Environmental assessment of proposed areas for offshore wind farms off southern Brazil based on ecological niche modeling and a species richness index for albatrosses and petrels

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ABSTRACT

The increasing number of offshore wind farms (OWFs) proposed off the Brazilian coast is a biodiversity management challenge that needs to be addressed with strategic and targeted environmental impact assessments. The effects of OWFs on birds are much better studied in the northern than southern hemisphere. Knowledge of species distributions is key to developing effective conservation strategies. Ecological niche modeling can support strategic siting decisions and identify the target species for which mitigation of the impacts of OWFs may be required. We used the maximum entropy algorithm (MaxEnt) for modeling species niche suitability, incorporating environmental variables and presence-only data from tracking and at-sea surveys for seven albatrosses and petrels, of which five are threatened by extinction. We used the predicted niche suitability index (NSI) to calculate niche overlaps, assess distribution patterns and generate spatial prioritizations across seasons based on a species richness index (RI). Atlantic Yellow-nosed Albatross *Thalassarche chlororhynchos*, Atlantic Petrel *Pterodroma incerta*, and Great Shearwater *Ardenna gravis* were selected as target species for monitoring in Brazilian shallow waters (0–200 m depth) in the warm season, and Atlantic Yellow-nosed Albatross and White-chinned Petrel *Procellaria aequinoctialis* in the cold season. The RI was higher in waters between 200 m and 1000 m depth, a preferred area for OWFs with floating foundations. We advocate for the incorporation of niche models in environmental impact studies, as a tool for improving conservation, environmental planning, and impact assessment.

1. Introduction

Brazil has committed to the United Nations Paris Agreement to strengthen a global response to climate change and address the

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global climate emergency by increasing the use of renewable energy resources (Brasil, 2022). On the one hand, offshore wind is a key renewable energy technology that contributes to the goal of reducing greenhouse gas emissions. On the other hand, wind energy development can have complex environmental impacts due to the large scale of some wind farms, their different infrastructure technologies, and their location in potentially vulnerable environments (Willsteed et al., 2018). No offshore wind farms (OWFs) are currently operating or under construction in Brazil, but several proposals are undergoing Environmental Impact Assessments (EIA). By October 2022, there were 66 EIAs for OWFs under advisement at the Brazilian environmental agency. These would add up to a 169 GW nameplate capacity, considering overlapping projects (IBAMA, 2022).

The EIA is a process, formalized through regulatory procedures, to evaluate and mitigate relevant effects of development proposals before major decisions and commitments (Senécal et al., 1999). Proper siting is the most important mechanism for reducing environmental impacts in the early planning stages (Bennun et al., 2021). Placing new OWFs at higher-risk sites may result in approval delays, and increased development and operational efforts and costs (Bennun et al., 2021). The potential of OWFs to mitigate climate change needs to be studied in more depth, by evaluating the positive and negative impacts of renewable energy alternatives using appropriate tools and methodologies to back the decision-making process (Bailey et al., 2014; Larsen, 2014). Best-practice principles require that EIA are practical and focused (Senécal et al., 1999). Thus, identifying habitats used by affected species is the first step in risk assessment and mitigation, which could involve limiting the construction and operation of turbines to locations and times of lower impact on biodiversity. This means selecting the safest turbine design, installing early warning systems to reduce the risk of collision, among other measures (Bennun et al., 2021; Maxwell et al., 2022). Substantial evidence of OWFs impacts, particularly on birds, include collisions (Masden and Cook, 2016), barrier or displacement effects which causes habitat loss and disruption of flight routes (Cook et al., 2018; Heinänen et al., 2020), change in breeding or feeding sites (Dierschke et al., 2016; Peschko et al., 2021), attraction (Rodríguez et al., 2019), and trophic cascades (Raoux et al., 2017; Pezy et al., 2020). However, few studies have analyzed the effects of OWFs on the pelagic ecosystem, and even fewer have involved targeted fieldwork (Abramic et al., 2022).

Seabird at sea surveys are logistically and financially challenging, often restricting their spatial and temporal coverage (Heinänen
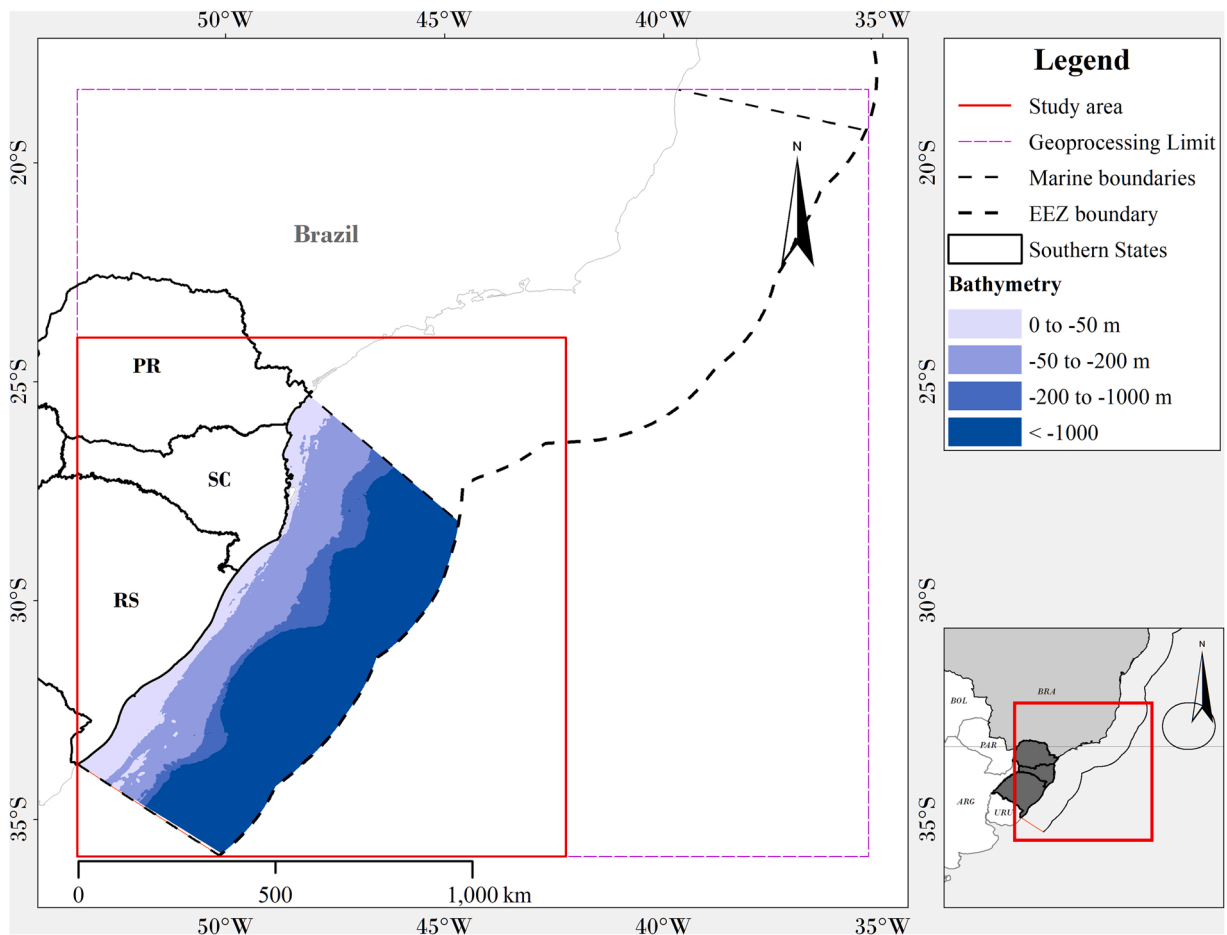
Fig. 1. Map of the study area in the southwest Atlantic Ocean, indicating the four bathymetric zones included in this study. The area is part of the Brazilian Exclusive Economic Zone (EEZ). The southern Economic Exclusive Zone (sEEZ) includes the coasts of the States of Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS).

et al., 2017). The order Procellariiformes (albatrosses, petrels and shearwaters) is a highly diverse group, with 45 species present in Brazilian waters (Pacheco et al., 2021). Seabirds are among the most threatened of all groups of birds globally (Dias et al., 2019). Knowledge of their distribution and habitat use is key to avoiding and mitigating threats such as OWFs (Azuaje-Rodríguez et al., 2022).

Spatial models can help decision-makers choose areas for development with the lowest impact on biodiversity and improve the consenting process by preventing conflicts from the early planning stages (May et al., 2021). Computer modeling provides a useful tool for predicting species distributions since it is usually much cheaper than carrying out extensive at-sea studies across the area of interest (Alexander et al., 2016). One approach to understanding at-sea distributions is to estimate the fundamental niches of each species (Sillero, 2011). Areas that fulfil the fundamental niche requirements denote the potential distribution of the species (Merow et al., 2013; McClellan et al., 2014). Ecological niche modeling (ENM) provides detailed predictions of occupied areas and habitats by correlating presence with a suite of environmental predictors (Guisan and Thuiller, 2005; Stirling et al., 2016). Predictions generated by ENMs allow species distributions to be extrapolated across space and time, and can be used in a variety of environments (Mannocci et al., 2017). MaxEnt is a well-known modeling method used to predict the species niche and potential geographic distribution based on the principle of maximum entropy applied to presence-only data to estimate a set of functions that relate environmental variables and habitat suitability (Phillips and Dudík, 2008; Phillips et al., 2017; Warren et al., 2020).

This study provides a framework that can be used for mitigating of the potential impacts of OWFs off Brazil, using ENM as a tool for environmental assessment of seasonal changes in marine areas and habitats used by seabirds, and for identifying the target species that are most at risk and require monitoring. The fundamental niches of seven procellariiform species were analyzed in the austral warm and cold seasons, and used to generate a richness index (RI) for identifying the seasons and the areas with greater biodiversity. The analysis focused on the niche suitability of areas used by each species, and the spatial conflicts with OWFs sites. Including this analysis in the early planning process could minimize their potential impacts of OWFs on Brazilian marine biodiversity, a country that has no marine spatial planning.

2. Material and methods

2.1. Study area

The ENM encompassed the region between 12°S and 40°S, and 60°W and 38°W, in the southwestern Atlantic Ocean. Spatial prioritization was evaluated between 25°S and 33°S, encompassing Brazil's southern Economic Exclusive Zone (sEEZ), which comprises the coasts of Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS) States (Fig. 1).

We divided the area into four bathymetric zones for analysis, reflecting the technologies available for installing wind turbines. The shallowest bathymetric zone (0–50 m depth) comprises 48,247 km^2 of the sEEZ, with the greatest wind potential and least technical requirements for installing OWFs (Hernandez et al., 2021). Waters between 50 and 200 m depth comprise the second largest zone of the sEEZ (101,711 km^2). In this area, floating wind turbines are preferred. The other zones are located between 200 m and 1000 m depth, and between 1000 m and 6750 m depth, summing to 38,392 km^2 and 210,825 km^2, respectively. The installation of OWFs is not financially viable in depths greater than 200 m with existing technologies. The potential for harvesting offshore wind resources in the sEEZ is huge: at 10 m above sea level, wind speeds reach 5–9 m.s^{-1} in January, and ~10 m.s^{-1} in July (Pimenta et al., 2019; Tavares et al., 2020b). The sEEZ is also a highly productive region, supporting major commercial fish stocks and with predators occupying higher trophic positions. This area is located at the junction of the Malvinas Current, which transports cold sub-Antarctic waters northward, and the Brazil Current, which transports warm tropical waters south and then east, forming the western margin of the Subtropical Convergence (Odebrecht and Castello, 2001).

2.2. Species selection

Studies on birds and the impacts of OWFs have mostly been carried out in the northern hemisphere, and concluded that gulls (Laridae) and gannets *Morus* spp. are the most vulnerable to collision effects and avoidance behavior (Furness et al., 2013; Cook et al., 2018). Presence records of coastal birds, shorebirds or seabirds off Brazil in public databases (Global Biodiversity Information Facility

Table 1
Procellariiform species included in ecological niche modeling in the southern Economic Exclusive Zone of Brazil, their threat status at global level (The International Union for Conservation of Nature [IUCN]) and national level (Brazilian Ministry of the Environment [MMA]), and whether listed by the Agreement on the Conservation of Albatrosses and Petrels (ACAP). CR: Critically Endangered; EN: Endangered; VU: Vulnerable; LC: Least Concern.

Species, author, and year	Common name	Species code	Degree of threat		ACAP
			IUCN	MMA	
Diomedea exulans Linnaeus, 1758	Wandering Albatross	DE	VU	CR	Yes
Thalassarche chlororhynchos (Gmelin, 1789)	Atlantic Yellow-nosed Albatross	TC	EN	EN	Yes
Pterodroma incerta (Schlegel, 1863)	Atlantic Petrel	PI	EN	EN	No
Procellaria aequinoctialis Linnaeus, 1758	White-chinned Petrel	PA	VU	VU	Yes
Procellaria conspicillata Gould, 1844	Spectacled Petrel	PC	VU	VU	Yes
Thalassarche melanophris (Temminck, 1828)	Black-browed Albatross	TM	LC	LC	Yes
Ardenna gravis (O'Reilly, 1818)	Great Shearwater	AG	LC	LC	No

(GBIF) or Ocean Biogeographic Information System (OBIS)) were too few for modeling of distributions. Gulls are scarce offshore, gannets are vagrants and there are no seaduck in Brazil (Pacheco et al., 2021), thus these groups were not included in our analyses. Furthermore, the minimum distance from shore recommended for OWFs installation in Brazilian waters is 18.5 km (IBAMA, 2019), which is why this study focused on pelagic seabird species, including several procellariiform species that frequently use the sEEZ during the breeding or non-breeding seasons, and are either present in high numbers or are threatened by extinction (Table 1): Wandering Albatross *Diomedea exulans*, Atlantic Yellow-nosed Albatross *Thalassarche chlororhynchos*, Atlantic Petrel *Pterodroma incerta*, White-chinned Petrel *Procellaria aequinoctialis*, Spectacled Petrel *Procellaria conspicillata*, Black-browed Albatross *Thalassarche melanophris* and Great Shearwater *Ardenna gravis*.

2.3. Data sources

2.3.1. Seabird occurrence data

The locations of seabirds within the sEEZ were obtained from two robust sources of in situ data: (1) At-sea surveys between 2009 and 2015 in the Brazilian EEZ, with the data held in the Waterbirds and Sea Turtles Laboratory database at the Federal University of Rio Grande (LAATM/FURG). The sampling protocols are described in Neves et al. (2006b), Gianuca (2011), and Daudt et al. (2019). Instantaneous, continuous and follower methods were used, as we were interested in presence data only; (2) Tracking of seabirds from BirdLife International (2021), mostly from deployments of satellite transmitters (Platform Terminal Transmitters - PTTs), GPS loggers and geolocators (Global Location Sensor or GLS loggers). We used occurrence data from 2003 to 2020 in the analyses. Deployment and other details are provided in Phillips et al. (2006), Bugoni et al. (2009), Mackley et al. (2011), Froy et al. (2015), Clay et al. (2018), Ronconi et al. (2018), and Frankish et al. (2020a). For further information on the at-sea survey and tracking datasets, see Appendix 1; Supplementary material 1. Occurrences were divided into warm (October to March) and cold (April to September) austral seasons. Analysis and selection of occurrence data, including scrutiny, filtering, and cleaning of duplicate records (Hijmans and Elith, 2019) were conducted in ArcGIS 10.6 software.

2.3.2. Marine environmental data

Key environmental parameters that characterize habitats and at-sea distribution of seabirds were based on bibliographic sources (Ainley et al., 2012; Bosch et al., 2018). In ENMs, these parameters include environmental variables that indicate habitat suitability and are statistically independent (Elith et al., 2011). Initially, we considered long-term averages (2000–2014) of eight spatial variables: sea surface chlorophyll (mg/m^3); sea surface carbon phytoplankton biomass (μmol/m^3); sea surface primary production (g/m^3/day); sea surface salinity (Practical Salinity Scale (PSS)) and sea surface temperature (°C) obtained from Bio-ORACLE v.2.1 (Assis et al., 2017); mean wind speed (m/s) at 10 m above the sea level raster file obtained with the 'rWind' v.1.1.7 package (Fernández-López and Schliep, 2019) in RStudio software (RStudio Team, 2020) from a time series of monthly averages using data from the Copernicus Marine Service (2021); bathymetry (m), and distance from coast (m) obtained from Sbrocco and Barber (2013). The raster files for each variable were converted to a WGS84 coordinate system with a spatial resolution of ~9.2 km using RStudio.

Highly collinear variables were identified using Variance Inflation Factors (VIF) within the 'sdm' package (Naimi and Araújo, 2016; Harisena et al., 2021). Sea surface chlorophyll (mg/m^3) and sea surface carbon phytoplankton biomass (μmol/m^3) were excluded due to high collinearity (VIF >10) with sea surface primary production (g/m^3/day).

2.4. Ecological niche modeling

Data were analysed using MaxEnt v.3.4.1 (Phillips et al., 2017) in the 'sdm' package in RStudio to generate ENMs represented by the seasonal niche suitability index (NSI) for the seven seabird taxa. The dataset was presence-only, and 10,000 background points were randomly sampled throughout the study area (Elith et al., 2020; Sillero et al., 2021) to reduce spatial bias associated with the patchiness of sampling effort and to adjust models (Phillips et al., 2009). The presence data were randomly split into 30% and 70% for model testing and calibration, respectively, and a 10-fold cross-validation procedure was used to estimate predictive performance on held-out folds (Elith et al., 2011; Merow et al., 2013). Habitat suitability was mapped using the average of the ten cross-validations (Peterson et al., 2011), to produce the final raster files for the NSI. Scores for habitat suitability vary from 0 (unsuitable habitat) to 1 (highly suitable habitat).

We evaluated the predicted habitat suitability using the area under the Receiver Operating Curve (ROC), known as the Area Under the Curve (AUC) (Fielding and Bell, 1997), the True Skill Statistic (TSS) (Allouche et al., 2006), and the Boyce Index (BI) (Hirzel et al., 2006). AUC and TSS were calculated using the 'sdm' package and the BI was calculated using the 'ecospat' package (di Cola et al., 2017) in RStudio. Model predictive performances based on AUC values were classified as follows: 0.6–0.7 = poor; 0.7–0.8 = average; 0.8–0.9 = good; and > 0.9 = excellent (Araújo and Guisan, 2006). The accuracy classification scores according to TSS were: < 0.2 = no predictive ability; 0.2–0.4 = poor; 0.2–0.6 = fair; 0.6–0.8 = good and > 0.8 excellent (Allouche et al., 2006). Even though the first two metrics are widely used in ENM, the BI is the most appropriate metric for presence-only models (Pearce and Boyce, 2006). It is a continuous index that varies between − 1 and + 1, were positive values indicate that the model predictions are consistent with the distribution of presences in the evaluated dataset (Hirzel et al., 2006; Scales et al., 2016).

We used Variable Importance (VI) to assess the importance of a particular predictor variable compared to other variables within the same model. VI values range from 0 to 1; higher values indicate more influence on the model and greater explanatory power independent of the other predictors, whereas a value close to zero indicates little independent explanatory power (Thuiller et al., 2009).

2.5. Niche overlap

We quantified the overlap in species ENM through the Schoener's niche overlap index (D) (Schoener, 1970; Warren et al., 2008), calculated with the 'ENMtools' package in RStudio and applied to pairs of models (Fourcade et al., 2014; Warren et al., 2021). The D index provides an ecological interpretation of niche similarities, ranging from 0 (no overlap) to 1 (all grid cells are occupied by both species), and was used to analyse the species' seasonal patterns. In our study, values of $D \geq 0.65$ were considered high and indicative of significant niche overlap.

2.6. Spatial prioritization and target species

The spatial prioritization described above identifies areas in which conservation may be relevant according to a conservation value index (Araújo et al., 2019), but does not indicate how many species are present in each site at the same time (Tobeña et al., 2016). We used niche suitability maps for warm and cold seasons to generate the RI, which ranged from 0 to 7, i.e., the minimum to the maximum number of species in the same raster cell (Stephenson et al., 2020; Sahri et al., 2021). The RI was based on the sum of the NSI values of all seven seabird species. We used ArcGIS 10.6 software to convert the NSI continuous values into Boolean layers, such that NSI < 0.7 was converted to 0, and NSI $\geq$ 0.7 was converted into 1 (Pineda and Lobo, 2009; Calabrese et al., 2014). The target areas for each species were selected with the high-suitability niche layers summed using the Sum Overlay Tool in ArcGIS 10.6.

The script for the analyses performed in RStudio is presented in the Appendix 1; Supplementary material 2.

3. Results

3.1. Seabird distributions

Based on the at-sea survey and tracking data, Atlantic Yellow-nosed Albatross and Atlantic Petrel were more common in the study area during the warm season, while the opposite was found for Wandering Albatross, White-chinned Petrel, Spectacled Petrel, and Great Shearwater (Table 2). Data for Black-browed Albatrosses were from at-sea surveys, while those for Wandering Albatrosses were obtained from tracking studies, because the species is difficult to distinguish from Tristan Albatross *Diomedea dabbenena* at sea.

3.2. Ecological niche modeling

All ENMs performed better than the random models. Based on the AUC, TSS, and BI, the predictive performance ranged from good to excellent in terms of discrimination power; AUC scores were > 0.90, and TSS scores were > 0.70, with good agreement among metrics. All BI values were higher than 0.9 and corresponded well with the presence locations and the model results (Table 2).

For each species and season, the models produced useful predictions for mapping. Variation in NSI between the warm and cold seasons is shown in Figs. 2 and 3. Results indicate that the sEEZ is an important area for all albatross and petrel species considered here, with areas with NSI > 0.7 in both seasons.

We calculated VI values for each predictor and model (Appendix 1; Supplementary material 3). Overall, warm-season distributions were best predicted by bathymetry (VI 0.25–0.65), distance to coast (VI 0.17–0.42), and wind speed (VI 0.03–0.42), while sea surface temperature and bathymetry (both VI 0.21–0.63) best described cold-season distributions. Salinity had the lowest independent explanatory power in the models (VI = 0.01–0.04 in the warm season and 0–0.25 in the cold season).

The niche overlap index (D) ranged from 0.36 to 0.91 (Table 3). Overlaps between cold and warm seasons were high for Wandering Albatross (0.79), Atlantic Yellow-nosed Albatross (0.80), Great Shearwater (0.82), and Black-browed Albatross (0.91), suggesting the use of similar habitat areas in both seasons. A lower overlap for the Atlantic Petrel (0.61), White-chinned Petrel (0.54) and Spectacled Petrel (0.55), indicates a greater seasonal change in habitat use and distribution.

Qualitatively, spatial variability in the NSI corresponded closely with the values of niche overlap. In all depth zones, areas with higher NSI were larger in the cold season. White-chinned Petrel presented the lowest seasonal niche overlap ($D = 0.54$), indicating a greater change in suitability, while the highest overlap value was for Black-browed Albatross ($D = 0.91$), indicating non-significant change in suitability (Fig. 4). There was limited overlap in the niche of Spectacled Petrel with the other species, in the cold season.

Table 2

Ecological niche modeling in the warm and cold season for procellariiform species in the Brazilian southern Economic Exclusive Zone. Number of presence points included in models divided into warm (October to March) and cold (April to September) austral seasons. Predictive performance of the models: Area Under the Curve (AUC), True Skill Statistic (TSS), and Boyce Index (BI). Species codes as in Table 1.

Species code	Presence warm	Presence cold	AUC warm	AUC cold	TSS warm	TSS cold	Boyce Index warm	Boyce Index cold
DE	140	258	0.95	0.96	0.76	0.83	0.95	0.95
TC	1971	261	0.95	0.94	0.81	0.81	0.98	0.94
PI	791	149	0.91	0.97	0.72	0.85	0.99	0.96
PA	212	814	0.98	0.95	0.88	0.82	0.98	0.99
PC	617	1436	0.98	0.97	0.89	0.87	0.99	0.99
TM	217	247	0.98	0.98	0.94	0.92	0.98	0.98
AG	227	846	0.91	0.92	0.71	0.72	0.97	0.99
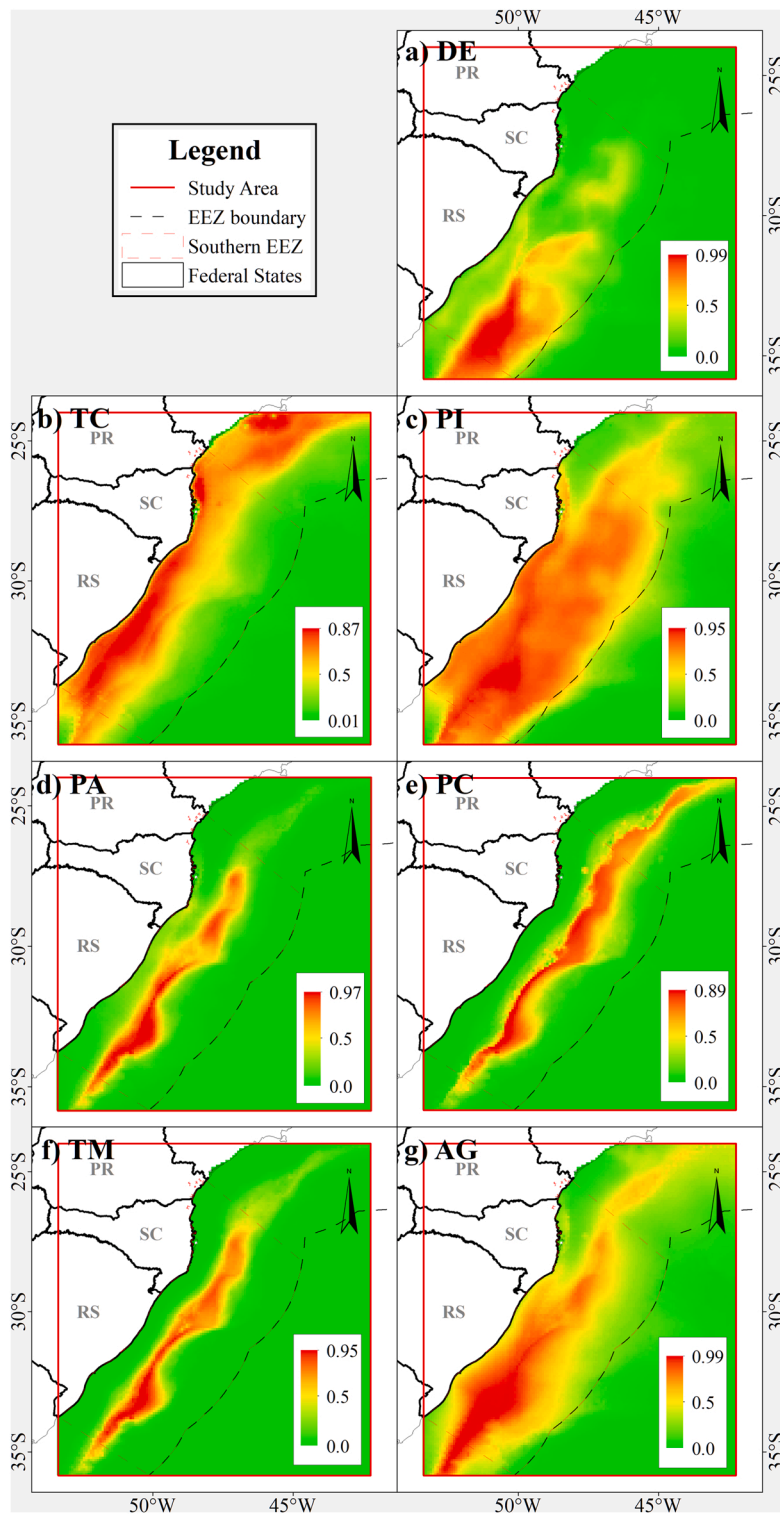
Fig. 2. Spatial predictions from ecological niche modeling of procellariiform species in the Brazilian southern Economic Exclusive Zone, in the warm season (October–March), displayed as niche suitability index (NSI) scaled from 0 to 1, and mapped to a) DE - Wandering Albatross, b) TC - Atlantic Yellow-nosed Albatross, c) PI - Atlantic Petrel, d) PA - White-chinned Petrel, e) PC - Spectacled Petrel, f) TM - Black-browed Albatross and g) AG - Great Shearwater. PR: State of Paraná, SC: State of Santa Catarina and RS: State of Rio Grande do Sul.
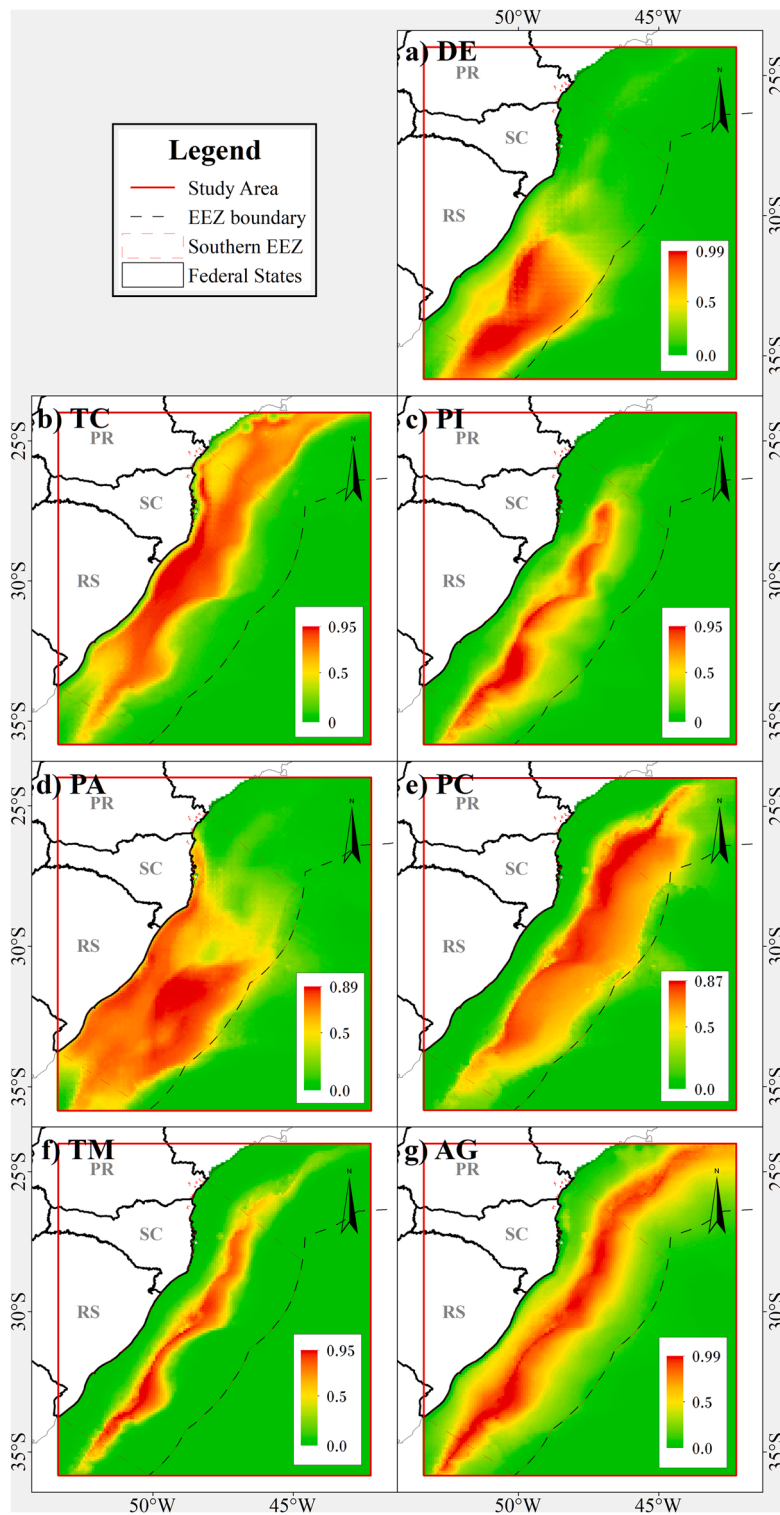
Fig. 3. Spatial predictions from ecological niche modeling of procellariiform species in the Brazilian southern Economic Exclusive Zone, in the cold season (April–September), displayed as niche suitability index (NSI) scaled from 0 to 1, and mapped to a) DE - Wandering Albatross, b) TC - Atlantic Yellow-nosed Albatross, c) PI - Atlantic Petrel, d) PA - White-chinned Petrel, e) PC - Spectacled Petrel, f) TM - Black-browed Albatross and g) AG - Great Shearwater. PR: State of Paraná, SC: State of Santa Catarina and RS: State of Rio Grande do Sul.

Table 3

Niche overlap using Schoener's *D* statistic based on ecological niche modeling of procellariiform species in the Brazilian southern Economic Exclusive Zone during cold and warm months. Schoener *D*'s values ≥ 0.65, marked in bold, were considered indicative of significant niche overlap. Species codes as in Table 1.

ENM code		DE		TC		PI		PA		PC		TM		AG	
		cold	warm	cold	warm	cold	warm	cold	warm	cold	warm	cold	warm	cold	warm
DE	warm	**0.79**		0.44	0.44	**0.66**	**0.69**	0.48	**0.70**	0.41	0.48	0.36	0.37	0.54	0.45
	cold			0.46	0.46	**0.65**	**0.68**	0.49	**0.72**	0.43	0.49	0.39	0.40	0.56	0.48
TC	warm			**0.80**		0.63	0.42	0.51	0.58	0.43	0.39	0.39	0.40	0.62	0.60
	cold					0.60	0.52	0.62	0.56	0.54	0.48	0.52	0.53	0.59	0.62
PI	warm					0.61		0.52	**0.73**	0.48	0.61	0.39	0.40	**0.75**	**0.67**
	cold							**0.69**	0.64	**0.67**	0.63	0.63	**0.65**	0.52	0.50
PA	warm							0.54		**0.66**	0.48	**0.79**	**0.78**	0.50	0.49
	cold									0.42	0.56	0.37	0.38	0.59	0.49
PC	warm									0.55		**0.72**	**0.76**	0.45	0.53
	cold											0.51	0.52	0.50	0.54
TM	warm											**0.91**		0.39	0.45
	cold													0.40	0.46
AG	warm													**0.82**	

The Atlantic Petrel showed the greatest niche overlap with other species in both seasons, particularly during the warm season when most of the sEEZ area was suitable. The results of all seasonal ENMs, presented as NSI > 0.5–0.7 and > 0.71–1, are in Appendix 1; Supplementary material 4.

3.3. Spatial prioritization and target species

Spatial prioritization by season and using the chosen approach (NSI >0.7), showed that about half of the areas in the sEEZ had low suitability for the studied species and the highest RI (five to seven predicted species) was in waters from 200 m to 1000 m depth, corresponding to the outer continental shelf and shelf-break in both seasons. (Fig. 5).

Between 0 and 50 m depth, the maximum RI included three species (Atlantic Yellow-nosed Albatross, Atlantic Petrel, and Great Shearwater) in the warm season, over a maximum extent of 5112 km^2 (10.3%). In the cold season, the RI reduces to two species (Atlantic Yellow-nosed Albatross and White-chinned Petrel), over a 3062 km^2 area (6.2%). Most of the area evaluated – 21,879 km^2 and 32,286 km^2 (44.1% and 65.3%) – had RI = 0 species in the warm and cold seasons, respectively.

The species composition in waters of 0–50 m and 50–200 m depth was the same (Atlantic Yellow-nosed Albatross, Atlantic Petrel and Great Shearwater). These three species occurred in a smaller percentage of this area in the warm season, whereas at least two species were present in about 70% of the area in the cold season. Waters from 200 m to 1000 m depth were the hotspot in terms of species occurrence. In the cold season, the entire area was suitable for at least one species, and 7.7% for all species according to the RI. About 38% of the area was predicted to hold at least five species. In the warm season, around 42% of this area would contain five to seven species. The largest area within the sEEZ is the depth zone from 1000 m to 6750 m. Despite its size, this zone was suitable for fewer species: in the cold season, no species was predicted to occur in 47.2% of the area, and two species (Wandering Albatross and Spectacled Petrel) in 40% of the area. Even in the warm season, a maximum of six species was predicted to occur in a very small portion (1.4%) of the area.

The results of spatial prioritization with RI mapped for NSI > 0.5 and > 0.8 are shown in the Appendix 1; Supplementary material 5, and the RI results by percentage of areas and bathymetric zones are shown in the Appendix 1; Supplementary material 6.

4. Discussion

The models we generated are spatially explicit, applicable to a wide range of taxa at various spatial scales, and relatively quick and cheap for assessing potential population-level impacts of different processes and threats (Bennun et al., 2021). Identifying key ecological requirements and species distribution in the oceans is crucial for effective species conservation and mitigation of risks associated with OWFs and other developments (Vignali et al., 2021). We predicted the key pelagic habitats for the seven species of procellariiform during the austral warm and cold seasons through NSI and RI. The ENM also improved our understanding of seasonal changes in habitat use of these highly mobile species (Oppel et al., 2012; Azuaje-Rodríguez et al., 2022). We emphasize that the good and the excellent predictive performances of our models reflect the quality of the complementary sampling methodologies (at-sea surveys and seabirds tracking).

Spatial analyses indicated that OWFs construction in areas between 0 and 50 m depth present the least risk to albatrosses and petrels, based on the low RI. Additionally, there are sites where all species had low niche suitability (NSI <0.7) in the coastal areas of SC and PR. Atlantic Yellow-nosed Albatross, Atlantic Petrel, White-chinned Petrel, and Great Shearwater were identified as the most important target species for impact monitoring, requiring greater attention due to their higher NSI in neritic waters (0 to ~200 m depth). Their NSI varied seasonally, with higher NSI (>0.7) areas for the Atlantic Yellow-nosed Albatross and the White-chinned Petrel in the cold season, and Atlantic Yellow-nosed Albatross, Atlantic Petrel and Great Shearwater in the warm season.

Based on RI = 07, the greatest potential conflict between seabirds and OWFs occurs in waters between with 200 m and 1000 m
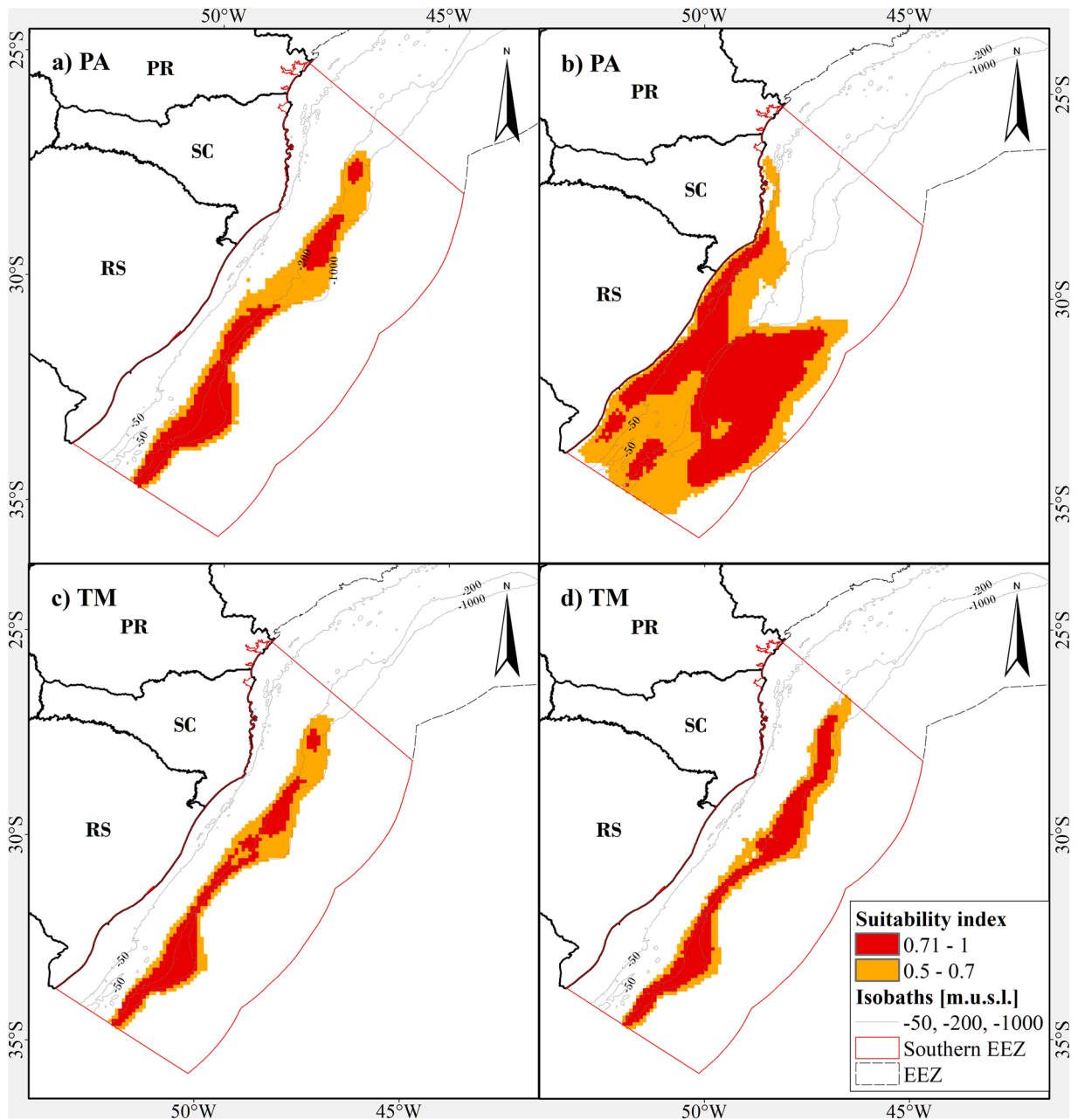
Fig. 4. Seasonal maps of ecological niche modeling of PA - White-chinned Petrel and TM - Black-browed Albatross, displayed as niche suitability index (NSI) > 0.5–0.7 and 0.71–1, to a) and c) warm season (October–March) and b) and d) cold season (April–September). PR: State of Paraná, SC: State of Santa Catarina and RS: State of Rio Grande do Sul.

deep, given that this area was highly suitable for all species. This also makes it an area of great relevance for seabirds conservation (Tancell et al., 2016; Dias et al., 2017). Current technology limits the installation of offshore wind turbines with fixed-bottom foundations in shallow waters (up to 60 m depth), which is fortunate according to our results that showed that this region has the lowest suitability for albatrosses and petrels. However, it is likely that in the near future, technical advances will allow for floating (and higher) structures to be installed in deeper waters, which will increase impacts in areas used by multiple seabird species, particularly in terms of the risks of collision or displacement.

In the sEEZ, some species are present during their non-breeding period, and others during the breeding season on long feeding trips, after which they return to incubate eggs or feed chicks at Tristan da Cunha, the Falkland Islands or South Georgia (Tancell et al., 2016; Dias et al., 2017). Our study documented clear seasonal changes in the pattern of use of the sEEZ, where the Wandering, Atlantic Yellow-nosed and Black-browed Albatrosses were present over deep waters throughout the year, since albatrosses spend their
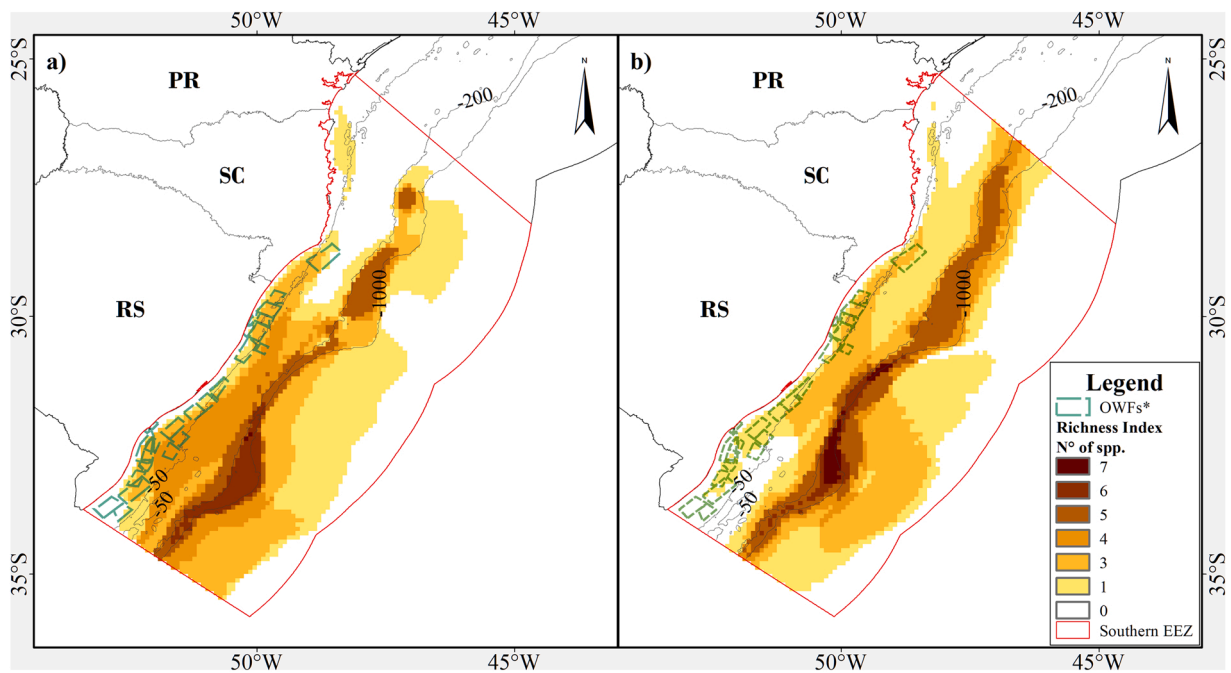
Fig. 5. Richness index (RI) of procellariiform species in the a) warm (October–March) and b) cold (April–September) seasons in the Brazilian southern Economic Exclusive Zone. Darker colours show hotspots of seabird richness per cell. PR: State of Paraná, SC: State of Santa Catarina and RS: State of Rio Grande do Sul. *Polygons represent the offshore wind farms (OWFs) with environmental licensing processes in the initial scoping phase.

non-breeding season exploiting the high productivity areas over the shelf break and around the Subtropical Convergence Zone (Wakefield et al., 2011; Clay et al., 2018).

Our results also showed that the Atlantic Yellow-nosed Albatross was particularly common in shallow waters and should be featured in early efforts to mitigate the risk from OWFs during all seasons, given the high suitability for this species throughout the year. The sEEZ is an important feeding area for post-breeding individuals from the Tristan da Cunha and Gough archipelagos during the austral summer, which feed in the sEEZ predominantly in the cold season (Tavares et al., 2020a). The Black-browed Albatross showed greater niche suitability in the upper continental slope (waters from 200 m to 1000 m depth). Some of the population from South Georgia spend their nonbreeding season at the Patagonian Shelf, and use the sEEZ (Phillips et al., 2005). Black-browed Albatrosses breeding in the Falkland Islands remain close to the Patagonian shelf all year-round (Paz et al., 2021), displaying a nonbreeding range that largely overlaps with the foraging areas used during the breeding season (Ponchon et al., 2019). Juvenile and immature Black-browed Albatross use areas such as the sEEZ during mid-autumn and winter (Bugoni et al., 2008; Bugoni and Furness, 2009).

The South American continental shelf break is an important foraging area exploited by the Atlantic Petrel year-round (Neves et al., 2006a; Pastor-Prieto et al., 2019). Our seasonal predictions indicated a larger area of highly suitable habitat (NSI >0.7) in the warm season to be occupied by adults which spend the non-breeding period (end of December to mid-April) off the coast of northern Argentina, Uruguay and southern Brazil. The lower winter NSI of the area coincides with the period when this species breeds at Gough Island (Ramos et al., 2017; Pastor-Prieto et al., 2019).

Our results indicated a clear niche segregation between the congeneric White-chinned Petrel and Spectacled Petrel. According to the NSI, the White-chinned Petrel makes extensive use of highly productive coastal waters. These are avoided by the Spectacled Petrel, who prefers the shelf break and the deep offshore mesotrophic or oligotrophic waters further north (Bugoni et al., 2009). Also, the White-chinned Petrel has an extensive foraging range that reduces competition with other procellariiform species (Phillips et al., 2006). During the cold months, this species occupies extensive shallow waters (0–50 m depth). These patterns agree with the information about the influx into sEEZ of nonbreeding adults and juveniles from the population breeding in South Georgia in April and May, the start of the cold season and the non-breeding period (Phillips et al., 2006; Frankish et al., 2020a). Similarly, our analyses show that the sEEZ is used by post-breeding Spectacled Petrels from Inaccessible Island (Bugoni et al., 2009). However, non-breeding birds are more common in shallower waters (<1000 m depth) during the summer, when fewer White-chinned Petrels are present (Reid et al., 2014).

The NSI for the Great Shearwater confirmed its presence in the sEEZ throughout the year, with a larger suitable area in the warm season (Neves et al., 2006a; Ronconi et al., 2018). Although this species performs a trans-equatorial migration, a huge population breeds at Tristan da Cunha and Gough Islands in the austral summer (Schoombie et al., 2018); as such, their predicted high occurrence in the sEEZ will consist of breeding individuals on long foraging trips during the warm season and staging individuals before or after the migration, in the cold season (Ronconi et al., 2018; Carvalho et al., 2022).

VI calculations showed the relevance of interactions between abiotic factors, including bathymetry and SST, for most species niche predictions. Both factors are known to be important drivers of distribution patterns of some Procellariiformes (Paz et al., 2021; Azuaje-Rodríguez et al., 2022). As described above, the continental shelf and shelf-break were clearly of high suitability for the studied species in terms of bathymetric zones. In general, SST is linked to global patterns of marine biodiversity (Tittensor et al., 2010). Wind was also an important influence on several species' habitat use (Wandering and Black-browed Albatrosses, White-chinned and Atlantic Petrels), which agrees with studies of tracked movements of albatrosses and petrels (e.g. Wakefield et al., 2009; Clay et al., 2020; Frankish et al., 2020b). Furthermore, flight height and flight behaviour are key factors in determining collision risk with turbines (Maxwell et al., 2022). Unfortunately, we were unable to find information on flight heights for our study species in the southern hemisphere, which could inform the selection of safe blade-tip heights above sea level. Data on flight heights of seabird species that use the sEEZ are therefore urgently required for improving OWFs risk assessments.

Our results also underline the importance of considering the dynamic nature of pelagic habitats when developing management plans and conservation initiatives to protect highly mobile animals such as seabirds. The future installation of OWFs in the sEEZ offers the opportunity for comparing the distribution (through tracking and at-sea surveys) of seabirds before, during, and after construction, by applying a before-after-control-impact monitoring program (Vanermen et al., 2015). A Brazilian biodiversity database compiling data from existing EIAs would allow a more strategic approach to risk assessment to be adopted. Indeed, such a database is a requirement under Brazilian legislation (ICMBio, 2014), but is yet to be implemented.

For the modeling area, no records of the Black-browed Albatross were obtained from tracking, nor records of the Wandering Albatross from on-board censuses. Thus, the in situ sampling methodologies should be complemented for better quality in EIA results. MaxEnt was appropriate for modeling the habitat suitability of these highly mobile species, and for predicting habitat use and distribution in non-sampled areas (Oppel et al., 2012; Tobeña et al., 2016; Smith et al., 2020). ENM can be used in EIA to predict the effects of future environmental changes and also in data-deficient years (Guisan and Zimmermann, 2000). However, these models should not be focused solely on initial planning, and do not replace in situ surveys for generating data for more robust models that should be used in developing environmental management strategies during the installation, operation and decommissioning of infrastructures. ENM and RI should be focused on local conditions, with campaigns and sampling scales appropriate to the particular threat or impact. Species presence, absence and abundance data can improve the overall prediction of the models (Araújo and New, 2007; Scales et al., 2016), and should be obtained as early as the EIA submission stage. To date, little attention has been paid to the possible impacts of OWFs on South Atlantic species (Rodríguez et al., 2019). Despite limitations and biases inherent to all niche modeling approaches, we are confident that ENM and the use of a RI can improve environmental planning by providing much-needed information on seasonal changes in the distributions and niches of sensitive species.

5. Conclusions

This study underlines the value of using ENM and a RI as integral parts of the process of biodiversity conservation, supporting strategic environmental assessments and spatial planning. These methods can be used to examine ecological patterns, identify target species, and select periods and areas where risks are highest, so that more attention is given to developing proper mitigation of biodiversity impacts. Furthermore, the RI can be used to identify key marine areas for different species or communities, assess the potential environmental impacts of other activities, and ensure that seabird surveys take place in appropriate areas (optimising the use of resources allocated to monitoring). The ENM and the RI results serve also as a baseline for studying changes in habitat of seabirds during the monitoring phase, specifically, for studies of displacement and the probability of collision with wind turbines.

Good practices in the EIA of OWFs stress the need for standardization in monitoring and impact analysis, and should ensure strategic marine spatial planning that focuses in particular on areas of high conservation value and environmental sensitivity (Lüdeke, 2017). The large number of proposed OWFs in the Brazilian EEZ represents a management challenge that needs to be met with early environmental planning and assessment. This study showed that OWFs in the shallowest areas of the sEEZ will require specific programs to avoid, mitigate or compensate impacts on the Atlantic Yellow-nosed Albatross, the Atlantic Petrel and the Great Shearwater in the warm season, and the Atlantic Yellow-nosed Albatross and the White-chinned Petrel in the cold season. In contrast, ENM showed that the predicted richness of procellariiform species is higher in waters between 200 m and 1000 m deep. As such, the predicted overlap of vulnerable seabirds with OWFs with fixed foundations on the sea bed is lower than a future scenario involving floating foundation technology operating in deeper waters.

The methods proposed in this work are not yet part of the EIA scoping practices for OWFs in Brazil (IBAMA, 2019). Given the multiplicity of insights derived from this study, we believe that ENMs and RI are a desired addition to the EIA toolbox for sites with little biodiversity data availability and no spatial planning. They provide a scientific basis on which to develop biodiversity conservation criteria, informing licensing processes and mitigation.

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CRediT authorship contribution statement

Carolina Alves Lemos: Conceptualization, Methodology, Modelling, Writing – original draft, Writing – review & editing,

Visualization. **Mauricio Hernández:** Conceptualization, Methodology, Writing – original draft, Visualization. **Cristiano Vilardo:** Conceptualization, Methodology, Writing – original draft, Visualization. **Richard Phillips:** Resources, Writing – review & editing. **Leandro Bugoni:** Resources, Writing – review & editing, Supervision. **Isabel Sousa-Pinto:** Resources, Supervision and editing.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2022.e02360.

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