

Distribution of marine climate refugia across OSPESCA member states: a historical perspective

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Abstract

Climate change is expected to reduce marine fisheries productivity across Central America and the Caribbean, increasing the need for spatial adaptation strategies that can be implemented across national boundaries. Marine climate refugia, areas that remain relatively buffered from environmental change, may help support climate-smart fisheries and conservation planning. Here, we identify historical marine macrorefugia across the Pacific and Caribbean Exclusive Economic Zones of member states of the Organización del Sector Pesquero y Acuícola del Istmo Centroamericano. Using Copernicus Marine physical reanalysis and biogeochemical hindcast, we analyzed changes in temperature, oxygen partial pressure, and chlorophyll-a from 1993 to 2020 across mixed-layer, epipelagic, and mesopelagic waters, during four seasons. Climate refugia were defined as areas where all three variables exhibited slow climate velocity or stable extreme-event frequency. Multi-stressor refugia occupied an average of 7.54% of total Exclusive Economic Zone area, but ranged from 0.00% to 87.85% depending on country, depth layer, season, and refugia metric. Climate-velocity refugia were concentrated mainly in surface and shelf waters, whereas extreme-event refugia were more common in deeper Caribbean waters. These findings show that potential refugia in the OSPESCA region are rare, dynamic, and strongly depth dependent.

Introduction

Climate change is already impacting tropical marine environments through warming, deoxygenation, acidification, sea-level rise, and changes in nutrient supply (Bindoff et al. 2019; Lam et al 2020). In the tropics, long-term climate trends are expected to emerge earlier and more clearly from the background of natural variability, pushing climatic conditions past the historical range species are adapted to (Rodgers et al. 2015; Bindoff et al. 2019; Pörtner and Farrell 2008). Together, these changes expose many tropical fish and invertebrates to conditions outside of their environmental tolerance range (Pörtner 2021), leading to shifts in distribution (Poloczanska et al. 2013; 2016; Pinsky et al. 2013; 2020), reduced growth, smaller body sizes and lower reproductive performance (Pörtner 2001; Sheridan and Bickford 2011; Cheung et al. 2013a; Lotze et al. 2019). These physiological responses and biogeographical shifts are expected to propagate through to the community level, reducing marine biomass and restructuring community composition across the tropics, with implications for fisheries productivity and catch potential (Lam et al. 2020; Cheung et al. 2010; Bindoff et al. 2019; Doney et al. 2012; Hoegh-Guldberg and Bruno 2010; Poloczanska et al. 2016; Cheung et al. 2010 2013b; FAO 2019; Free et al. 2019). Given the scale of these projected impacts, there is a clear need to identify adaptation options, particularly ones that can be implemented in the data-deficient contexts common across much of the tropics. Marine climate refugia, areas that remain relatively buffered from climate change, can be identified primarily from environmental data, making them feasible to implement in many data-deficient contexts.

Central America is projected to experience large declines in potential fisheries catches (Cheung et al. 2010; FAO 2019) that can reach losses of 90% on the Pacific (between El Salvador and Costa Rica Exclusive Economic Zones (EEZs)) and ~ 50–70% on the Caribbean (Costa Rica and Panama EEZs) by the end of the century under high-emissions scenarios (Cheung et al. 2018). As catch potential declines and species distributions shift across national boundaries, fishers may respond by intensifying effort and, in some cases, by tracking stocks into neighboring jurisdictions (Mendenhall et al. 2020; Pinsky et al. 2018; 2020; Sumaila et al. 2011). These responses can undermine sustainability and, where governance is fragmented and enforcement capacity limited, increase the risk of transboundary competition and conflict over shared or shifting resources (Mendenhall et al. 2020; Pinsky et al. 2018; Spijkers and Boonstra 2017). Considering these challenges, regional cooperation becomes a necessary tool to improve fisheries sustainability under climate change.

The Organización del Sector Pesquero y Acuícola del Istmo Centroamericano (OSPESCA), the specialized fisheries and aquaculture body of the Central American Integration System (SICA), offers a platform for collective adaptation among

Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama, and the Dominican Republic (OSPESCA 2024). Across the OSPESCA region, national climate adaptation plans increasingly emphasize the need for targeted, climate-informed research to address compounding ecological, social, and economic stressors that undermine ecosystem resilience (OSPESCA 2024; Dirección de Cambio Climático and Ministerio de Ambiente y Energía 2022; Bindoff et al. 2019). These priorities are reflected in recent Nationally Determined Contributions (NDCs) submitted to the United Nations Framework Convention on Climate Change (UNFCCC), which highlight climate adaptation, monitoring, and resilient ocean governance (Belize 2025; Costa Rica 2025; Dominican Republic 2020; El Salvador 2022; Guatemala 2022; Honduras 2025; Nicaragua 2025; Panama 2025). Yet, marine climate refugia represent a largely unexplored opportunity for the region, one that could complement existing adaptation commitments and provide a concrete, spatially explicit tool for climate-resilient ocean governance across OSPESCA member states.

Here, we identify historical macrorefugia based on climatic stability within OSPESCA EEZs, identifying areas with slow climate velocity or no increase in the frequency of extreme events (Burrows et al. 2011; Keppel et al. 2012; Morelli et al. 2016). We apply a stepwise approach that (1) quantifies climate velocity of temperature, oxygen, and chlorophyll-a, (2) characterizes recent extremes and their frequency across the same variables, and (3) integrates these metrics to map potential climate refugia. Mapping candidate climate refugia provides a basis for identifying areas that have remained relatively stable environmental conditions: where the three variables exhibited slow-moving climate velocity or stable extreme-event frequency. This can support climate-ready marine spatial planning, informing the design of marine protected areas (MPAs) and corridors, surveillance and monitoring, and fisheries management measures (Wilson et al. 2020; Arafeh-Dalmau et al. 2021).

Methods

This study assessed recent trends in temperature, oxygen partial pressure and chlorophyll-a within the EEZs of the eight member countries of OSPESCA: Belize, Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, Panama and the Dominican Republic. Monthly data spanning 1993–2020 were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS), including outputs from both physical reanalysis and biogeochemical hindcast models. Physical variables, sea surface temperature and salinity, were derived from the GLORYS12V1 global physical reanalysis, which provides data at $\sim 1/12^\circ$ (~ 8 km) horizontal resolution with 50 vertical levels (Jean-Michel et al. 2021). Biogeochemical variables, chlorophyll-a and dissolved oxygen, were obtained from the Global Ocean Biogeochemistry Hindcast model, developed by Mercator Ocean, with a coarser horizontal resolution of 0.25° and 75 vertical layers (Aumont et al. 2015). To ensure consistency across variables, the physical variables were interpolated onto the coarser $0.25^\circ \times 0.25^\circ$ biogeochemical raster bilinear regridding. Dissolved oxygen concentrations (mL L^{-1}) were converted to partial pressure (pO_2 , μatm) following Morée et al. (2023), using temperature and salinity as additional inputs.

The analysis was structured across three depth layers reflecting biologically relevant vertical zones (Doxa et al. 2022). The mixed layer extended from the surface to the average mixed layer depth in each grid cell, the epipelagic zone, spanned from the mixed layer to a fixed depth of 200 meters. The mesopelagic zone extended from 200 to 1000 meters.

We estimated the climate velocity of temperature, oxygen partial pressure, and chlorophyll-a over the 1993–2020 period. Monthly data for each variable were aggregated into seasonal climatologies based on four standard trimesters: December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON) (Fiedler and Lavin 2017). These four seasons were chosen because the major oceanographic features that structure the Eastern Tropical Pacific, including the California, equatorial and Humboldt upwelling systems, the Tehuantepec wind, Thermal Dome, and Panama upwelling system, vary strongly in intensity and spatial extent across these trimesters (Fiedler and Lavin 2017). For each grid cell and depth layer, temporal trends were calculated using ordinary least squares regression on seasonal means, while spatial gradients were derived from the 1993–2020 seasonal climatologies. Climate velocity (km yr^{-1}) was estimated as the ratio of the temporal trend to the spatial gradient for each variable (Burrows et al. 2011;

García Molinos et al. 2019). Grid cells with climate velocities between -2 and $+2$ km yr⁻¹ were classified as slow-moving or stable (Burrows et al. 2014).

To evaluate the frequency of extreme events, we applied a percentile-based anomaly detection method using the 1993–2013 period as a baseline climatology. For temperature, marine heatwaves were defined as months with anomalies above the 90th percentile of the baseline distribution for each grid cell and month, following an adapted version of the marine heatwave framework for monthly data (Frölicher et al. 2018). For oxygen and chlorophyll-a, extreme events were identified as months falling below the 10th percentile of the respective baseline distributions. These thresholds were applied to the post-baseline period (2014–2023), and seasonal frequencies of extreme events were calculated for each depth layer. A grid cell was classified as stable with respect to extremes if $\leq 10\%$ of post-baseline months exceeded the defined threshold for a given variable.

Areas characterized by slow or non-moving climate velocity or no increase in extreme-event frequency were quantified for each basin, season, and depth layer and expressed as a percentage of total area. For each depth layer within each basin, total area was calculated by summing the areas of grid cells in which the entire depth interval of the layer was represented, ensuring depth-layer metrics reflected averages across the full depth range. Climate area was then computed, for each season, variable, basin, and depth layer, as the summed area of grid cells meeting either (i) the slow/non-moving climate-velocity criterion for all three variables or (ii) the no-increase extreme-event criterion for all three variables. Finally, we expressed climate refugia as a percentage of total area by dividing the refugia area (km²) by the corresponding total basin area (km²) for the same depth layer and multiplying by 100.

Results

Climate-Velocity Refugia

In the Caribbean basin, climate-velocity refugia in the mixed layer covered the highest proportion of total EEZ area in Belize, whereas in the epipelagic zone they were most extensive in Honduras, Nicaragua and Costa Rica EEZs. By contrast, climate-velocity refugia were scarce in the Caribbean mesopelagic zone, covering only 1% of the Dominican Republic's EEZ. In the Eastern Tropical Pacific, climate-velocity refugia covered the highest proportion of the mixed layer in El Salvador, Nicaragua, and Panama, and of the epipelagic zone in El Salvador, and Nicaragua. No climate-velocity refugia were identified in the mesopelagic zone of the Eastern Tropical Pacific.

Spatially, mixed-layer climate-velocity refugia were most concentrated near coastlines, including regions surrounding the Thermal Dome, the Panama upwelling system, and within the Belize EEZ. These areas were strongly seasonal, with greater spatial extent from December to May (Fig. 1). In the epipelagic layer, three-variable overlap of slow or non-moving climate velocities occurred along the outer continental shelf in Pacific EEZs (Fig. 2). In the mesopelagic zone, climate refugia were limited to small, isolated patches, primarily within the Dominican Republic EEZ (Fig. 3).

Extreme-Event Refugia

In the Caribbean basin, extreme event refugia occurred mainly in the mesopelagic zone, particularly in the EEZs of Nicaragua, Costa Rica, and Panama, where they encompassed 50.67–87.85% of the total EEZs across the different seasons. In the Eastern Tropical Pacific, extreme event refugia occurred in the mixed layer, particularly in the EEZs of Panama, in the epipelagic zone of El Salvador and Nicaragua EEZs, and in the mesopelagic zone of the Nicaragua and El Salvador EEZs (Table 1).

Table 1

Percentage of each OSPESCA member-country Exclusive Economic Zone (EEZ), grouped by basin (Caribbean and Eastern Tropical Pacific), classified as multi-stressor climate refugia (temperature, oxygen partial pressure and chlorophyll-a) using two approaches, climate velocity and extreme-event stability, across three depth layers (mixed layer, epipelagic layer, mesopelagic layer). Values are reported as the mean and standard deviation (s.d.) of the EEZ-area percentage for each basin–depth–method combination (mean and s.d. summarised across seasons.)

Exclusive Economic Zones	Climate velocity						Extreme event					
	Mixed layer		Epipelagic		Mesopelagic		Mixed layer		Epipelagic		Mesopelagic	
Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	
Caribbean	13.79	30.27	1.12	1.52	0.25	0.74	0.41	1.50	0.42	1.09	29.63	36.87
Belize	24.42	16.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Costa Rica	3.00	6.01	2.19	2.88	0.00	0.00	0.00	0.00	0.00	0.00	87.85	15.35
Dominican Republic	0.11	0.22	0.51	1.02	1.76	0.00	2.15	4.02	0.32	0.48	0.57	1.15
Honduras	0.73	0.67	1.80	1.80	0.00	0.00	0.11	0.22	0.00	0.00	0.00	0.00
Nicaragua	1.36	1.64	1.78	0.29	0.00	0.00	0.13	0.27	0.79	1.57	50.67	7.29
Panama	2.26	0.66	1.29	1.07	0.00	0.00	0.80	1.01	0.66	0.77	68.34	14.07
Eastern Tropical Pacific	11.69	15.77	23.40	25.23	0.00	0.00	2.59	6.50	4.70	8.22	2.20	5.13
Costa Rica	4.86	3.57	12.24	8.17	0.00	0.00	0.38	0.56	2.30	1.88	1.10	1.27
Guatemala	1.00	1.15	6.42	5.47	0.00	0.00	2.32	4.13	1.86	3.71	0.50	0.58
Nicaragua	18.99	25.63	50.58	32.48	0.00	0.00	2.02	3.07	8.12	14.63	5.30	10.59
Panama	18.06	8.71	9.24	6.08	0.00	0.00	7.74	13.85	3.52	2.76	0.00	0.00
El Salvador	15.54	21.63	38.51	27.12	0.00	0.00	0.45	0.90	7.70	11.89	4.03	4.79

Spatially, mixed-layer extreme-events refugia were very rare in the region, occurring mainly in the Caribbean during Jun–Aug and in the Eastern Tropical Pacific during Mar–May (Fig. 4). In the epipelagic layer, areas within Pacific EEZs showing a three-variable overlap, where temperature, oxygen, and chlorophyll-a simultaneously exhibited no increase in extreme events, were concentrated near the thermal dome, with strong seasonal patterns (Fig. 5). In the mesopelagic zone, extreme event climate refugia were restricted to small, isolated patches near the thermal dome in the Pacific and along the Central American coast, as well as in the Caribbean within the Costa Rican and Panamanian EEZs (Fig. 6).

Discussion

Our results show that multi-stressor marine climate refugia are scarce and spatially fragmented across the EEZs of OSPESCA member countries. Between 1993 and 2020, areas where temperature, oxygen, and chlorophyll-a simultaneously showed slow climate velocities or stable frequencies of extreme events occupied, on average, 7.54% of total EEZ area, although values ranged widely from 0.00% to 87.85% depending on the EEZ, depth layer, season, and refugia metric. For example, in the Costa Rican Caribbean EEZ, 87.85% of the total area was classified as an extreme-event refugia in the mesopelagic layer, whereas no climate refugia was identified for extreme events in the mixed layer or epipelagic, and climate velocity refugia were nearly absent across all depth layers (0.00–2.88%). Refugia present across all seasons were also uncommon, suggesting that many may function as temporal windows of reduced exposure, with

benefits that depend on whether they coincide with sensitive life stages such as spawning, recruitment, or juvenile growth.

Refugia patterns were depth-dependent, with distinct outcomes based on whether they were defined by long-term trends or extreme events. Climate-velocity refugia were most common in surface and shelf waters and generally absent in deep layers. In contrast, extreme-event stability often occurred at depth for specific variables and EEZs. These vertical mismatches may affect ecological connectivity across the water column, because pelagic food webs, nutrient transfer, and the movements of many organisms depend on links between surface, midwater, and deeper habitats (O’Leary and Roberts et al. 2018; Griffiths et al. 2017).

The extent of potential climatic stability was much greater when temperature, oxygen, and chlorophyll-a were evaluated separately (Supplemental Figs. 1–18) than when all three variables were required to remain stable. Larger areas showed slow climate velocities or stable frequencies of extreme events for one or two variables than for all three together. For example, areas off Costa Rica and Nicaragua on the Pacific coast showed slow velocities in temperature or chlorophyll-a, but rapid oxygen change. In contrast, parts of the Dominican Republic EEZ showed stable oxygen and temperature but variable chlorophyll-a. The ecological relevance of partial refugia will depend on the extent to which environmental changes counteract or compound one another, which varies across species. For instance, stable or increasing oxygen and primary productivity may help offset some physiological effects of warming, such as increased metabolic rates and oxygen demand. In such cases, species may tolerate elevated temperatures if food availability and oxygen supply are sufficient to meet heightened energetic requirements (English et al. 2022; Kim et al. 2023; Köhn et al. 2022; Le Grix et al. 2023; Stramma et al. 2012). Further analysis is needed to assess the ecological consequences of partial refugia, including effects on population trends, species composition, and fisheries yield.

Exposure-based refugia should be used as prioritization tools or hypotheses that require validation through biological data and monitoring (Barrows et al. 2020). Areas with slow-moving climate velocities or stability in extreme events may support higher relative abundance or slower rates of decline, especially for marine organisms living near their environmental tolerance limits (Brown and Thatje 2014; Brown and Thatje 2015; Harrison and Noss 2017; Morelli et al. 2016). Therefore, baseline environmental conditions across EEZs shape the potential effect of refugia. In areas where present-day conditions are already near species’ physiological limits, even minor additional changes in temperature or oxygen could exceed tolerance thresholds. In these contexts, refugia may serve not just to slow population decline, but to support persistence under increasingly stressful conditions (Deutsch et al. 2015; Keppel et al. 2024; Pörtner 2021). In Central America, these high-risk baseline conditions are concentrated along the Pacific coasts of Guatemala, El Salvador, Nicaragua, and Costa Rica, as well as in the Caribbean EEZs of Costa Rica and Panama (Cheung et al. 2018).

The potential benefits of marine climate refugia also depend on non-climatic human impacts. Unsustainable activities such as overfishing, habitat loss, and pollution can reduce ecosystem resilience and service provisioning regardless of climate exposure (Gissi et al. 2021; Kavousi and Keppel 2018). Because refugial function may decline in areas with high non-climate stress, exposure layers should be integrated with data on species sensitivity, fisheries pressure, social priorities, and local knowledge to identify areas most likely to support biodiversity and fisheries under climate change (Kavousi and Keppel 2018; Keppel et al. 2015). Conversely, well-managed or conservation-oriented uses, such as MPAs, can enhance biomass, biodiversity, and ecosystem resilience (e.g., Sala et al. 2021). Building on this, recent studies show that sustainable fisheries management and biodiversity conservation can reduce climate risk (Boyce et al. 2024; Chavez-Molina et al. 2023; Cheung et al. 2024), and that regional coordination can improve resilience and outcomes under warming (Palacios-Abrantes et al. 2022; Vogel et al. 2023).

Regional approaches to climate smart fisheries management are especially important for transboundary species, whose distributions shift across national jurisdictions in response to environmental variability and change. For example, highly migratory billfish in the Eastern Tropical Pacific exhibit climate-driven redistributions between coastal and offshore areas

and across EEZs (Haulsee et al. 2022). OSPESCA provides a basis for managing refugia as connected systems because it already coordinates harmonized fisheries policies, regional monitoring systems, and joint management measures among member countries. Following recommendations for climate refugia management (Morelli et al. 2016), member countries could jointly define the resources and objectives that refugia are intended to support, evaluate climate risk by considering exposure, species sensitivity, and adaptive capacity, and prioritize management interventions in sites according to three-dimensional connectivity, size, seasonality, and feasibility. Concrete management measures could include MPAs and OECMs, adaptive fisheries instruments such as dynamic seasonal closures or effort controls, and coordinated early-warning systems for marine heatwaves and deoxygenation events that trigger pre-agreed management responses across member states. Improving the data infrastructure that underpins these measures, including enhanced monitoring of fishing effort, catch composition, spatial fleet behavior, would allow exposure layers to be integrated with real-time fishery data, enabling detection of climate-driven shifts in stock availability and fishing effort to provide feedback for adaptive management responses.

Climate refugia should be viewed as dynamic components of adaptation because under current conditions, they occupy a small portion of marine space (Ban et al. 2016; Kocsis et al. 2021; Pidd et al. 2025; Zhuang et al. 2025), and past exposure patterns do not guarantee future stability. Climate-smart planning increasingly emphasizes connectivity, exposure gradients, and ecological plasticity (Kavousi and Keppel 2018; McClanahan et al. 2024; Morelli et al. 2016). In this framework, the refugia identified here represent areas of slower change that may support persistence but should be paired with corridors and protected destinations that allow for species movement and adaptation (Morelli et al. 2020). As interest in integrating refugia into marine spatial planning increases, the indicators used in this study, climate velocity, extreme events offer actionable inputs for regional planning processes (Johnson and Kenchington 2019). Ultimately, embedding climate exposure into regional fisheries governance aligns with broader blue economy objectives, where identifying areas of relative environmental stability can help safeguard fisheries-dependent livelihoods, reduce income volatility for coastal communities, and support diversification strategies in the face of climate risk.

Declarations

Competing Interests

Tayler McLellan Clarke and Fabio Quesada-Pérez were engaged as consultants by the Federación Costarricense de Pesca (FECOP) to conduct this research, which was funded through Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH [Contract No. 83489092, Project Reference No. 20.9024.9-001.00]. No other competing interests are declared.

Author Contribution

J.C.C., M.M., and D.M.F. contributed to the conceptualization of the study, leading the development of the research objectives. T.M.C. developed the analytical framework and methodology, curated the data, conducted the formal analysis, and some of the visualizations, with constant input and feedback from all co-authors. F.Q.P. contributed to data curation, methodology, and visualization. J.C.C., L.V.A., M.M., and D.M.F. contributed to methodology and interpretation of the results. J.C.C., M.M., L.V.A. and D.M.F. contributed to funding acquisition and project administration. T.M.C. wrote the original draft of the manuscript. All authors contributed to the discussion and interpretation of the results and reviewed and edited the manuscript. All authors approved the final version of the manuscript.

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Data Availability

The underlying oceanographic data were sourced from two Copernicus Marine Service products: the Global Ocean Physics Reanalysis (GLOBAL_MULTIYEAR_PHY_001_030; https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description) and the Global Ocean Biogeochemistry Hindcast (GLOBAL_MULTIYEAR_BGC_001_029; https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_BGC_001_029/description), both of which are publicly accessible through the Copernicus Marine Service.

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Figures

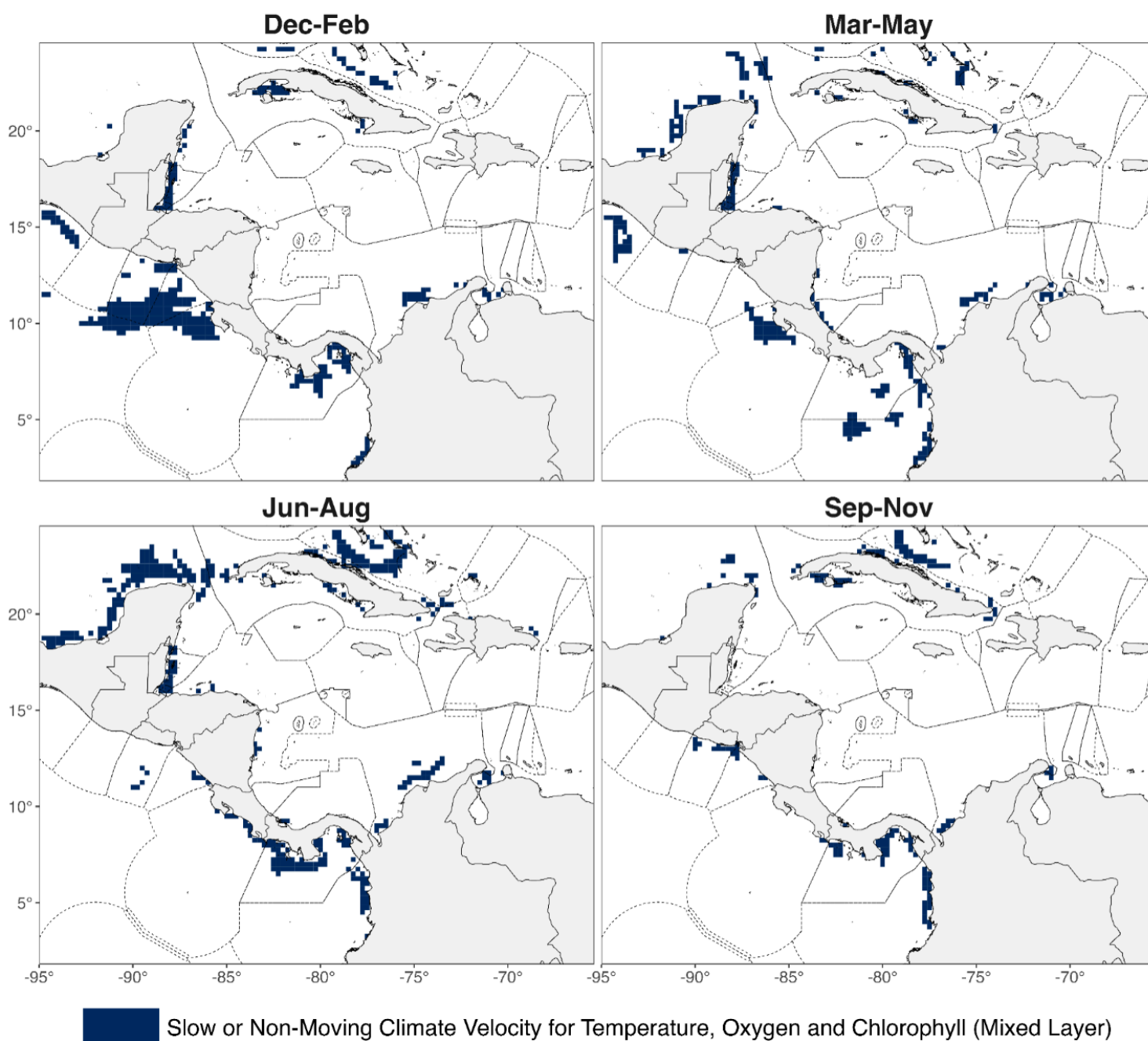


Figure 1

Spatial distribution of historical climate refugia within OSPESCA member-country EEZs and surrounding high seas identified using the climate-velocity method in the mixed layer. Panels are shown by season, where titles indicate the three-month periods of December–February, March–May, June–August, and September–November. Climate refugia are defined as grid cells where temperature, oxygen partial pressure and chlorophyll-a exhibit slow or non-moving climate velocity (between -2 km yr^{-1} and $+2 \text{ km yr}^{-1}$) over 1993–2020 within each seasonal window.

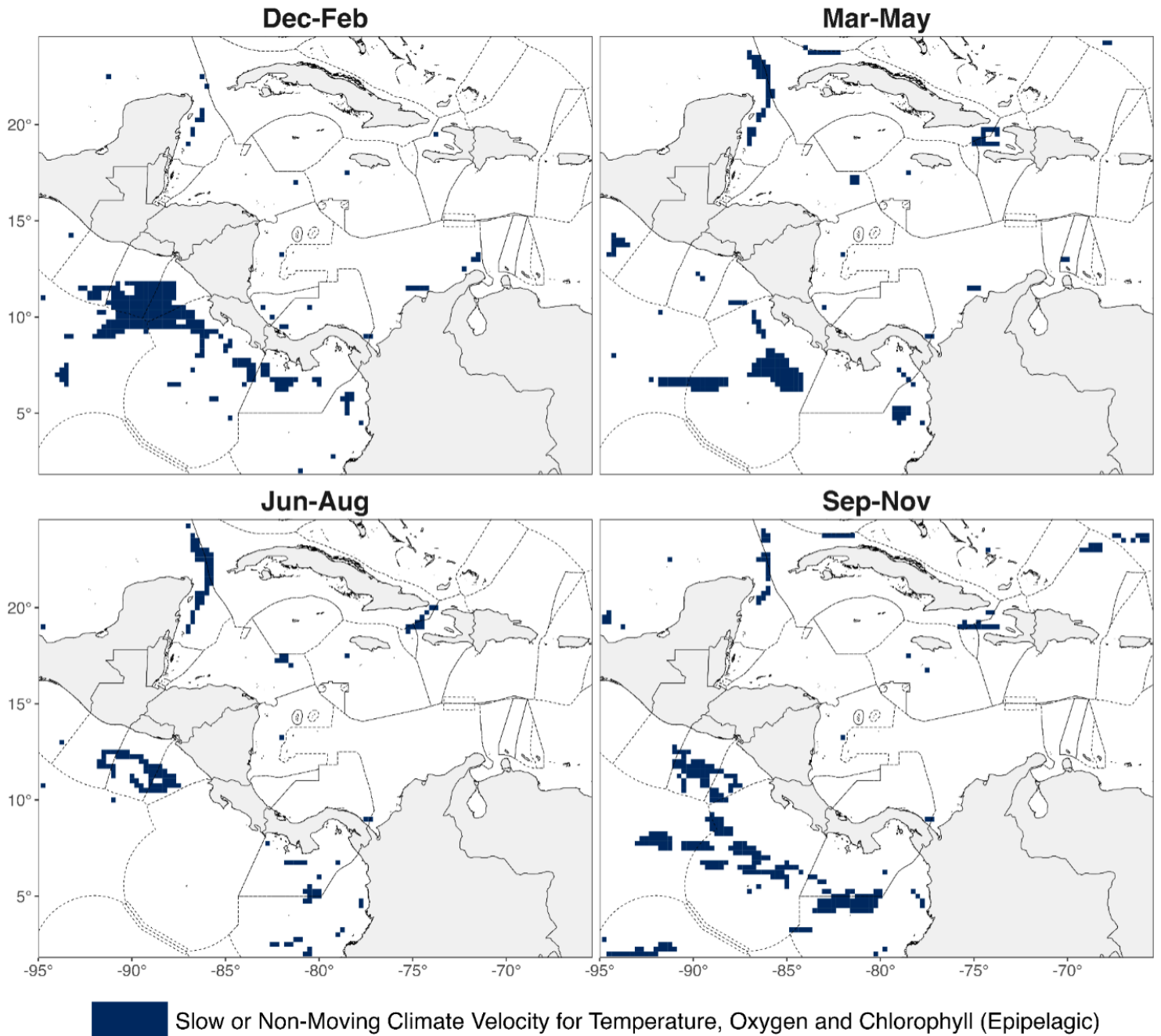


Figure 2

Spatial distribution of historical climate refugia within OSPESCA member-country EEZs and surrounding high seas identified using the climate-velocity method in the epipelagic zone (mixed layer–200 m). Panels are shown by season, where titles indicate the three-month periods December–February, March–May, June–August, and September–November. Climate refugia are defined as grid cells where temperature, oxygen partial pressure and chlorophyll-a exhibit slow or non-moving climate velocity (between -2 km yr^{-1} and $+2 \text{ km yr}^{-1}$) over 1993–2020 within each seasonal window.

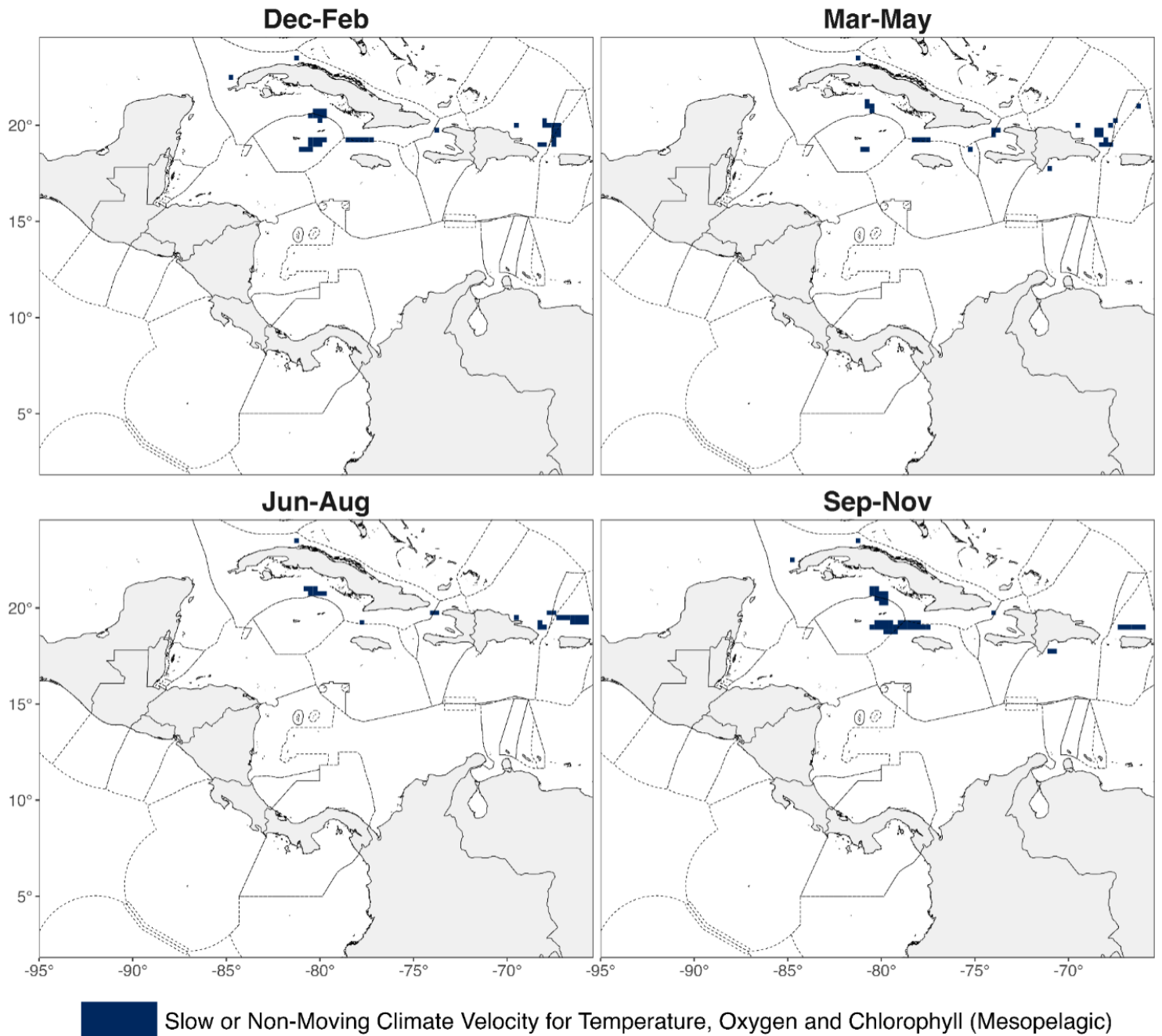


Figure 3

Spatial distribution of historical climate refugia within OSPESCA member-country EEZs and surrounding high seas identified using the climate-velocity method in the mesopelagic zone (200–1000 m). Panels are shown by season, where titles indicate the three-month periods December–February, March–May, June–August, and September–November. Climate refugia are defined as grid cells where temperature, oxygen partial pressure and chlorophyll-a exhibit slow or non-moving climate velocity (between -2 km yr^{-1} and $+2 \text{ km yr}^{-1}$) over 1993–2020 within each seasonal window.

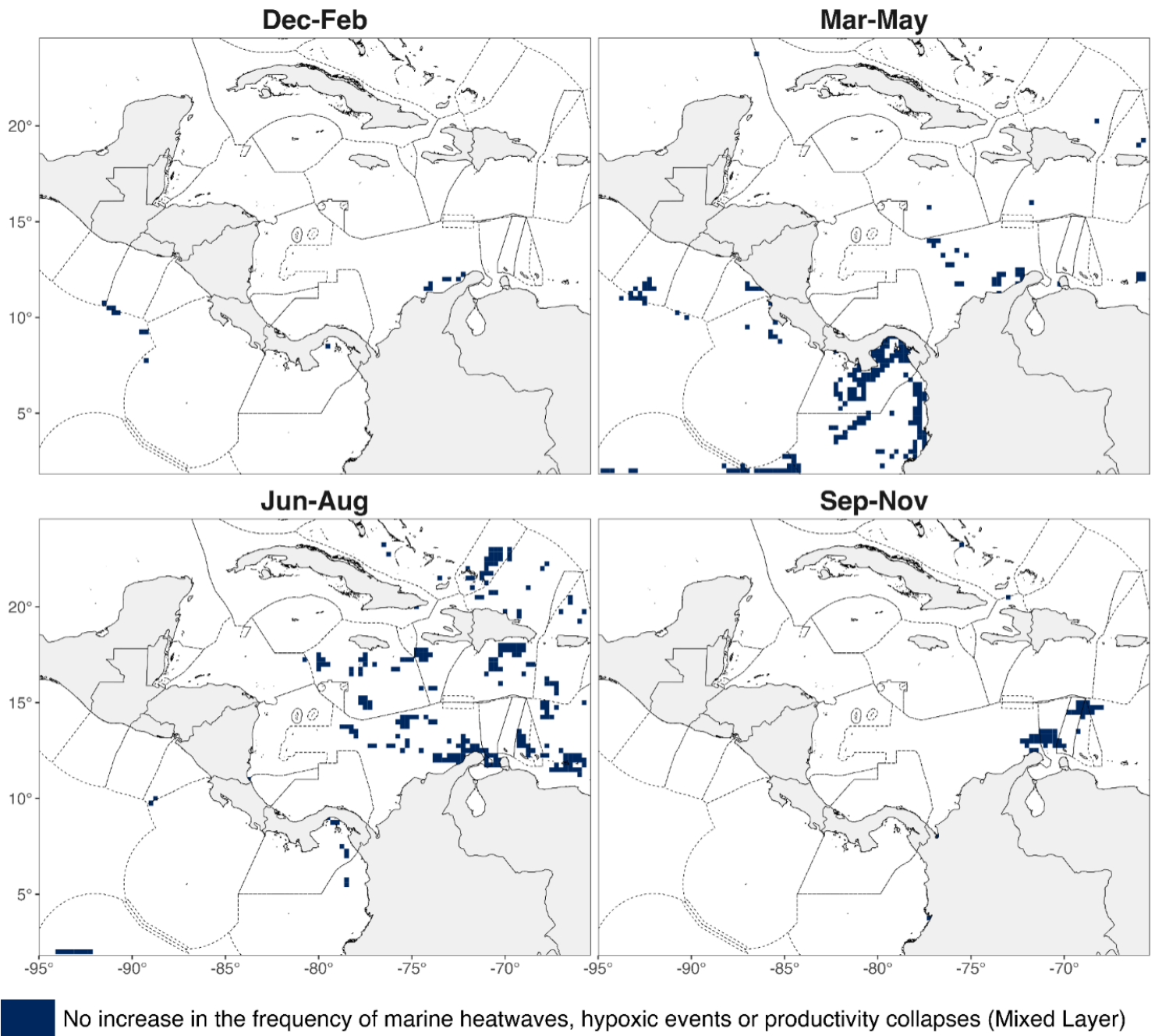


Figure 4

Spatial distribution of historical climate refugia within OSPESCA member-country EEZs identified using the extreme-event stability method in the mixed layer. Panels are shown by season, where titles indicate the three-month periods December–February, March–May, June–August, and September–November. Under the extreme-event stability definition, refugia are grid cells where the frequency of extreme events did not increase during 2014–2020 relative to 1993–2013 within each seasonal window.

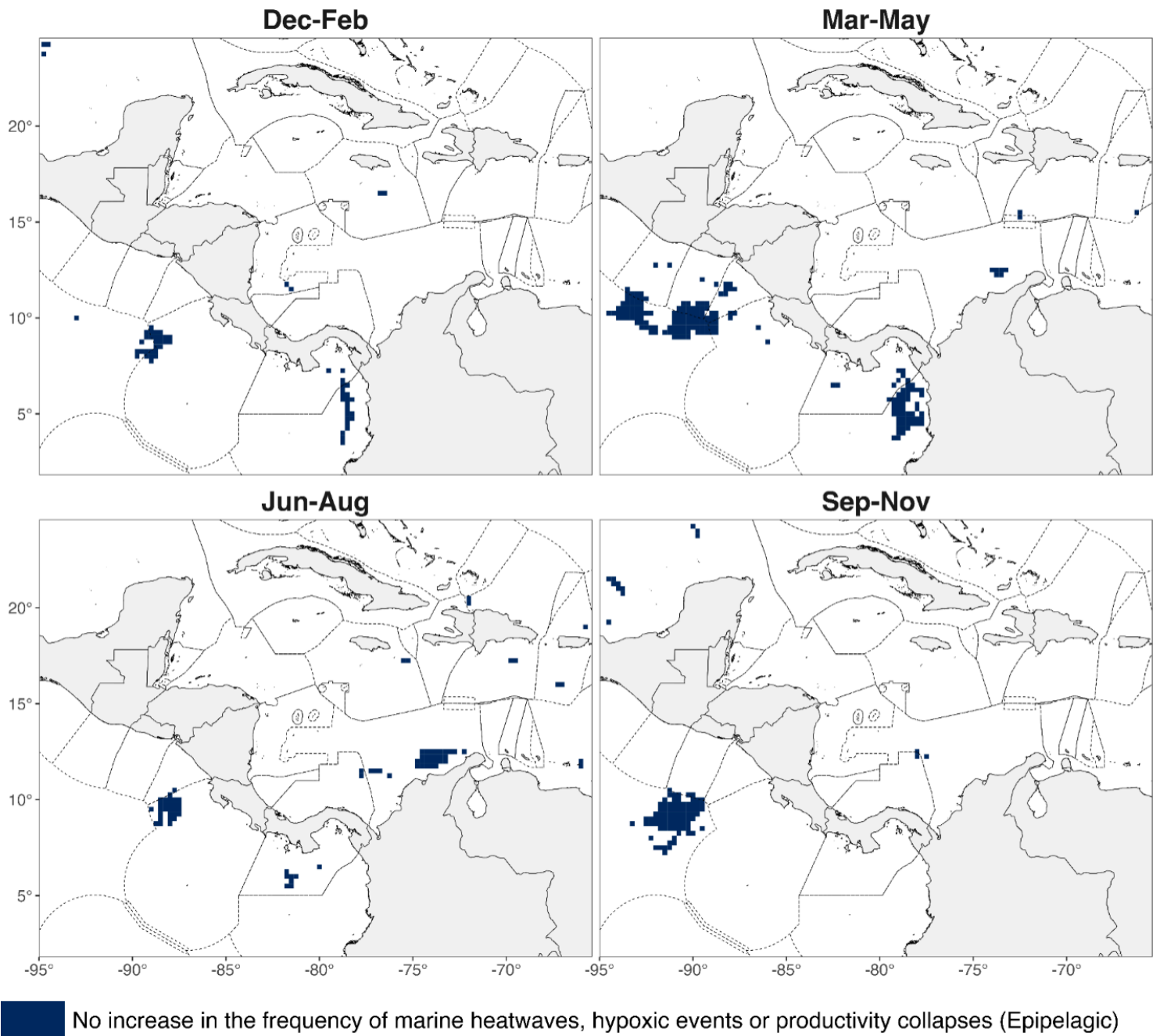
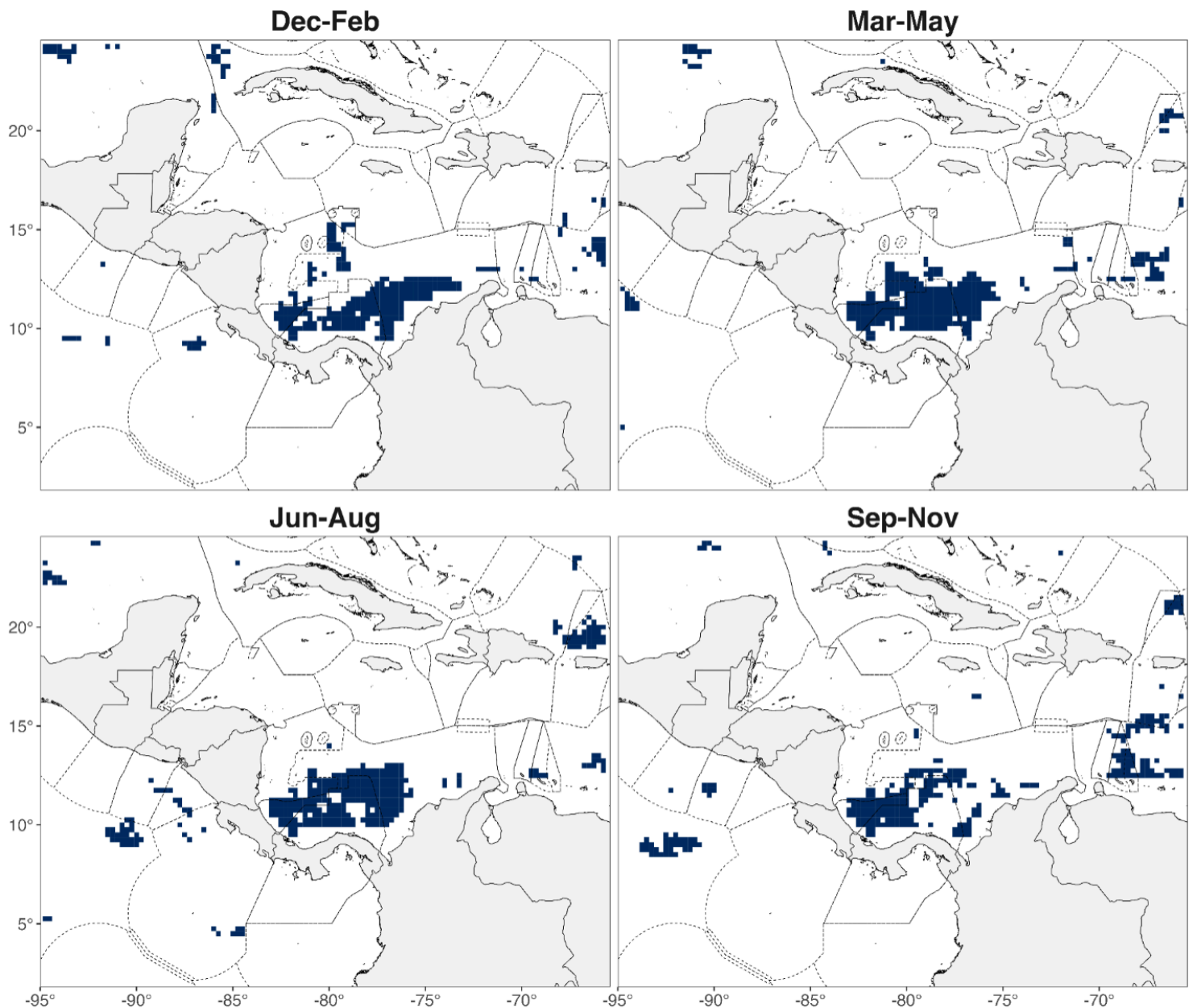


Figure 5

Spatial distribution of historical climate refugia within OSPESCA member-country EEZs identified using the extreme-event stability method for in the epipelagic zone (mixed layer–200 m). Panels are shown by season, where titles indicate the three-month periods December–February, March–May, June–August, and September–November. Extreme-event refugia are grid cells where the frequency of extreme events did not increase during 2014–2020 relative to 1993–2013 within each seasonal window.



 No increase in the frequency of marine heatwaves, hypoxic events or productivity collapses (Mesopelagic)

Figure 6

Spatial distribution of historical climate refugia within OSPESCA member-country EEZs identified using the extreme-event stability method in the mesopelagic zone (200–1000 m). Panels are shown by season, where titles indicate the three-month periods December–February, March–May, June–August, and September–November. Extreme-event refugia are grid cells where the frequency of extreme events did not increase during 2014–2020 relative to 1993–2013 within each seasonal window.

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