MHW on community dynamics.

Although understanding macroalgal responses to thermal stressors remains complex, this study highlights potential ecological new trends. Finally, facing the given scarcity of ecological studies on macroalgal communities from SWAO, biotic shifts were discussed, filling and detecting gaps regarding marine conservation issue and their connections with thermal changes, and improving the understanding of the current stressors. Besides expanding and updating the regional algal diversity database and reporting new records, valuable baseline to support further long-term monitoring efforts.

Declarations

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Author contributions **F Pellizzari** -- conceptualization, funding acquisition, methodology, project administration, sampling coordination, biotic and abiotic data curation, morphological analysis, investigation, validation, original draft writing. **M Santos-Silva** -- sampling, laboratorial and numerical analysis, abiotic data acquisition validation, and review. **KC Santos** -- samplings, numerical data acquisition, editing. **Y Tavares** -- review and editing, biotic and abiotic data statistical and numerical analysis. **NS Yokoya** -- analysis, review and editing. **P Convey** -- review and editing, biotic and abiotic data curation and validation. All authors discussed the results.

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Data Availability The data that support the findings of this study are open-source and available from the following resources: AWI (<https://explore.webodv.awi.de>), US NOAA Global Climatology Network (<https://www.ncdc.noaa.gov/cdo-web/>), NOAA Atlas <https://www.ncei.noaa.gov/access/metadata>), Marine heatwaves Tracker (<https://www.marineheatwaves.org>), Copernicus Marine Services (<https://marine.copernicus.eu/about/producers/sst-tac>)

Conflict of interest The authors declare no conflict of interest.

References

1. Airolidi L, Beck MW (2007) Loss, status and trends for coastal marine habitats of Europe. *Ocean Mar Biol: Annual Rev* 45:345–405. <https://doi.org/10.1371/journal.pone.0010791>
2. ARGO (2024) Argo float data and metadata from Global Data Assembly Centre (Argo GDAC). SEANOE. <https://doi.org/10.17882/42182>
3. Azarian C, Bopp L, Pietri A, Sallée JB, D'Ovidio F (2023) Current and projected patterns of warming and marine heatwaves in the Southern Indian Ocean. *Prog Oceanogr* 215. <https://doi.org/10.1016/j.pocean.2023.103036>
4. Baselga A, Leprieur F (2015) Comparing methods to separate components of beta diversity. *Methods Ecol Evol* 6(9):1069–1079. <https://doi.org/10.1111/2041-210X.12388>
5. Bettim AL, Marochi MZ, Metri R, Guilherme PD (2025) Impacts of marine heatwaves on benthic estuarine populations. *Clim Change* 178. <https://doi.org/10.1007/s10584-025-04022-2>
6. Brijs J, Tran LL, Moore C, Souza T, Schakmann M, Grellman K, Johansen JL (2025) Outlasting the Heat: Collapse of Herbivorous Fish Control of Invasive Algae During Marine Heatwaves. *Glob Change Biol* 31:8. <https://doi.org/10.1111/gcb.70438>
7. Borburema HDS, Almeida-Faria G, Silveira SLC, Sávio LC, Gomes VS, Nauer F, Soriano EM (2025) Agarophyte seaweeds exhibit differential responses to marine heatwaves depending on the species and climatic season. *J Appl Phycol* 37:1479–1491. <https://doi.org/10.1007/s10811-025-03460-w>
8. Briggs CJ, Blanchette CA, Lubchenco J, Hacker SD (2021) Habitat attributes mediate herbivory and influence community development in algal metacommunities. *J Ecol* 109:913–925. <https://doi.org/10.1111/1365-2745.13520>

9. Chefaoui RM, Martínez BDC, Viejo RM (2024) Temporal variability of sea surface temperature affects marine macrophytes range retractions as well as gradual warming. *Sci Rep* 14(1):14206
10. Choi HY, Park MS, Kim HS et al (2024) Marine heatwave events strengthen the intensity of tropical cyclones. *Commun Earth Environ* 5:69. <https://doi.org/10.1038/s43247-024-01239-4>
11. Cotas J, Gomes L, Pacheco D, Pereira L (2023) Ecosystem Services Provided by Seaweeds. *Hydrobiology* 2:75–96. <https://doi.org/10.3390/hydrobiology2010006>
12. Duarte M, Sanhueza N, Vásquez JA, Tala F, González AV (2025) Kelps on the move: Potential future distribution areas in the face of climate change, on the Pacific coast of South America. *PLoS ONE* 20(9):e0332591. <https://doi.org/10.1371/journal.pone.0332591>
13. European Union EUCMS (2024) E.U. Copernicus Marine Service Information (CMEMS). 10.48670/moi-00101. Accessed on 29 Jun 2026) Copernicus Marine ServiceGlobal Ocean OSTIA Sea Surface Temperature and Sea Ice Analysis
14. Faria AVF, Plastino EM (2022) Ecotypic differentiation in populations of Brazilian coast: recognizing adaptation to temperature in *Gracilariopsis tenuifrons*. *Rhodophyta) J Appl Phycol* 34:2793–2805. <https://doi.org/10.1007/s10811-022-02721-2>. Gracilariales
15. Faria AVF, Martins NT, Ayres-Ostrock LM, Gurgel CFD, Plastino EM (2023) Phylogeography of the red alga *Gracilariopsis tenuifrons* (Gracilariales) along the Brazilian coast. *J Phycol* 59:1041–1052. <https://doi.org/10.1111/jpy.13363>
16. Ferreira AP, Chow F, Machado GBO, Leite FPP (2026) Changes in macroalgal palatability and herbivore's behavior under ocean warming scenarios: consequences for top-down control. *Mar Environ Res* 213. <https://doi.org/10.1016/j.marenvres.2025.107667>
17. Gao G, Zhao X, Jiang M, Gao L (2021) Impacts of Marine Heatwaves on Algal Structure and Carbon Sequestration in Conjunction with Ocean Warming and Acidification. *Front Mar Sci* 8. <https://doi.org/10.3389/fmars.2021.758651>
18. Gianelli I, Orlando L, Cardoso LG et al (2023) Sensitivity of fishery resources to climate change in the warm-temperate Southwest Atlantic Ocean. *Reg Environ Change* 23:49. <https://doi.org/10.1007/s10113-023-02049-8>
19. Gissi E, Manea E, Mazaris AD, Frascchetti S, Almpnidou V, Bevilacqua S, Coll M, Guarnieri G, Lloret-Lloret E, Pascual M, Petza D, Rilov G, Schonwald M, Stelzenmüller V, Katsanevakis SA (2021) A review of the combined effects of climate change and other local human stressors on the marine environment. *Sci Total Environ* 755(1). <https://doi.org/10.1016/j.scitotenv.2020.142564>
20. Good SA, Embury O (2024) ESA Sea Surface Temperature Climate Change Initiative (SST_cci): Level 4 Analysis product, version 3.0. NERC EDS Centre for Environmental Data Analysis, 09 April 2024. 10.5285/4a9654136a7148e39b7feb56f8bb02d2
21. Goes M, Dong S, Foltz GR, Goni G, Volkov DL, Wainer I (2024) Modulation of western South Atlantic marine heatwaves by meridional ocean heat transport. *J Geophys Research: Oceans* 129. <https://doi.org/10.1029/2023JC019715>

22. Gorman D, Horta PH, Flores AAF, Turra A, Berchez FAS, Batista MB, Lopes Filho ES, Melo MS, Ignacio BL, Carneiro IM, Villaça RC, Széchy MTM (2020) Decadal losses of canopy-forming algae along the warm temperate coastline of Brazil. <https://doi.org/10.1111/gcb.14956>. *Global Change Biology*
23. Gouvea LP, Schubert N, Martins SDL, Sissini M, Ramlov F, Rodrigues ER, Bastos EO, Freire VC, Maraschin M, Simonassi JC, Varela DA, Franco D, Cassano V, Fonseca AL, Barufi BJ, Horta PA (2017) Interactive effects of marine heatwaves and eutrophication on the ecophysiology of a widespread and ecologically important macroalga. *Limnol Oceanogr*. <https://doi.org/10.1002/lno.10551>
24. Grenno FE, Santos CZ, Schiavetti A, Profice CC (2023) NGO scientific collaboration networks for marine conservation in the southern cone: A case study. *Environ Sci Policy* 148. <https://doi.org/10.1016/j.envsci.2023.103554>
25. Guiry MD (2024) How many species of algae are there? A reprise. Four kingdoms, 14 phyla, 63 classes and still growing. *J Phycol* 60:214–228. <https://doi.org/10.1111/jpy.13498>
26. Guiry MD, Guiry GM (2026) AlgaeBase. World-wide electronic publication, National University of Ireland, Galway. <https://www.algaebase.org>. Accessed 13 April 2026
27. Hanley ME, Firth LB, Foggo A (2024) Victim of changes? Marine macroalgae in a changing world. *Ann Botany* 133:1–16. <https://doi.org/10.1093/aob/mcad185>
28. Hesse L, Weiss M, Mezger SD, El-Khaled YC, Mueller B, Lago AK, Schwarzmeier M, Wild C (2025) Different photosynthetic responses to heat and light favors green and red over brown macroalgae in the mediterranean sea. *Sci Rep* 15:42556. <https://doi.org/10.1038/s41598-025-28235-8>
29. Hobday AJ, Alexander LV, Perkins SE, Smale DA, Straub SC, Oliver ECJ, Benthuyssen JA, Burrows MT, Donat MG, Feng M, Holbrook NJ, Moore PJ, Scannell HA, Gupta AS, Wernberg T (2016) A hierarchical approach to defining marine heatwaves. *Prog Oceanogr* 141:227–238. <https://doi.org/10.1016/j.pocean.2015.12.014>
30. Hobday AJ, Oliver ECJ, Gupta AS, Benthuyssen JA, Burrows MT, Donat MG, Holbrook NJ, Moore PJ, Thomsen MS, Wernberg T, Smale DA (2018) Categorizing and naming marine heatwaves. *Oceanography* 31:162–173. <https://doi.org/10.5670/oceanog.2018.205>
31. Horinouchi Y, Mochizuki K, Ichihara K, Togashi T (2024) In a grain of sand: An overlooked over-summering habitat of macroalgae. *Ecology* 105. <https://doi.org/10.1002/ecy.4447>
32. IPCC (2023) Climate change 2023: Synthesis report. In: Lee H, Romero J (Eds.) Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change pp. 35–115 <https://doi.org/10.59327/IPCC/AR6-9789291691647>
33. Ishida K, Tachibana M, Yao Y, Wada Y, Noda T (2023) The impact of marine heatwaves on rocky intertidal communities: evidence of accumulative carryover effects of marine heatwaves. *Front Mar Sci*. <https://doi.org/10.3389/fmars.2023.1146148>
34. Marochi MZ, Grande FR, Pardo JCF, Montenegro A, Costa TM (2022) Marine heatwave impacts on newly hatched planktonic larvae of an estuarine crab. *Estuar Coast Shelf Sci* 278:108122. <https://doi.org/10.1016/j.ecss.2022.108122>

35. Mazzuco ACZ, Gaurisas DY, Vassoler A, Coppo GC, Pacheco CFO, Araujo GAA, Alves FMM, Bernardino AF (2026) Marine heatwaves shift intertidal marine communities in the SW Atlantic. *PeerJ* 14 <http://doi.org/e20858.10.7717/peerj.20858>
36. Nychka D, Furrer R, Paige J, Sain S (2017) fields: Tools for spatial data. R package version 10.3. <https://github.com/NCAR/Fields>
37. Nauer F, Oliveira MC, Plastino EM, Yokoya NS, Fujii MT (2022) Coping with heatwaves: How a key species of seaweed responds to heat stress along its latitudinal gradient. *Mar Environ Res*. <https://doi.org/10.1016/j.marenvres.2022.105620>. 177
38. Nogueira NCO, Reboita MS, Drumond A (2026) Sea Surface Temperature Variability in the South Atlantic Ocean and Its Connection to the South American 1991–2020 Climate. *J Mar Sci Eng* 14(3):283. <https://doi.org/10.3390/jmse14030283>
39. Ortiz M, Nunes BH, Jordan F (2020) Trophic Networks and Ecosystem Functioning. In: Gómez I, Huovinen P (eds) *Antarctic Seaweed*. Springer. pp 309–330 https://doi.org/10.1007/978-3-030-39448-6_16
40. Pierce D (2019) ncdf4: Interface to Unidata netCDF (Version 4 or Earlier) Format Data Files. R package version 1.17. <https://doi.org/10.32614/CRAN.package.ncdf4>
41. Pascelli C, Riul P, Riosmena-Rodríguez R, Scherner F, Nunes M, Hall-Spencer JM, Oliveira EC, Horta PA (2013) Seasonal and depth-driven changes in rhodolith bed structure and associated macroalgae off Arvoredo island (southeastern Brazil). *Aquat Bot* 111:62–65. <https://doi.org/10.1016/j.aquabot.2013.05.009>
42. Pellizzari FM, Bernardi J, Silva EM, Santos-Silva MC, Yokoya NY (2014) Benthic marine algae from the insular areas of Paraná, Brazil: new database to support the conservation of marine ecosystems. *Biota Neotrop* 14. <https://doi.org/10.1590/1676-060320140615183049>
43. Pellizzari FM, Santos-Silva MC, Silva EM, Oliveira MC, Yokoya NS, Pupo D, Rosa LH (2017) Diversity and spatial distribution of seaweeds in the South Shetlands Islands, Antarctica: an update database for environmental monitoring under climate change scenarios. *Polar Biol* 40:1671–1685. <https://doi.org/10.1007/s00300-017-2092-5>
44. Pellizzari FM, Rosa LH, Yokoya NS (2020) Biogeography of Antarctic Seaweeds Facing Climate Changes. In: Gómez I, Huovinen P (eds) *Antarctic seaweeds*, 1st edn. Springer, pp 83–102. https://doi.org/10.1007/978-3-030-39448-6_5
45. Pellizzari FM, Mello JPS, Santos-Silva MC, Osaki VS, Brandini FP, Convey P, Rosa LH (2023) New records and update distributional patterns of macroalgae from the South Shetland Islands and Weddell Sea. *Antarct Sci* 35:1–13. <https://doi.org/10.1017/S095410202300010X>
46. Pellizzari FM, Santos KC, Osaki VS, Rosa LH (2025) Marine heatwaves and changes in macroalgae richness and composition from Antarctic Peninsula and South Shetland Islands: concise review. *Annals Brazilian Acad Sci* 97:e20240580. <https://doi.org/10.1590/0001-3765202520240580>
47. Pellizzari FM, Oliveira MC, Yokoya NS, Mansilla A, Marambio J, Küpper FC, Convey P (2026) Antarctic and Arctic Seaweeds: Reassessing Diversity, Ecophysiological Adaptations, and Changes in

- Biogeographical Distribution as a Survival Strategy Facing Meteorological Changes. In: Fernandes-Duarte AW, Passarini MRZ, Elster J, Singh PK, Kumar A (eds) Polar Microbes and Climate Change. Springer. https://doi.org/10.1007/978-3-032-07096-8_3
48. Perez R, Garzoli S, Hummels R, Ansorge I (2023) Inclusive science in the South Atlantic. *Commun Earth Environ* 4:11. <https://doi.org/10.1038/s43247-022-00646-9>
 49. Piñeiro-Corbeira C, Barreiro R, Cremades J, Arenas F (2018) Seaweed assemblages under a climate change scenario: Functional responses to temperature of eight intertidal seaweeds match recent abundance shifts. *Science Report* 8:12978 <https://doi.org/10.1038/s41598-018-31357-x>
 50. R Development Core Team (2024) A language and environment for statistical computing. (Version 4.04.4) [Software]. R Foundation for Statistical Computing, Vienna (Austria). <https://www.R-project.org/>
 51. Reagan JR, Boyer TP, García HE, Locarnini RA, Baranova OK, Bouchard C, Cross SL, Mishonov AV, Paver CR, Seidov D, Wang Z, Dukhovskoy D (2024) World Ocean Atlas 2023. NOAA National Centers for Environmental Information, Dataset. Accession 0270533
 52. Resende JFJ, Bezerra JNS, Borburema HDS, Oliveira VP (2025) Future environmental scenarios favor the performance of *Ulva lactuca* – Implications for the intensification of green tides. *Mar Environ Res*. <https://doi.org/10.1016/j.marenvres.2025.107262>. 210
 53. Schlegel RW, Smit AJ (2018) heatwaveR: A central algorithm for the detection of heatwaves and cold-spells. *J Open Source Softw* 3:821. 10.21105/joss.00821
 54. Scherner F, Horta PA, Oliveira EC, Simonassi JC, Hall-Spencer JM, Chow F, Nunes JMC, Pereira SMB (2013) Coastal urbanization leads to remarkable seaweed species loss and community shifts along the Southwestern Atlantic. *Mar Pollut Bull* 76:106–115. <https://doi.org/10.1016/j.marpolbul.2013.09.019>
 55. Segaran TC, Azra MN, Handayani KS, Lananan KF, Xu J (2023) Seaweed and climate change: A mapping review. *Mar Environ Res* 190:106216. <https://doi.org/10.1016/j.marenvres.2023.106216>
 56. Smith KE, Aubin M, Burrows MT, Filbee-Dexter K, Hobday AJ, Holbrook NJ, King NG, Moore PJ, Gupta SA, Thomsen M, Wernberg T, Wilson E, Smale DA (2024) Global impacts of marine heatwaves on coastal foundation species. *Nat Commun* 15:50–52. 10.1038/s41467-024-49307-9
 57. Smith JN, Mongin M, Thompson A, Jonker MJ, Da'th G, Fabricius KE (2020) Shifts in coralline algae, macroalgae, and coral juveniles in the Great Barrier Reef associated with present-day ocean acidification. *Glob Change Biol*. <https://doi.org/10.1111/gcb.14985>
 58. Straub SC, Wernberg T, Thomsen MS, Moore PJ, Burrows MT, Harvey BP, Smale DA (2019) Resistance, Extinction, and Everything in Between – The Diverse Responses of Seaweeds to Marine Heatwaves. *Frontiers in Marine Science*. Sec. Global Change and the Future Ocean 6 <https://doi.org/10.3389/fmars.2019.00763>
 59. Tavares YAG, Semanovich NP, Camargo JCM, Pellizzari FM (2020) Feeding habits of the sea urchin *Echinometra lucunter* L. (Echinoidea) in a remote Southwestern Atlantic Island, Trindade, Brazil. *Pan-American J Aquat Sci* 15:303–319

60. Vergara-Carranza C, López N, Piñón-Gimate A (2024) Use of intertidal macroalgae as bioindicators of anthropogenic nutrient disturbance in the rocky coasts of the tropical central Mexican Pacific. <https://doi.org/10.7773/cm.y2024.3416>. Ciencias Marinas 50

61. Wernberg T, Straub SC (2024) Low light exacerbates effects of marine heatwaves on seaweeds. Mar Ecol Prog Ser 747:49–59. <https://doi.org/10.3354/meps14695>

62. Wernberg T, Thomsen MS, Burrows MT, Filbee-Dexter K, Hobday AJ, Holbrook NJ, Montie S, Moore PJ, Oliver ECJ, Gupta AS, Smale DA, Smith K (2025) Marine heatwaves as hot spots of climate change and impacts on biodiversity and ecosystem services. Nat Reviews Biodivers 1:461–479. <https://doi.org/10.1038/s44358-025-00058-5>

63. Wernberg T, Bennett S, Babcock RC, de Bettignies T, Cure K, Depczynski M, Dufois F, Fromont J, Fulton CJ, Hovey RK, Harvey ES, Holmes TH, Kendrick GA, Radford B, Santana-Garcon J, Saunders BJ, Smale DA, Thomsen MS, Tuckett CA, Tuya F, Vanderklift MA, Wilson S (2016) Climate-driven regime shift of a temperate marine ecosystem. Science 353:169–172. <https://doi.org/10.1126/science.aad8745>

64. Wickham H (2016) ggplot2: Elegant Graphics for Data Analysis. Springer-, New York

Figures

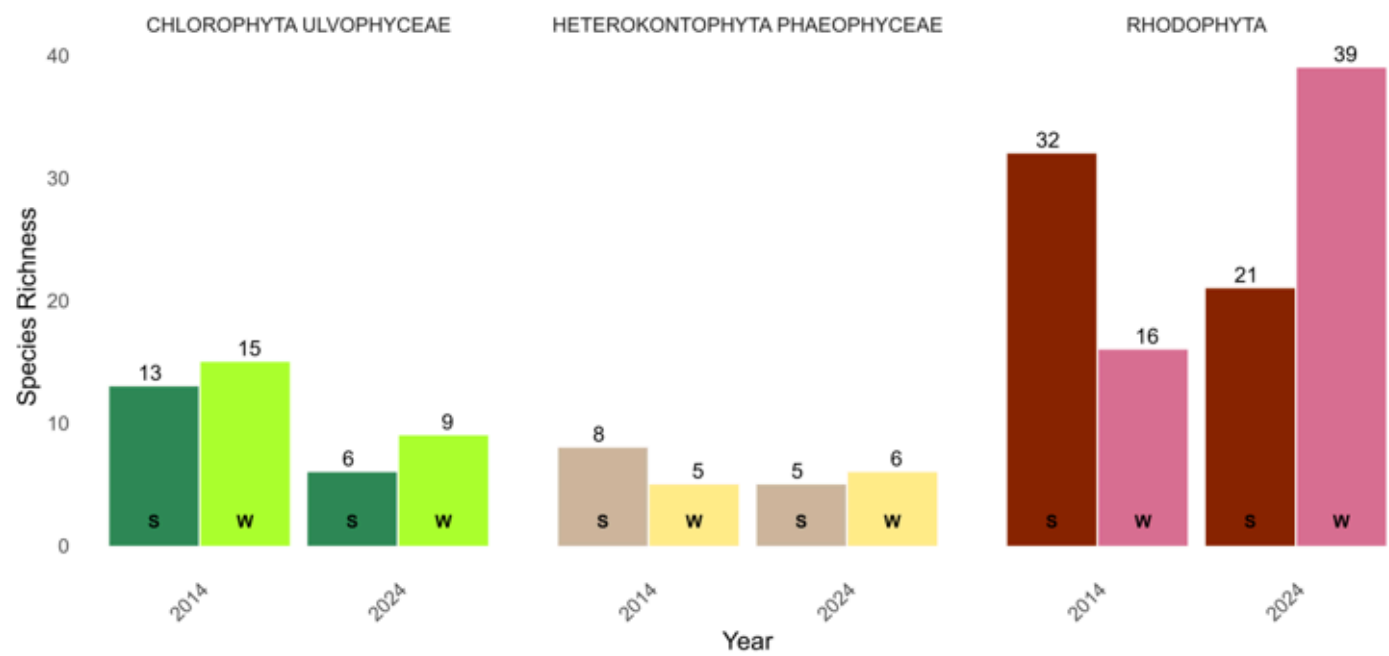


Figure 1

Ten years apart seasonal seaweed species richness (by algal group) previously reported for Farol Island (Pellizzari et al. 2014), compared with the present survey (2024) based on samples collected along the same coastal island, in Southern Brazil, SWAO. S = summer and W= winter

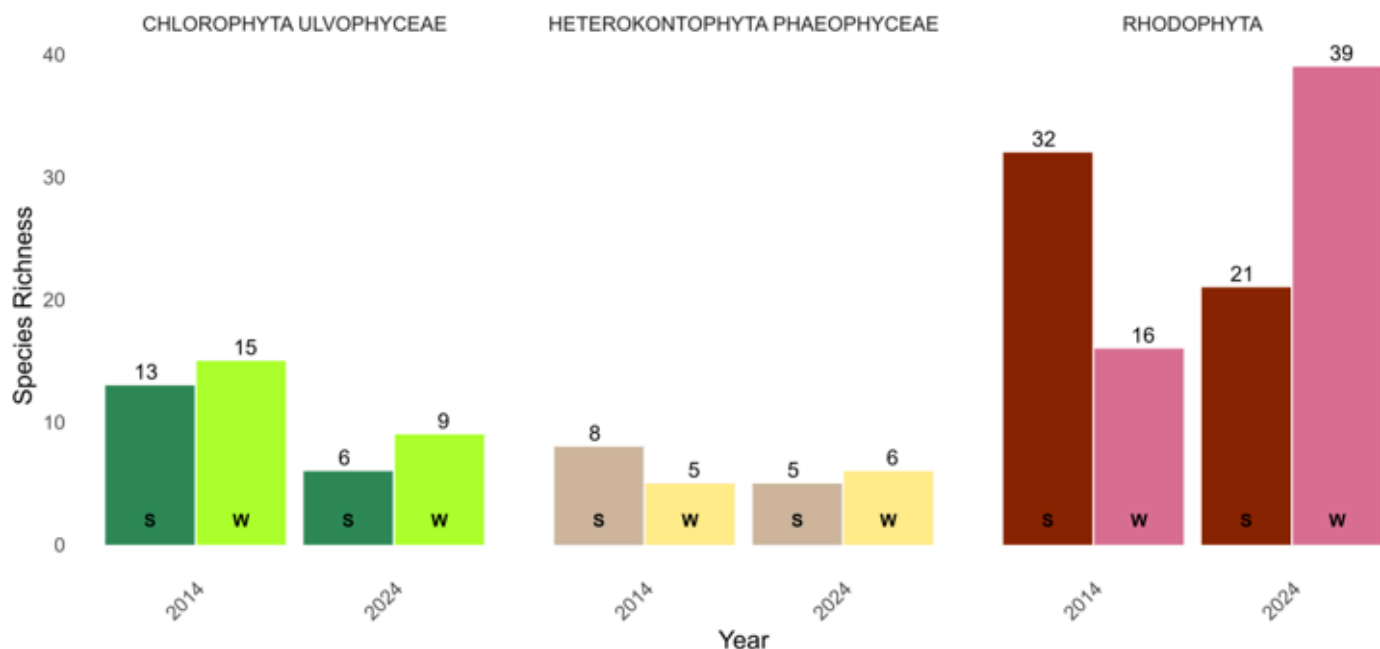


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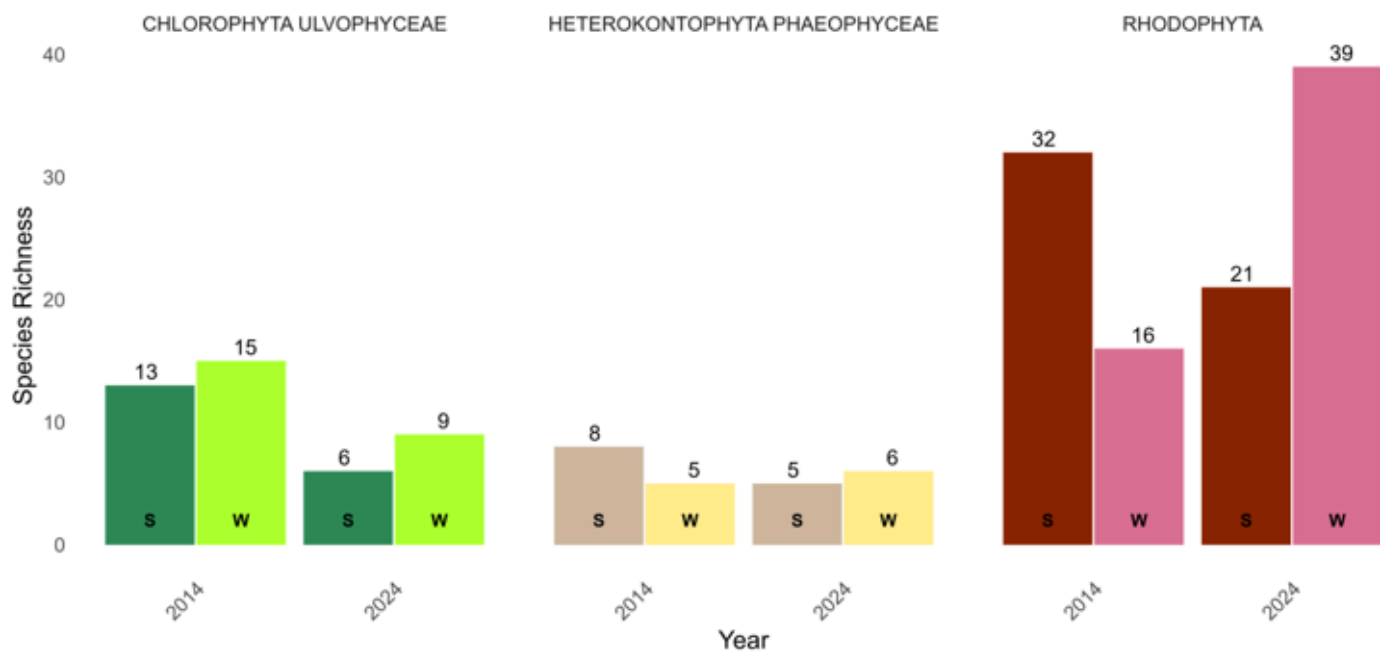


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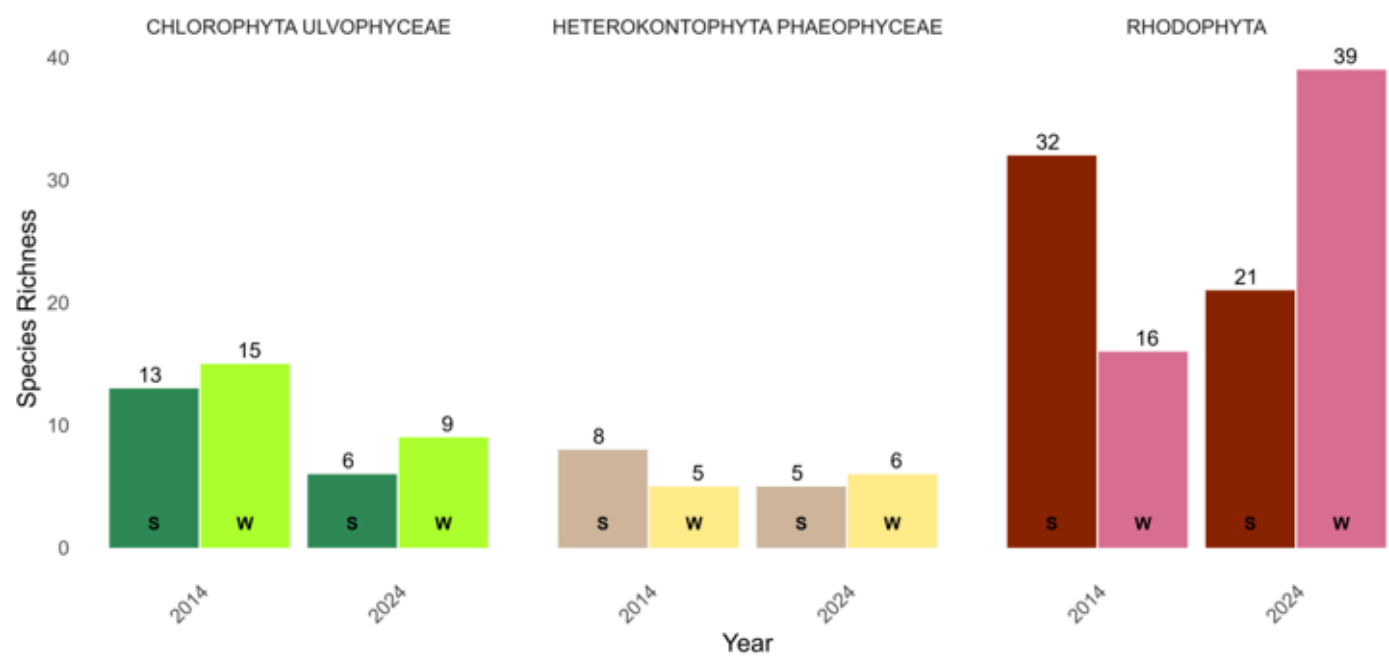


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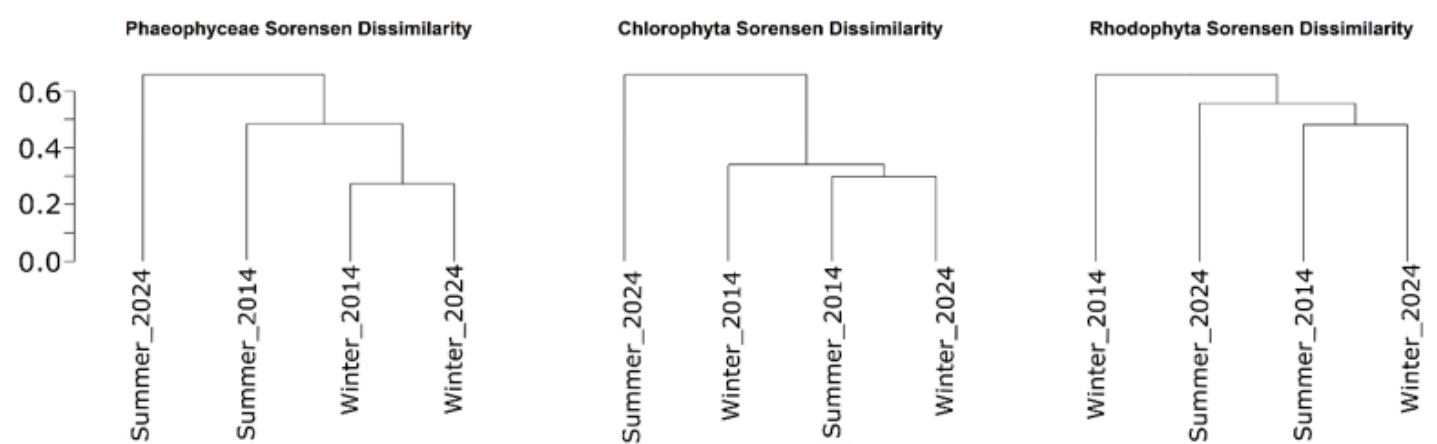


Figure 2

Dendrogram showing the dissimilarity among seaweed assemblages at Farol Island (Southern Brazil), based on Sørensen's index and the unweighted pair group method with arithmetic mean (UPGMA). Samples were collected during summer and winter, in two surveys ten-years apart (2014 and 2024)

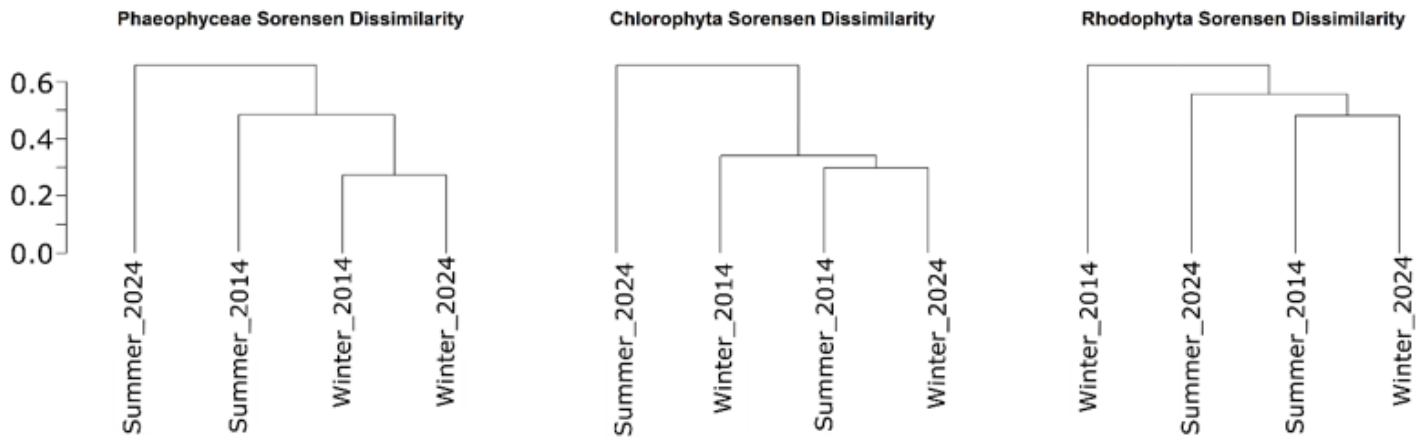


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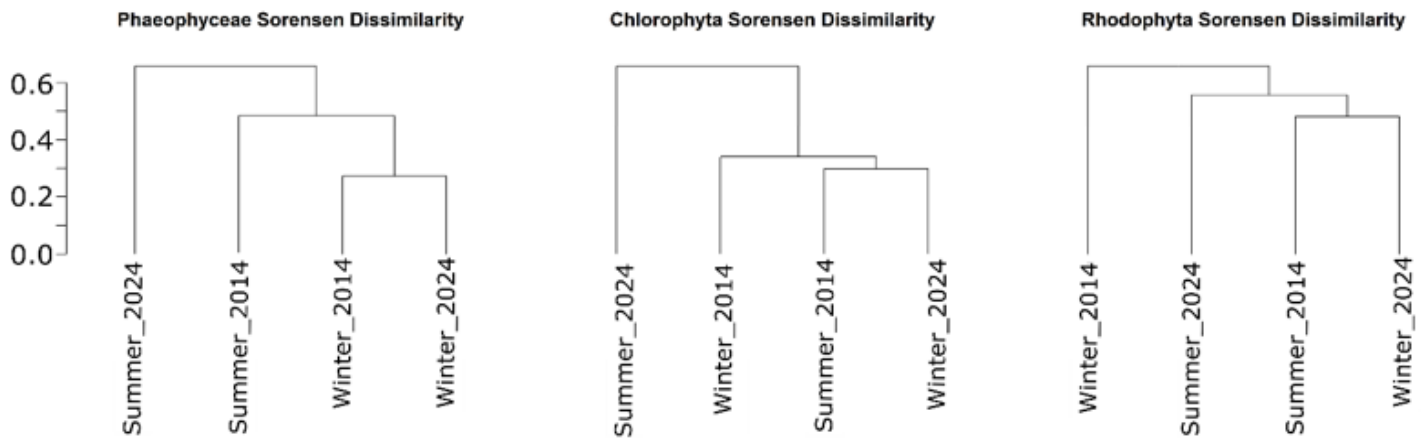


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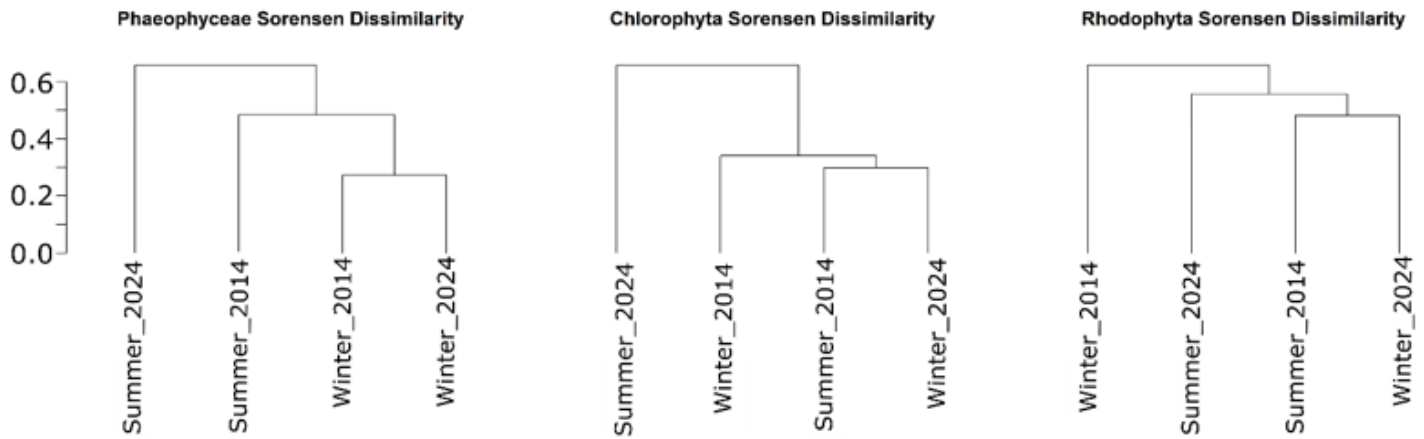


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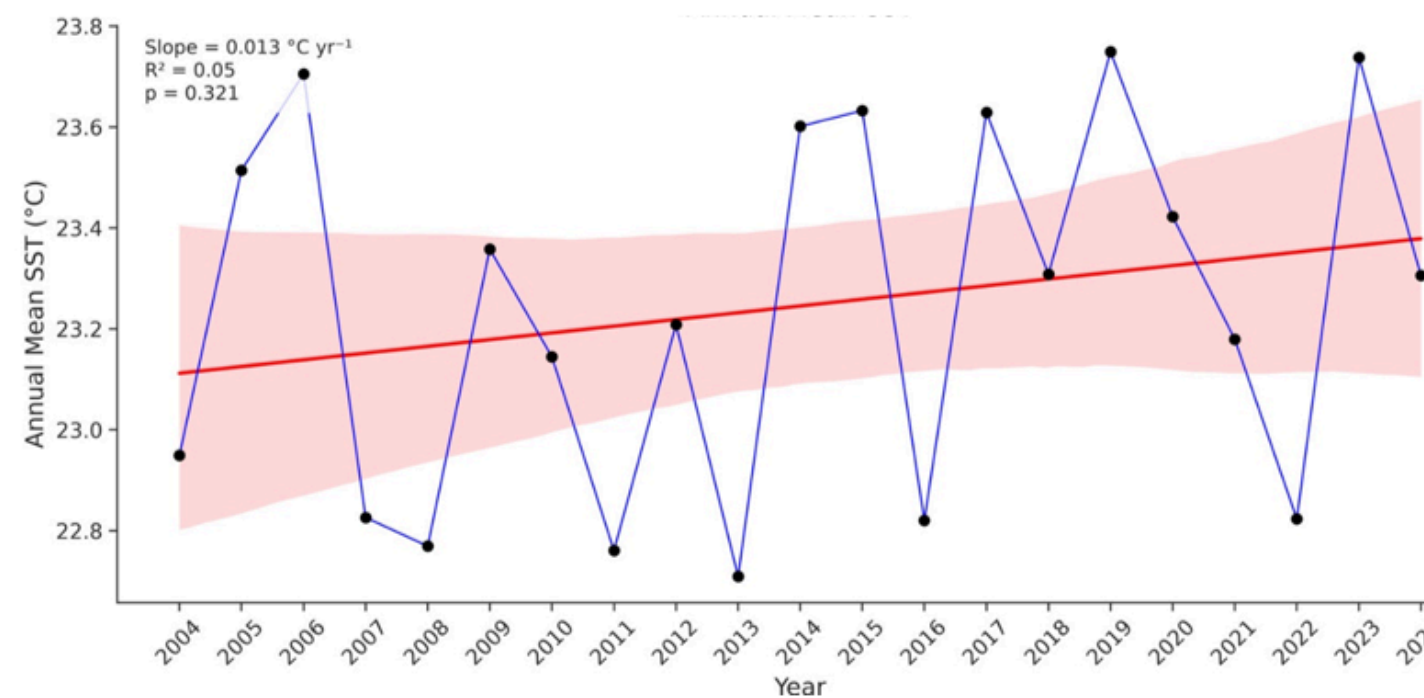


Figure 3

Annual mean sea surface temperature (SST) in the Paraná coastal shelf region from 2004 to 2024 based on Copernicus Marine Service (EU/CMS 2024) data. Black circles indicate annual mean SST values connected by a blue line. The red line represents the linear regression trend, and the shaded area denotes the 95% confidence interval. The estimated warming trend was 0.013°C year⁻¹ (Good and Embury 2024)

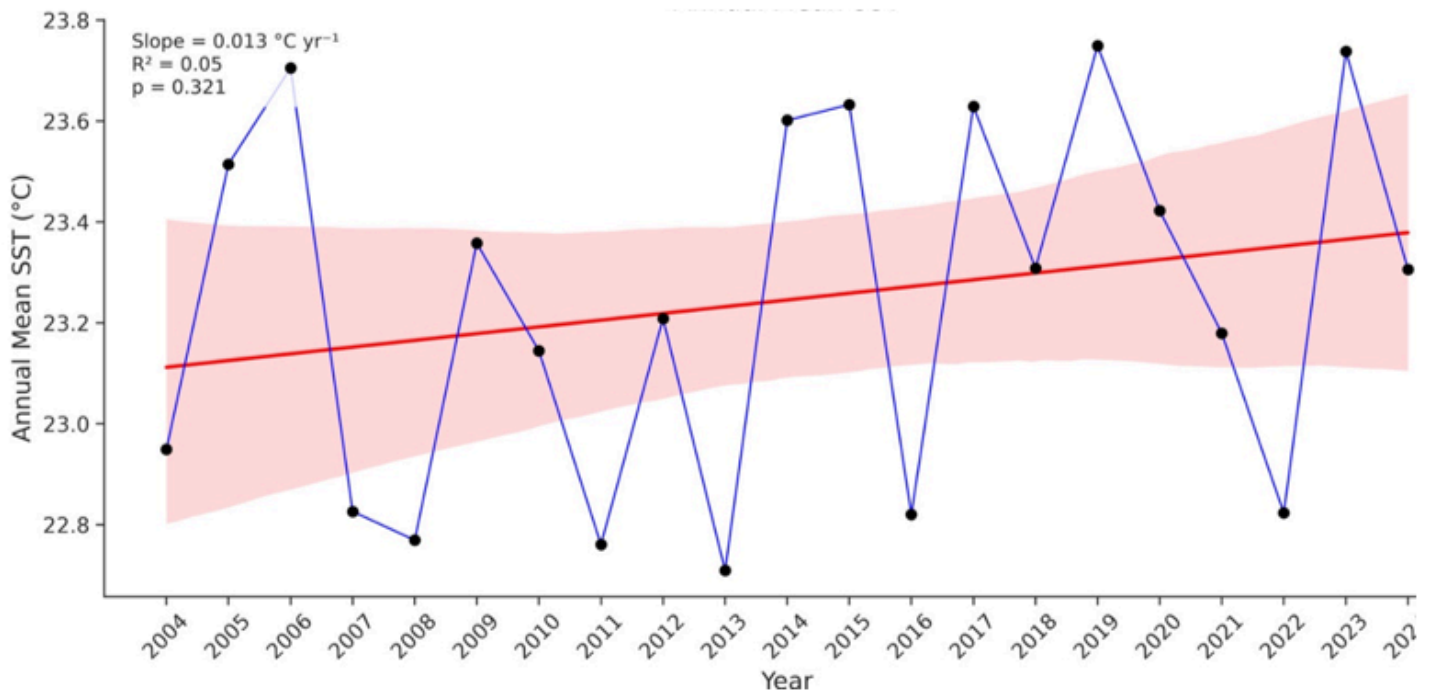


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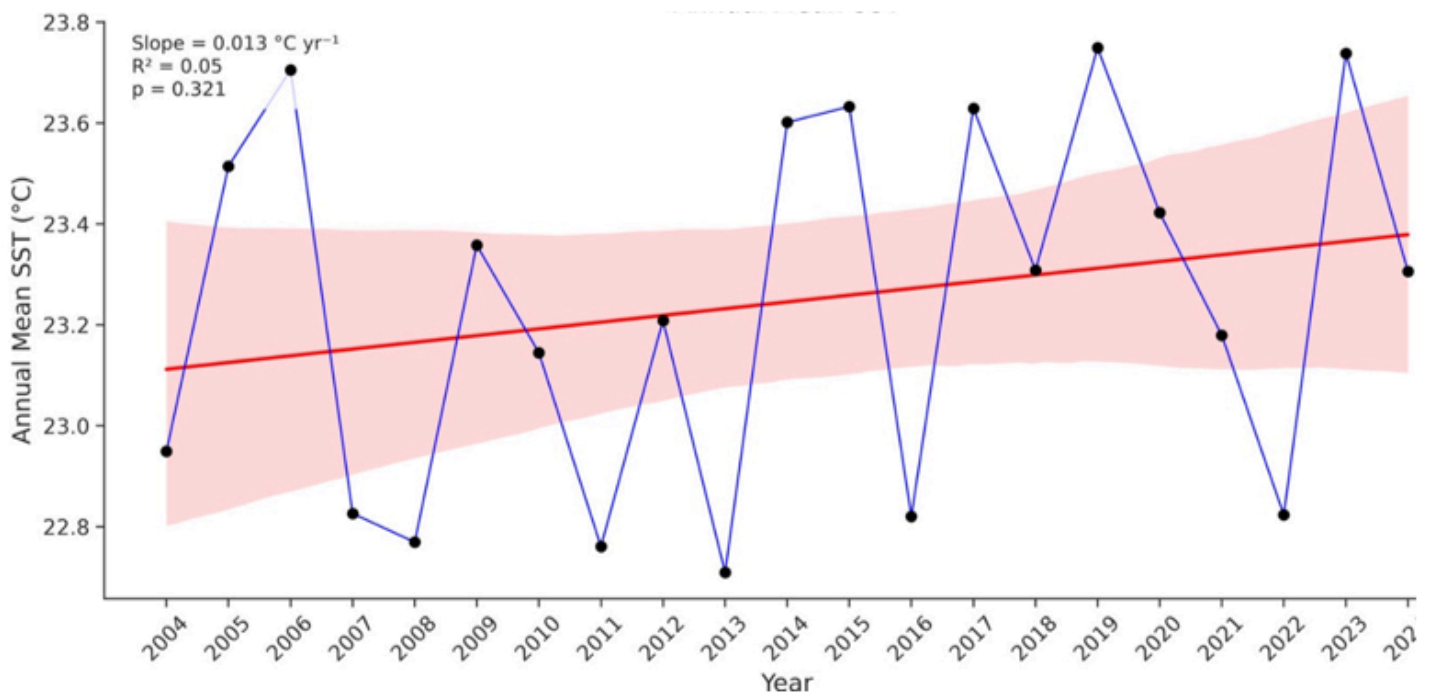


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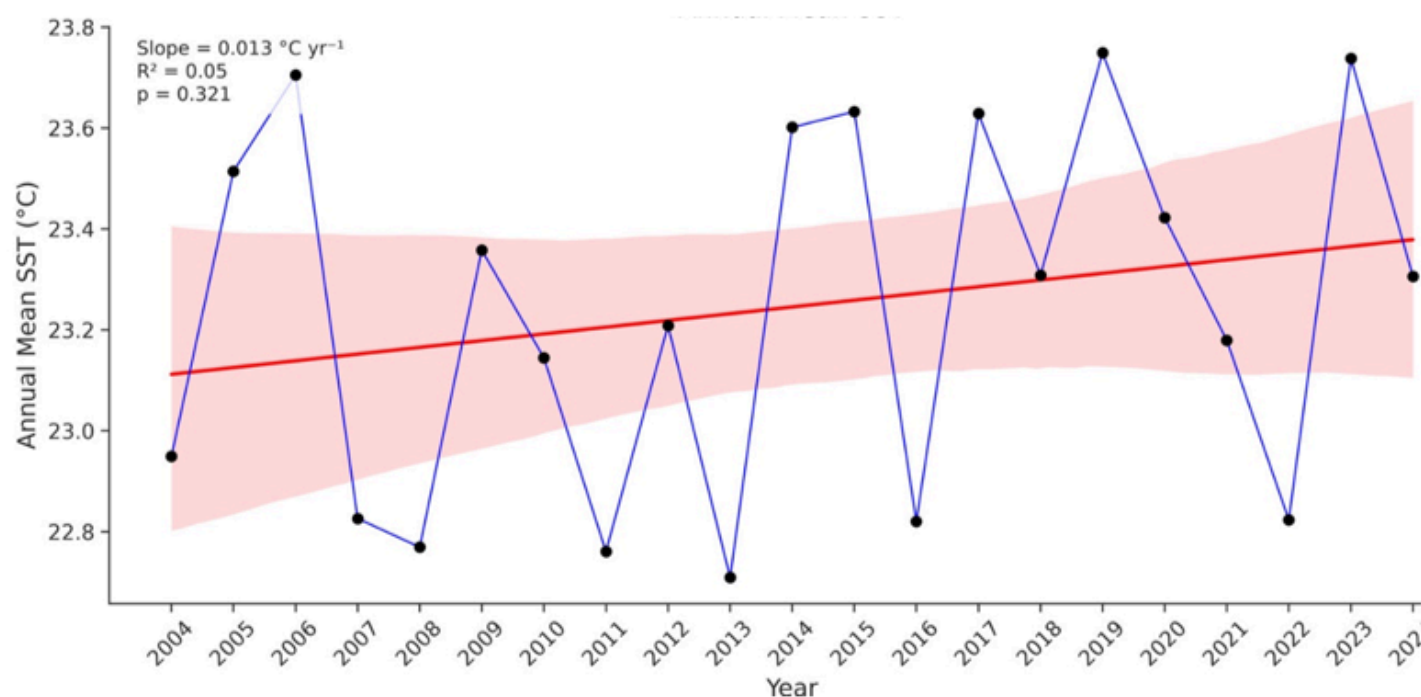


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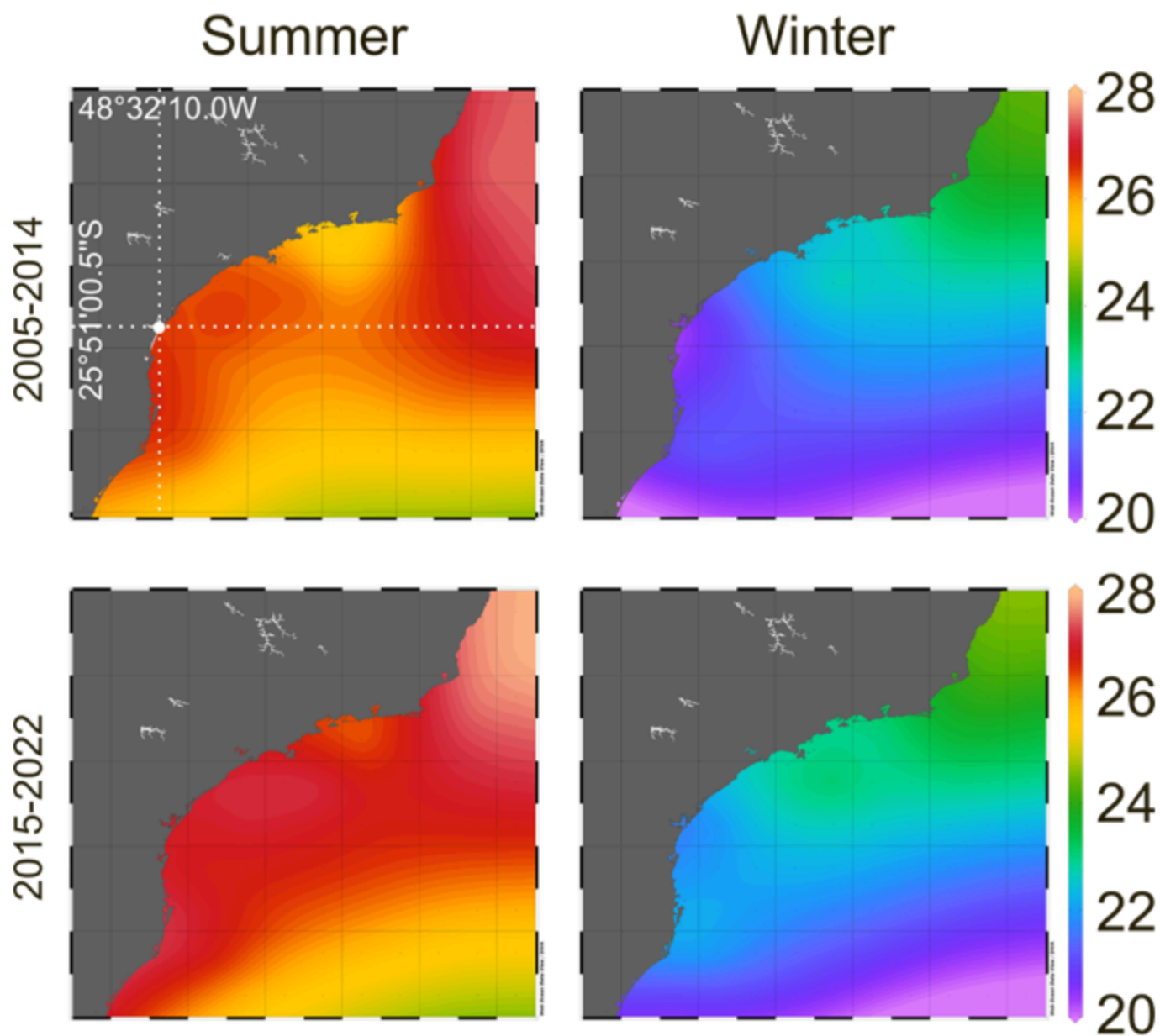


Figure 4

Spatial patterns of sea surface temperature (SST in °C) along the SWAO, Brazilian coast. The white dot indicates the sampling site, Paraná State. Data from coastal shelf floats (between 2005-2014 and 2015-2022) retrieved from WOA 2023/NOAA and plotted using Ocean Data View (<https://odv.awi.de>, 2020)

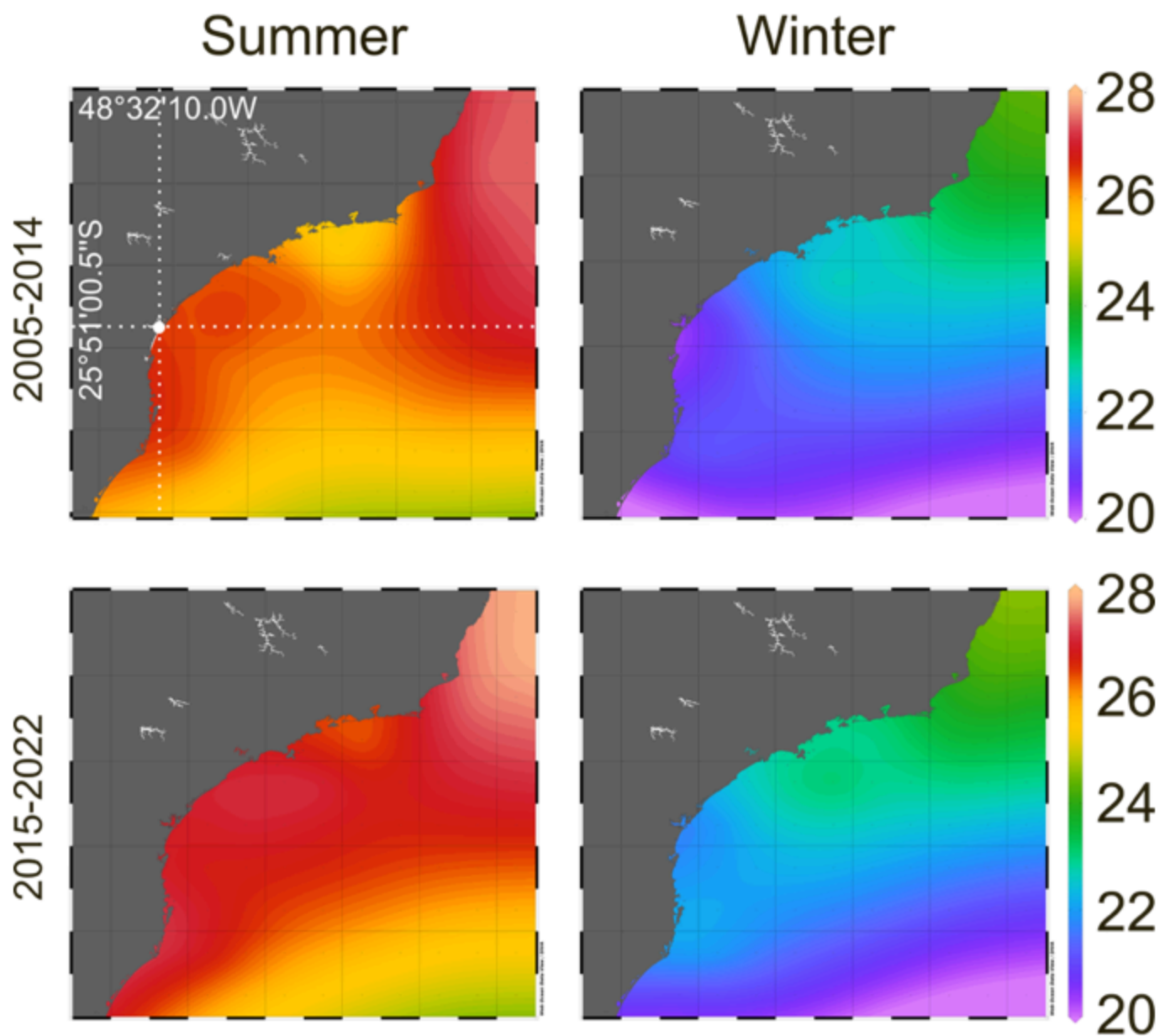


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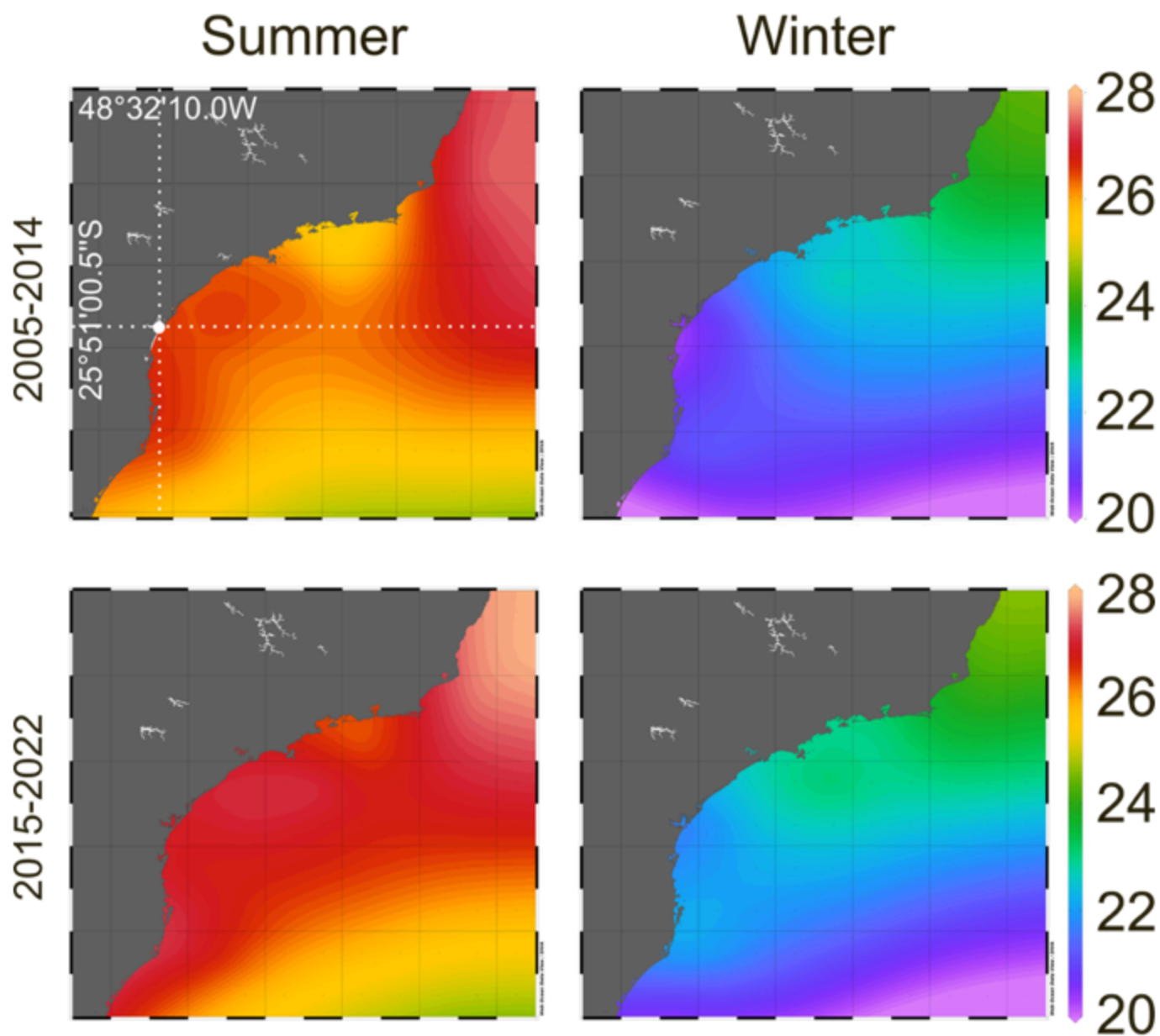


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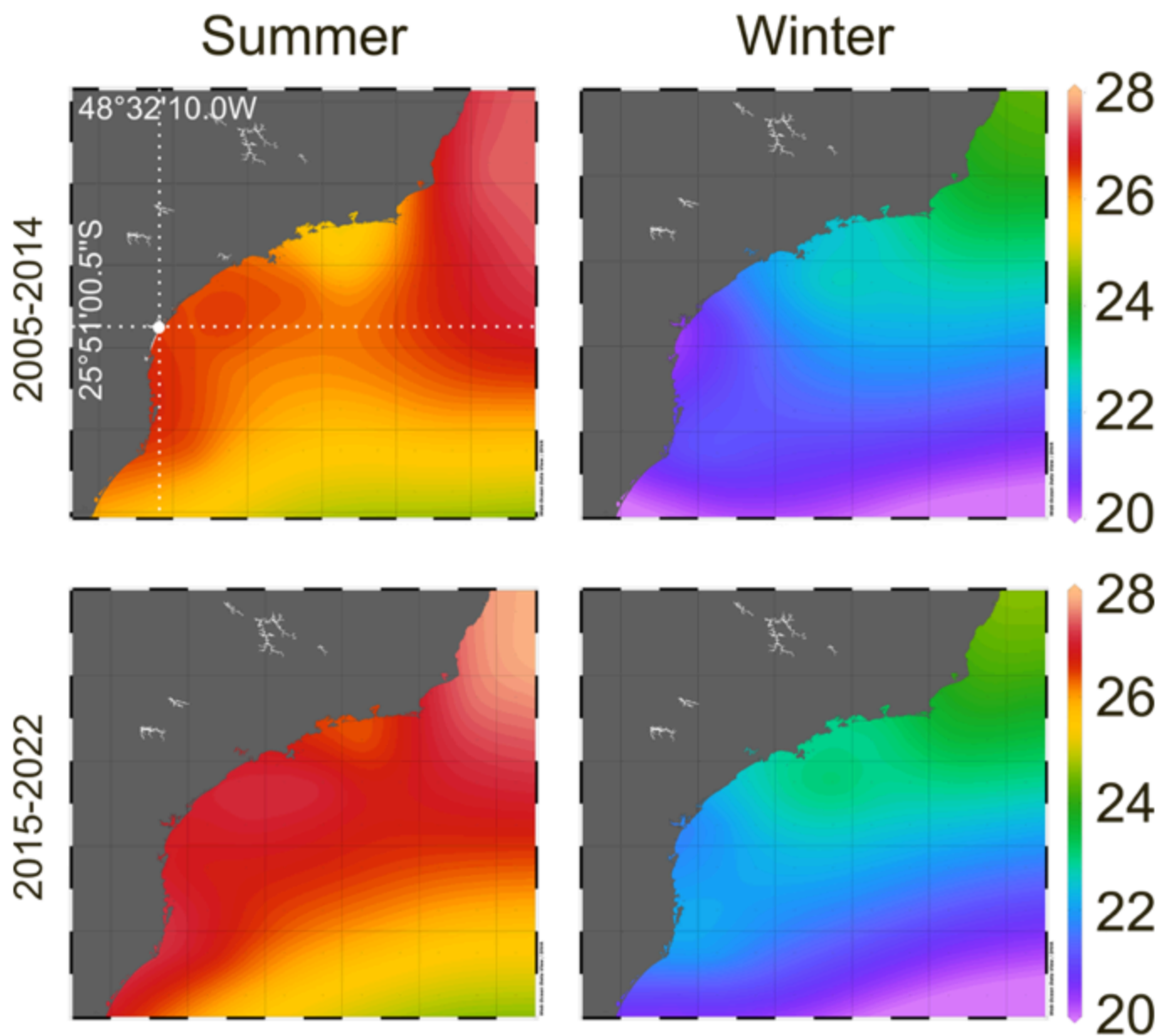
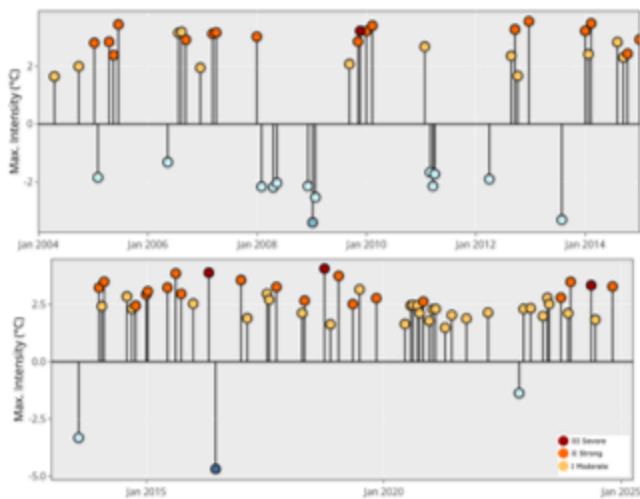


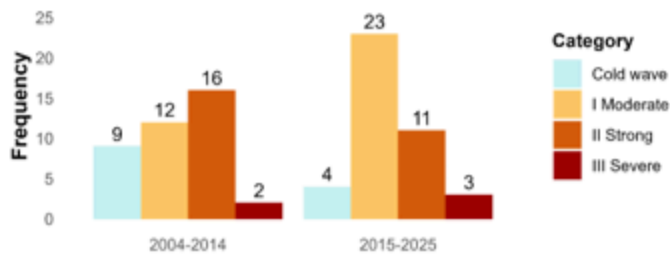
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a



b



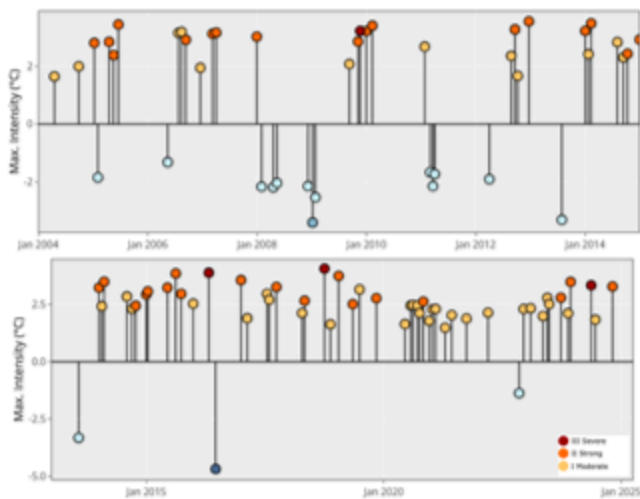
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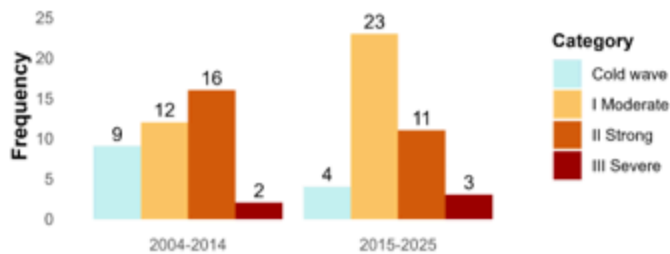
Figure 5

Lollipop plots above the main axis represent the frequency and maximum intensity ($^{\circ}\text{C}$) of MHW along the Brazilian coast, SWAO. (a) Events recorded during two periods, 2004 and 2014 and 2015 and 2025. Intensity categories: severe (red), strong (orange) and moderate (yellow). Event duration is represented by the height of the lollipop, while frequency is indicated by the spacing events. Cold waves are shown below the axis, where water green (moderate), light blue (strong), gray (severe), blue gray (extreme), and lilac ("ice"); (b) Frequency and intensity of MHW (by categories) and cold waves, considering all the years/seasons long over the past two decades, (c) Subset data of summer and winter frequency of MHW by category over the past two decades (Source: marineheatwaves.org)

a



b



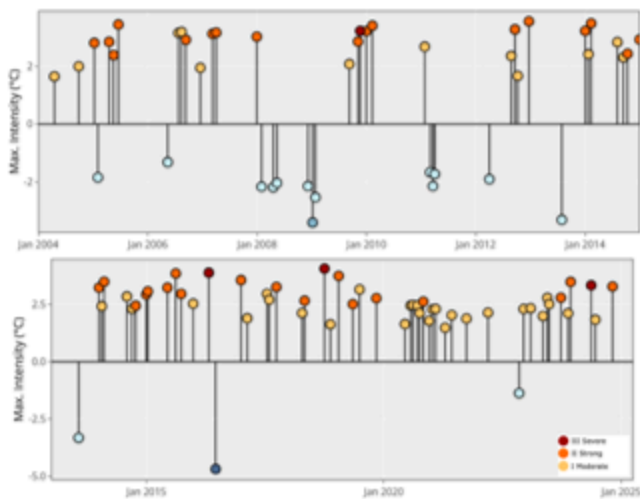
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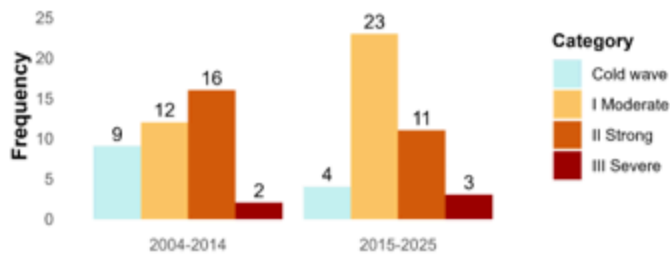
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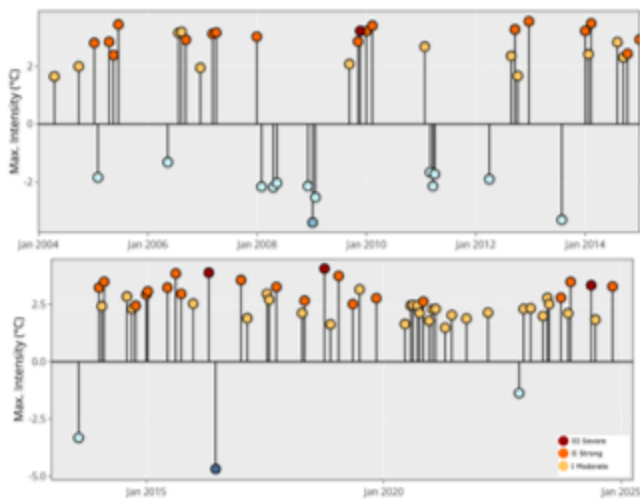
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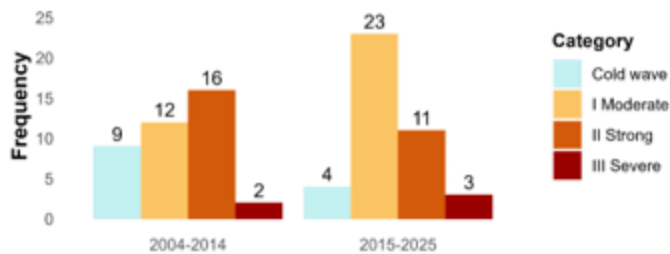
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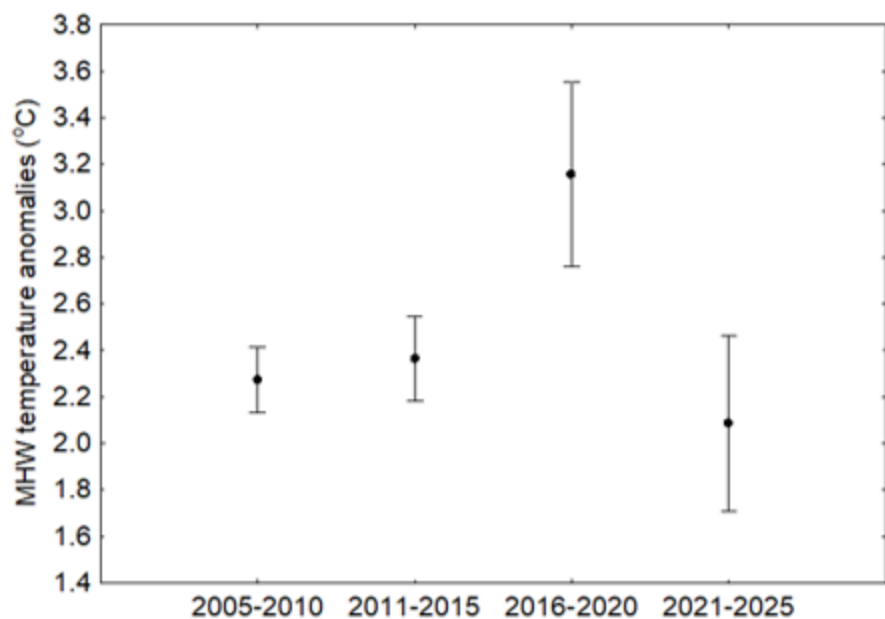
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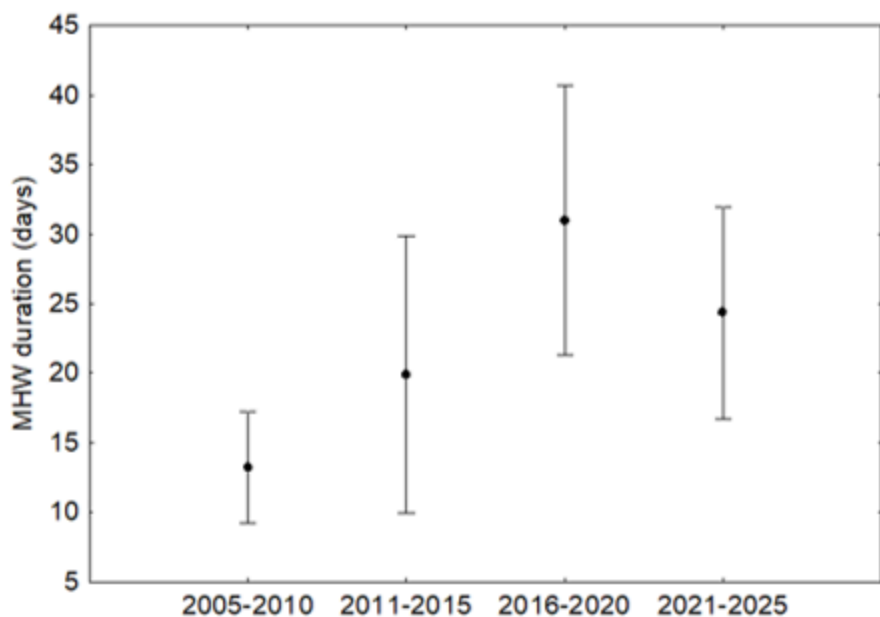
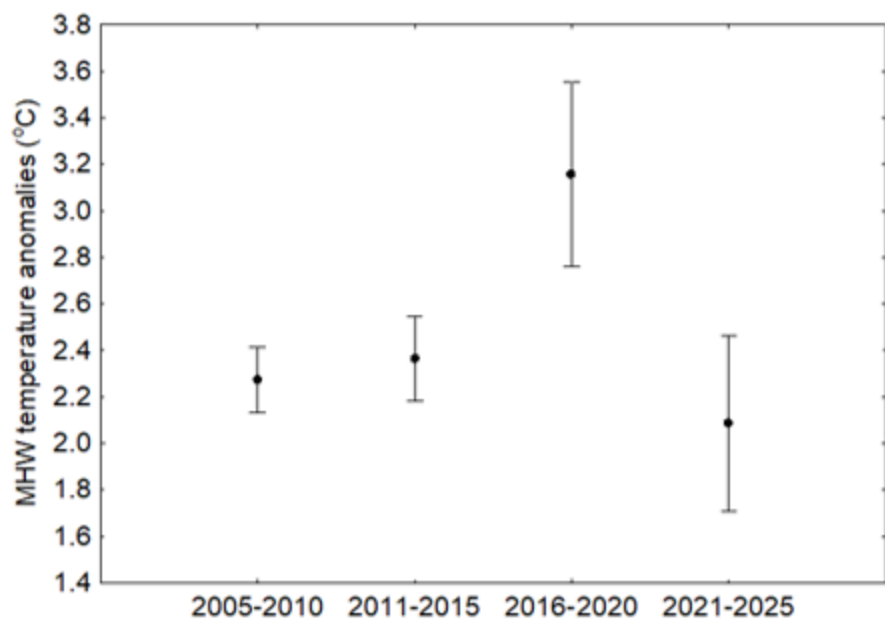


Figure 6

Marine Heatwave (MHW) events variation in the past two decades (between 2005-2025) by categories ("strong" and "severe") along the Paraná cost, Southern Brazil. (a) Daily mean $\pm$ SD of the sea surface temperature (SST anomalies in $^{\circ}$ C). (b) MHW duration in days (mean $\pm$ SD)

a



b

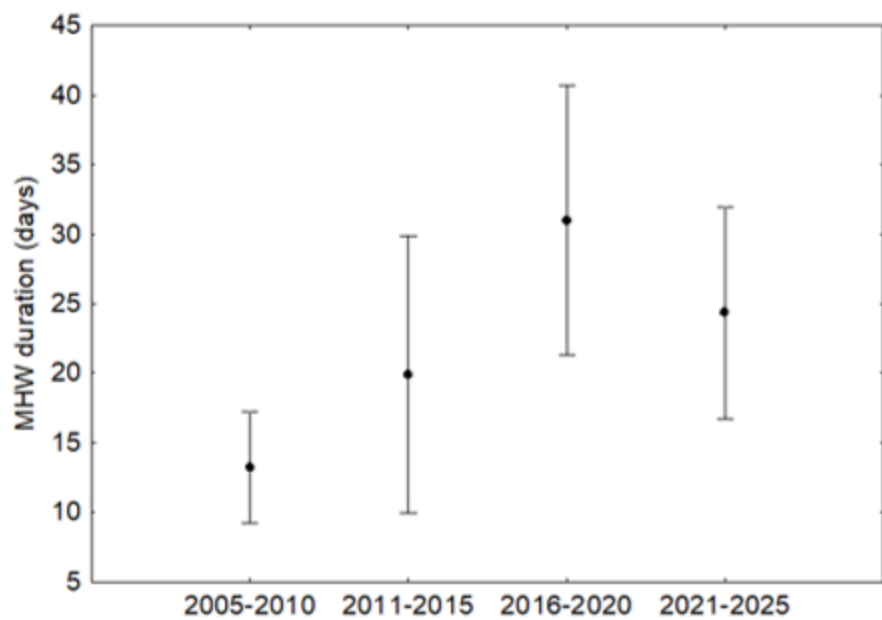
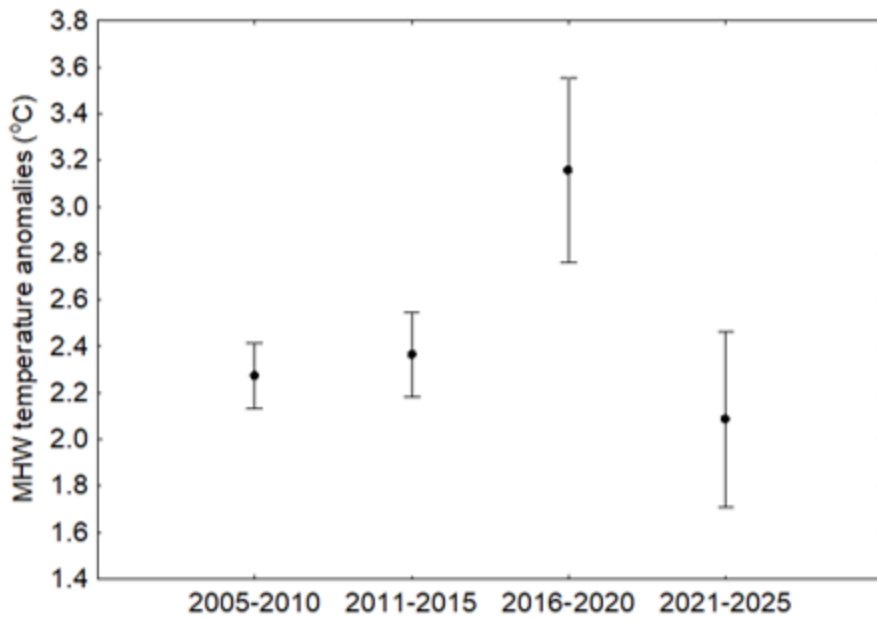


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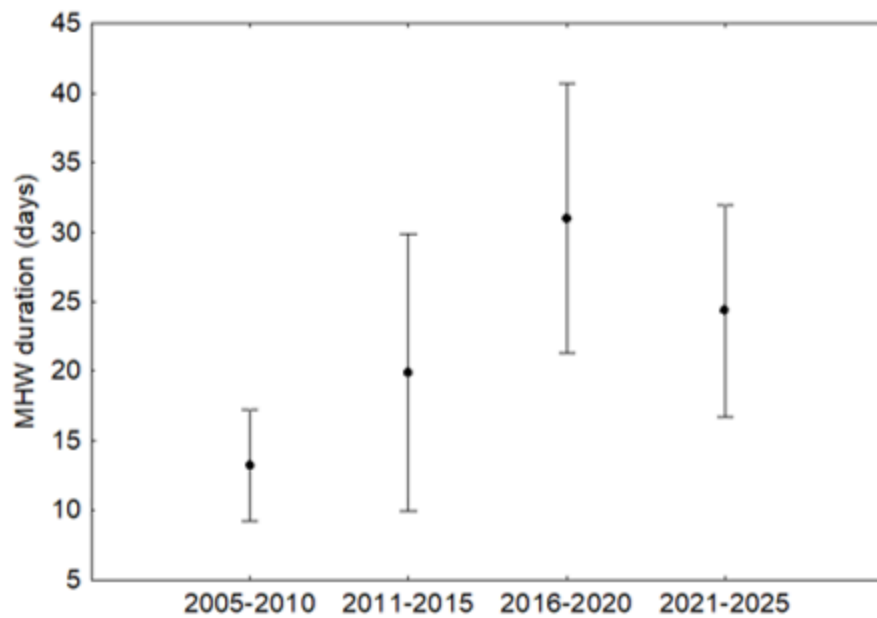
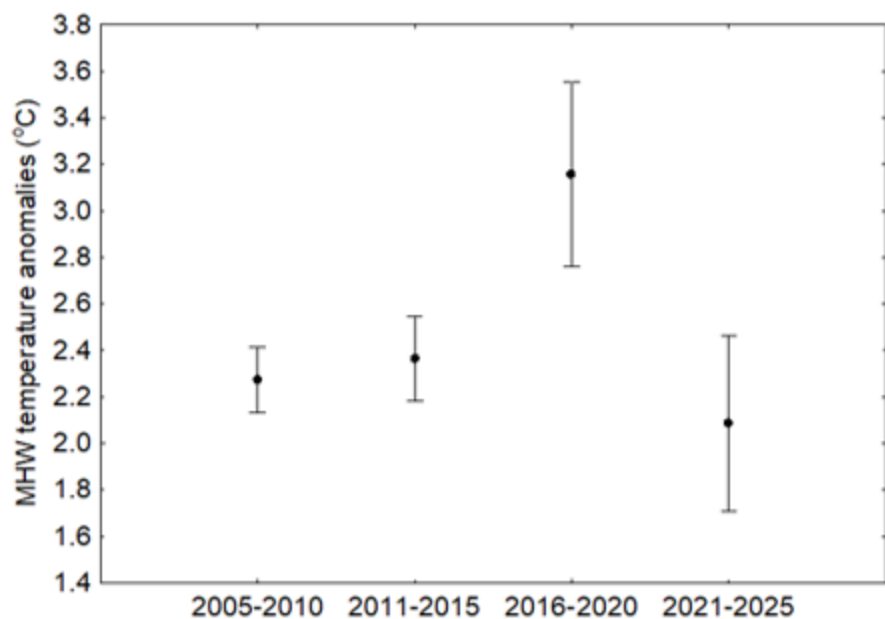


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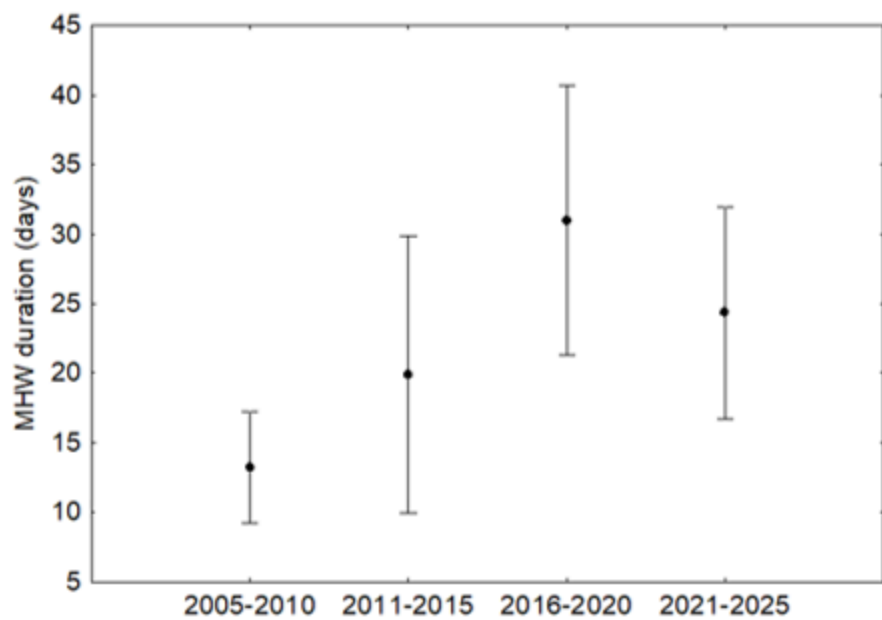


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