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Identifying global marine climate refugia through a conservative approach to ocean biodiversity preservation

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Global changes threaten marine species, making marine climate refugia essential for biodiversity conservation and climate change mitigation. Our analysis maps sensitive and stability zones across the global ocean. We define marine climate refugia as climate-resilient zones with global conservation consensus under the worst-case emissions scenario for 2100. Marine climate refugia span 17.6 million square kilometres, with 96% within exclusive economic zones. Only 34% of oceanic areas and 29% of marine protected areas (MPAs) and other effective area-based conservation measures (OECMs) lie in stability zones. Twenty large-scale patches form the principal bodies of marine climate refugia, with 85% crossing multiple exclusive economic zones. Conservation gaps cover 70% of marine climate refugia. Closing these gaps could increase global ocean protection to 14% and exclusive economic zones protection to 30%. To achieve the 30 by 30 target, we recommend expanding MPAs and OECMs based on marine climate refugia locations and addressing transnational management challenges.

The ocean encompasses more than 90% of the habitable space on our planet and offers ecosystem services of immense value to humanity[1–3]. However, irresponsible anthropogenic activities and escalating climate change are leading to irreversible degradation of marine and coastal ecosystems, thereby undermining the ocean's ability to provide these services[4,5]. By 2100, as much as 90% of marine life may face a high or critical risk of extinction[6]. In situ conservation networks, including marine protected areas (MPAs) and other effective area-based conservation measures (OECMs), represent the most effective strategies for managing human activities and responding to climate change[7–9]. Following the unfulfilled Aichi Targets, COP15 proposed an even more ambitious 30 by 30 target, aiming to safeguard at least 30% of marine ecosystems by 2030[10]. The uneven distribution of biodiversity and associated anthropogenic pressures necessitates strategic prioritization efforts to mitigate species loss[11]. With the approaching deadline for this global vision, the prioritization of identifying critical marine areas—designated as global marine conservation priorities—has once again become a key issue at the 2025 UN Ocean Conference[12,13].

Despite the challenges associated with surveying and researching the vast and complex oceans, notable explorations regarding marine conservation priority areas have been conducted[14–16]. A conservation strategy that prioritizes flagship species, which are species selected to garner support for biodiversity conservation within a specific geographical or socio-cultural context, can attract conservation investments[17–19]. These species can also provide an umbrella effect, serving as proxies for safeguarding numerous other species within the same ecological community and thereby contributing to regional biodiversity conservation efforts[18,20]. Certain designations for high seas biodiversity conservation have deliberately reconciled benefits and costs[21–23]. Furthermore, ecosystem services are being increasingly

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integrated into marine spatial decision-making and effectiveness assessments[24–26]. Nonetheless, these studies are hindered by limitations in spatial scale and representativeness, as well as a lack of standardized justification for the selection of designated areas, thereby complicating the global implementation of marine conservation priorities. Influential international organizations, including the International Union for Conservation of Nature, the Secretariat of the Convention on Biological Diversity, and the World Wildlife Fund, have proposed several criteria and regions for global marine conservation priority areas that have gained recognition from both scientists and a growing number of national governments. Nevertheless, similar to existing marine protected areas, the impacts of climate change have not been fully discovered in these areas, thereby rendering their long-term benefits uncertain[27–29].

Cooling and warming events in history have allowed refugia such as the Amazon, Congo Basin, Russia's boreal forests, the Arctic, and the Hengduan Mountains to support biodiversity by maintaining stable conditions despite climate change[30–33]. As a result, refugia should be prioritized for marine conservation. Previous efforts have focused on establishing criteria to assess marine climate refugia and propose potential conservation regions[34–36]. However, few studies have included refugia mapping, and most are limited to regional scales or specific aspects of marine biodiversity. Forecasting climate change patterns is a prerequisite for the designation of refugia and presents an ongoing challenge for climate change science. Current methods still have limitations in accurately capturing the detailed climate change patterns at smaller spatial scales in the ocean. For example, climate velocity, defined as a metric that quantifies the speed and direction of climate displacement at any spatial location, predominantly emphasizes simplistic indicators; however, marine climate change is inherently a multidimensional phenomenon[4,37,38]. The niche shifting method, which refers to predicting the changes in species distribution patterns before and after climate change, is evidently influenced by species-specific biome preferences[39,40]. Climate novelty analysis quantifies the difference between the typical climate at a specific location and its closest match in global climate baseline data, helping to assess climate change exposure[41,42]. However, this approach overlooks the specifics of climate variables and fails to account for spatial autocorrelation, as outlined in Tobler's First Law of Geography (spatial autocorrelation)[43].

This study seeks to identify marine climate refugia (MCR) on a global scale. To achieve this objective, we design two criteria for MCR: (i) climate resilience, which ensures stability even under the most pessimistic climate change scenarios, and (ii) conservation consensus, which necessitates acknowledgement from at least two globally representative marine conservation priority areas. We further analyse the climate change risk of existing in situ conservation networks and emphasize the importance of establishing large-scale marine protected areas across exclusive economic zones (EEZs) to address gaps in global MCR. This study first advocates for a conservative strategy for global marine conservation and then delineates the responsibilities associated with MCR for coastal countries and regions. We contend that MCR does not constitute merely a vision but rather the foundation for global marine conservation, representing the last hope for marine life amid impending global changes.

Results

Global marine climate change patterns

Based on the Getis–Ord Gi* statistic hotspot analysis of climate variability outputs from Zonation, we identified sensitive zones (hot spots) and stability zones (cold spots) under the SSP5-8.5 scenario (more details in the method section). The sensitive zones, accounting for 88% of all hot spots, encompass 36% of the global ocean and are primarily distributed in the Arctic Ocean, North Atlantic Ocean, and Southern Ocean (Figs. 1a and S1). Additionally, the stability zones encompass 34% of the ocean and account for 86% of all cold spots (Figs. 1a and S1). Global marine climate change has latitudinal zonality (Fig. 1b, e). The torrid and frigid zones represent the peaks of the sensitive zone distribution, with the northern frigid zone being the most vulnerable to future climate change (Fig. 1b). Conversely, the stability zones are most concentrated in the southern temperate zone, whereas the torrid and frigid zones demonstrate troughs in their distributions (Fig. 1b). Both the sensitive zones and the stability zones exhibit a landward-shifting distribution trend along the horizontal gradient, with peak values observed in EEZs (Fig. 1c, f). Furthermore, the vertical zonality patterns of both the sensitive zones and stability zones are consistent, with peaks observed in the bathypelagic and abyssopelagic zones, respectively (Fig. 1d, g). The sensitive and stability zones were widely distributed in shallow waters at depths of less than 1000 metres (Fig. 1g).

Global marine conservation priority areas

Using a spatial overlay of four globally recognized conservation prioritization layers (CPAs), we found that forty-one percent of the global ocean has been designated as at least one CPA (Figs. 2a and S2). Among these areas, the Ecologically or Biologically Significant Marine Areas represent the largest area, making up 21% of the global ocean, whereas the Key Biodiversity Areas constitute the smallest area, accounting for merely 2% (Fig. 2a, b). Although the CPAs overlap, the proportion of their overlapping areas constitutes only 22%, and the extent of highly overlapping areas is even lower at 3% (Fig. 2a, c). All overlapping areas are defined as conservation consensus areas (CCAs) in this study. The CCAs constitute 9% of the global ocean, exhibiting a spatial distribution that is closer to land or islands and is surrounded by other CPAs (Fig. 2a). The CCAs make up 44%, 48%, 23%, and 70% of the Species–Genetic–Phylogenetic Diversity CPA, Global 200 Ecoregions, Ecologically or Biologically Significant Areas, and Key Biodiversity Areas, respectively (Fig. 2a).

Global marine climate refugia

By intersecting conservation consensus areas (CCAs, identified from overlapping CPA layers) with climate stability zones, we delineated marine climate refugia (MCR) (Fig. 3a). Twenty-nine percent of CCAs are situated in sensitive zones and are anticipated to face challenges associated with climate change in the future (Fig. S3). Conversely, 50% of CCAs located in stability zones constitute MCR for the global ocean (Fig. S3), encompassing a total area of 17,622,073 square kilometres, with 96% residing within an exclusive economic zone (EEZ) (Fig. 3a). MCR are distributed across 105 exclusive economic zones (Table S4). Notably, MCR areas were largest within the EEZs of Indonesia, French Polynesia, Hawaii, and the Philippines. Among the 340 independent patches of MCR, 20 met the area criteria for designating large-scale marine protected areas, with their cumulative area representing 85% of the total MCR area (Fig. 3b). The largest patch encompasses an area of approximately 3.4 million square kilometres. Sixteen large-scale patches of MCR spatially span two or more EEZs (Fig. S4 and Table S5).

Effectiveness of marine in situ conservation networks

We evaluated spatial overlap between identified MCR and marine protected areas (MPAs) and other effective area-based conservation measures (OECMs) using the World Database on Protected Areas. Among existing MPAs and OECMs, 27% are situated in sensitive zones, 29% in stability zones, and 14% in marine climate refugia (MCR) (Figs. 1a and 4a). Currently, MPAs and OECMs cover 10% of the global ocean and 23% of the global EEZ area, with 94% of these areas designated within EEZs. However, there remains a 70% in situ conservation gap within MCR, encompassing an area of 12,347,319 square kilometres (Fig. 1a). Currently, there are 99 EEZs with conservation gaps, of which 14 have gaps exceeding 160,000 square kilometres (Fig. 1b and Table S6). French Polynesia, Indonesia, and the Philippines have gaps of 2,553,091, 2,551,351, and 761,999 square kilometres, respectively

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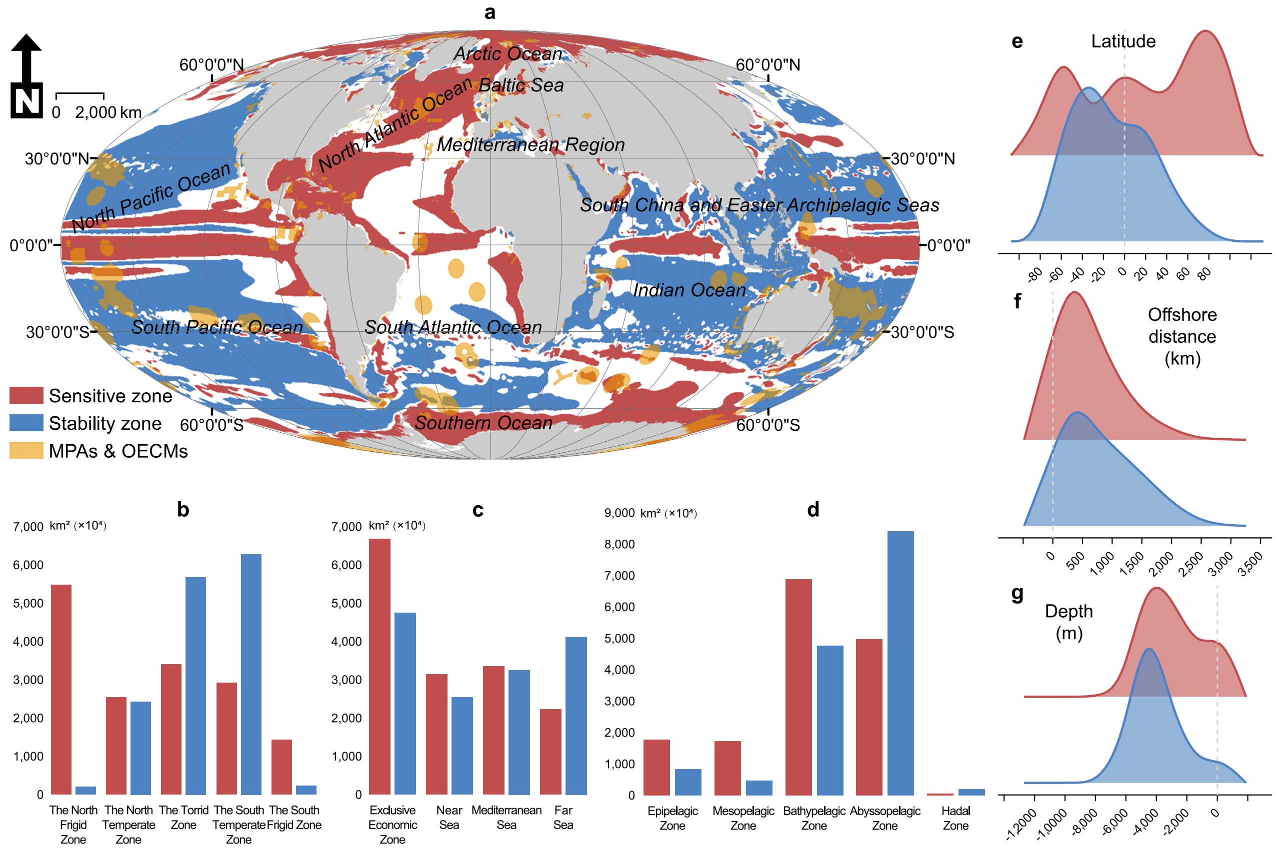

Fig. 1 | Spatial distribution patterns of sensitive and stability zones in the global ocean under the SSP5-8.5 scenario for the period 2090–2100. a Spatial distributions of sensitive and stability zones, marine protected areas (MPAs), and other effective area-based conservation measures (OECMs) in the global ocean. Statistics for sensitive and stability zones across **b** latitudinal zonality, **c** horizontal zonality, and **d** vertical zonality. Distribution trends of sensitive and stability zones in **e** latitudinal zonality, **f** horizontal zonality, and **g** vertical zonality. White areas represent other oceanic regions. The Y-axis in the Ridgeline Plot (**e, f** and **g**) indicates grid cell counts corresponding to latitude bands, horizontal gradients, and water depths.

(Fig. 4b). These MCR gaps are expected to be addressed in the future, increasing in situ conservation ratios for the global ocean and EEZs to 14% and 30%, respectively. Additionally, 17 large-scale patches of MCR are partially covered by MPAs or OECMs; however, their average coverage rate is only 20% (Fig. S5).

Discussion

To address the implementability, spatial scale, and climate change limitations of previously designated marine conservation priority areas, we first reveal the distribution patterns of global marine climate change and marine climate refugia (MCR) under the most pessimistic emission scenario. Our findings indicate that almost all MCR are found within exclusive economic zones and that the existing in situ conservation network not only addresses the risks posed by climate change but also presents a significant conservation gap. Consequently, we further clarified the responsibilities of countries and regions and determined the necessity of constructing large-scale marine protected areas across borders and regions in the future. Notably, the identified climate refugia represent a conservative baseline for ocean biodiversity protection, setting minimum thresholds for ecosystem preservation. While they fall short of the 30 by 30 target, they offer a foundation for future marine conservation. Areas with strong climate disturbances often show greater ecological vulnerability. Therefore, these regions, along with climate-sensitive species such as the migratory marine megafauna, should be integrated into an expanded conservation strategy[44,45].

Thermal properties, chaotic dynamics, and high connectivity define the universality and complexity of marine climate change[46,47]. The integration of systematic conservation planning and hotspot analysis represents an exploration of climate change pattern identification. Theoretically, the advantage of systematic conservation planning lies in its capacity to reveal regions with relatively greater absolute changes across multidimensional variables based on the cost–benefit principle, prioritizing them after all spatial units are assessed. This results in continuous priority values with increased spatial contrast. The hotspot analysis approach adheres to geographical spatial autocorrelation laws and further refines climate change patterns by detecting statistically significant clusters of high-priority values of climate variation alongside the stable low-priority value areas.

A clear observation of spatial heterogeneity in global marine climate change is evident. Substantial portions of the oceanic regions surrounding the equator and polar areas are projected to undergo significant climate change in the future. Temperatures in tropical and polar regions have demonstrated significant dynamic fluctuations over the past 485 million years[48]. Distributions of the horizontal and vertical gradients of the sensitive zones and stability zones are consistent with those of the sea area (Fig. S6). Marginal seas exhibit heightened sensitivity to dominant climatic factors, including land–sea distribution, atmospheric circulation, and ocean currents. Consequently, these regions (closer to shorelines and shallower depths) often contain more sensitive zones. In contrast, extensive bathypelagic and abyssopelagic zones contain numerous sensitive and stability zones. Research has demonstrated that these regions are highly important for predicting global climate change events, including sea level rise and extreme weather patterns[49]. Furthermore, the North Atlantic Ocean is generally

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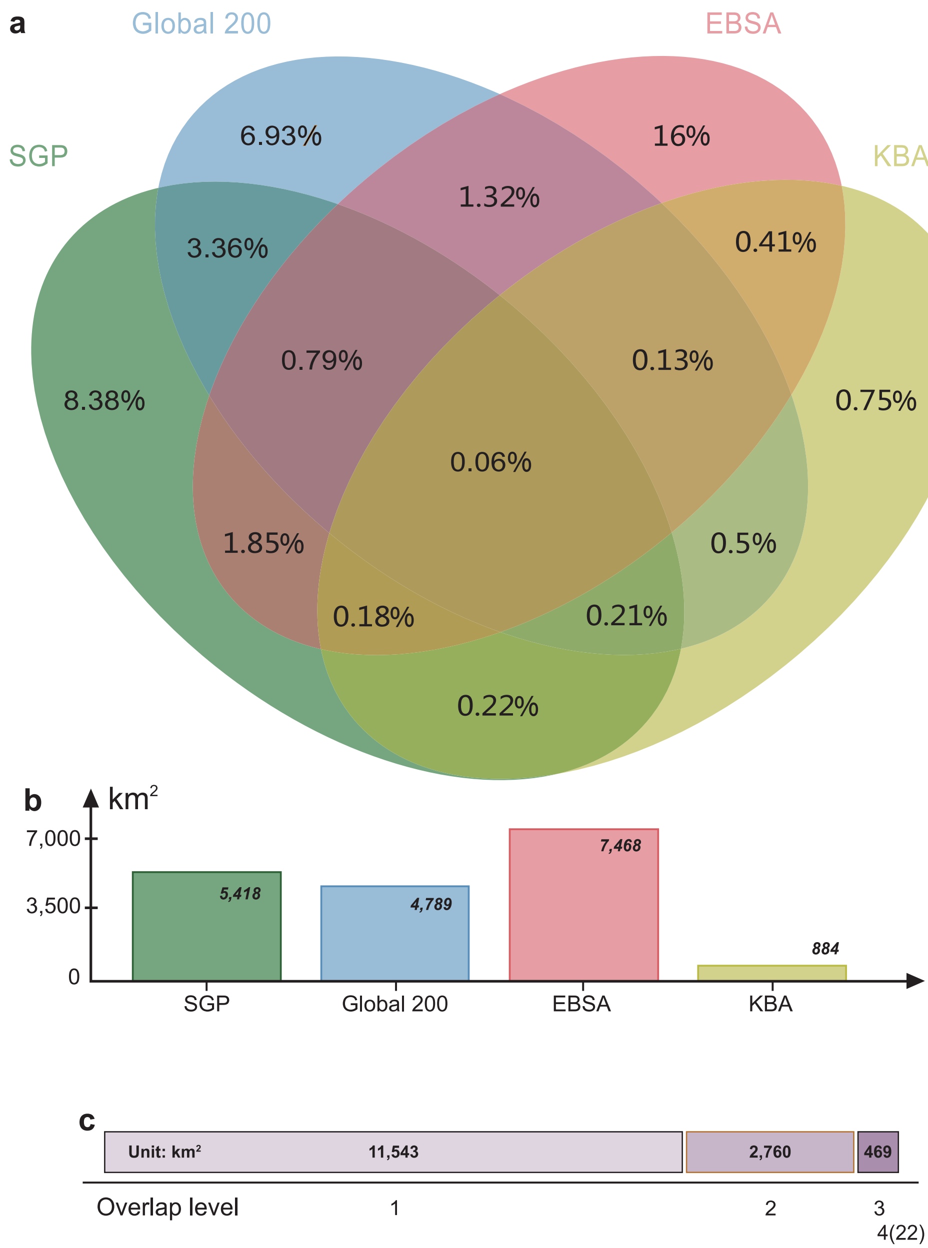

Fig. 2 | Spatial relationships of global marine conservation priority areas (CPA). **a** Spatial overlap relationships across Species–Genetic–Phylogenetic Diversity CPA (SGP), Global 200 Ecoregions (Global 200), Ecologically or Biologically Significant Marine Areas (EBSA), and Key Biodiversity Areas (KBA). **b** Total areas of SGP, Global 200, EBSA, and KBA. **c** The CPA sizes with different overlap intensities.

identified as a sensitive zone in this study, and its significant interannual to multidecadal fluctuations provide strong evidence to support this finding[50–52].

Uncertainties in climate model projections and scenario assumptions jointly shape the spatiotemporal evolution of future climate trajectories, affecting both timing and expression of impacts[53,54]. This study used climate data from CMIP6 Earth System Models under the SSP5-8.5 scenario, which represents the most severe climate change pathway. To address model uncertainties conservatively, we applied a zonal modeling framework combined with hotspot analysis to assess multivariate climate variability across global oceans and identify regions of relative resilience. Despite these efforts, regional model divergences may remain substantial, highlighting the need for multi-scenario sensitivity analyses in future research, particularly to support emerging conservation goals such as the 30×30 target and terrestrial biodiversity protection[55,56].

Only 29% of the existing in situ conservation networks are located within stability zones, suggesting uncertainty about the future effectiveness of conservation efforts, especially in areas located within sensitive zones. This research revealed that MCR can maintain stability even under the most pessimistic climate scenarios; however, 70% remain exposed outside existing in situ conservation networks. Fortunately, most MCR are located primarily within exclusive economic zones (EEZs), resulting in greater feasibility for in situ conservation within EEZs than in high seas[57]. As practitioners advance in the establishment of marine protected areas, an increasing number of scholars and managers have begun to recognize the need for sufficient space to effectively protect and restore marine biodiversity, leading to a growing call for the establishment of large-scale marine protected areas[58,59]. Our findings indicate that only 6% of patches of MCR meet the size criteria for large-scale MPAs, yet these patches encompass 85% of the total area of MCR. Additionally, 85% of large-scale patches of

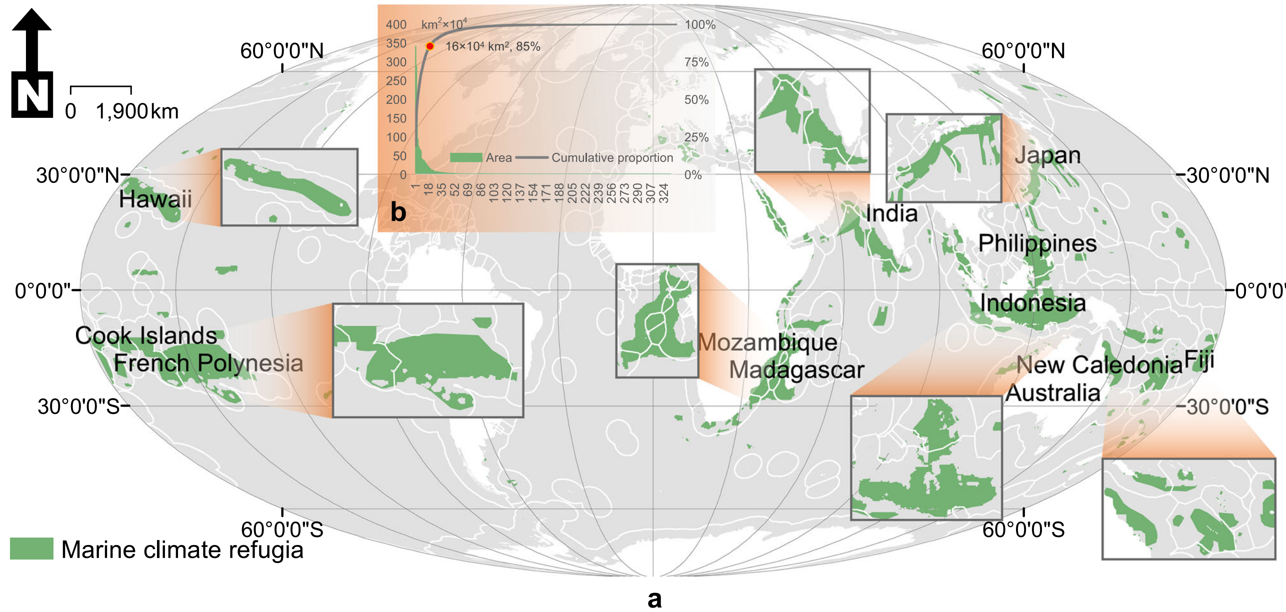

Fig. 3 | Spatial distribution of global marine climate refugia. a Spatial distribution of marine climate refugia (MCR) and exclusive economic zones (EEZs). The names marked in **a** are the EEZs with MCR areas exceeding 500,000 square kilometres, and these MCRs have been highlighted. **b** Area cumulative curve of independent MCR patches. White lines in **a** represent the boundaries of EEZs.

MCR have already established some foundation for in situ conservation, suggesting that these protection gaps can be addressed through future expansion. Furthermore, 80% of large-scale patches of MCR span multiple national or regional EEZs, presenting both challenges for spatial management and opportunities for international collaboration.

In conclusion, significant hotspots (p_value ≤ 0.01) of future marine climate change account for 36% of the global ocean; however, only 29% of existing marine protected areas (MPAs) and other effective area-based conservation measures (OECMs) are situated within stability zones. The marine climate refugia (MCR) identified in this study not only mitigate the impacts of climate change but also represent a global consensus on ocean conservation; however, a 70% conservation gap remains. On the one hand, 96% of MCR are situated within exclusive economic zones (EEZs), clarifying their protection responsibilities. This spatial delineation directly offers scientifically-grounded implementation pathways for accelerating action and mobilizing all actors to conserve and sustainably use the ocean proposed by the 2025 UN Ocean Conference. Conversely, 20 large-scale patches form the primary components of MCR, accounting for 85% of the total area. While 17 of these patches already have some foundation for in situ conservation efforts, 16 patches span multiple EEZs, which may present challenges to overcome. Integrating MCR into existing in situ conservation networks could encompass 30% of EEZs and 14% of the global oceans, supporting the IPBES Spatial Planning and Connectivity Assessment (https://www.ipbes.net/spatial-planning-assessment). Notably, this study does not advocate for the reduction of any existing in situ conservation areas and proposes implementing sustainable management strategies in MCR.

Methods

Identification of climate change patterns

Calculation of climate variability. The marine biodiversity conservative conservation strategy discussed in this study is designed to ensure its adaptability in the face of future extreme climate change scenarios. Therefore, we used the 2010-2020 current conditions as the baseline and focused on climate variability in the most pessimistic future scenario (2090-2100 fossil-fuelled development SSP5-8.5 scenario of high emissions and low challenges to adaptation)[16,60]. We normalized all the variable layers using fuzzy membership (linear type, range: 0-1) to eliminate dimensionality differences. The climate variability of each variable was subsequently calculated using Eq. (1).

$$V = |X_i - Y_i| \tag{1}$$

V represents the climate variation value (range: 0-1), whereas X_i and Y_i represent the current and future values, respectively, of the i-th variable.

By conducting correlation analysis, we selected variables with a correlation coefficient not exceeding 70% (Table S1 and S2) for further analysis, thus effectively eliminating the influence of multicollinearity. The spatial analysis and map drawing of this study were based on ArcGIS (version 10.8.1).

Integrated climate variability. The optimization algorithm used in Systematic Conservation Planning effectively balances multiple objectives and spatial costs, making it widely applicable in complex spatial decision-making[61,62]. In this study, we utilized the Zonation (version GUI 4.0.0) model to prioritize global ocean units based on their climatic variability and geographical location. All the variation value layers corresponding to the 11 variables were input as target layers, with core-area and edge removal designated as the cell removal rules. The warp factor was set to 1 to ensure the identification of the optimal solution, while all other model parameters were retained at their default settings. The resulting output was a continuous raster in which lower-priority values corresponded to more stable under future climate conditions.

Hotspot analysis. We employed the Getis–Ord Gi* statistic to identify statistically significant hot and cold spots associated with global marine climate change[63,64]. The output raster from Zonation served as the input feature for hotspot analysis, with the priority value designated as the analysis weight. In this study, sensitive zones were defined as extremely significant hot spots (Gi_Bin=3, p_value < 0.01), indicating spatial clustering of high climate change intensity; stability zones were defined as extremely significant cold spots (Gi_Bin = -3, p_value < 0.01), indicating spatial clustering of low climate change intensity.

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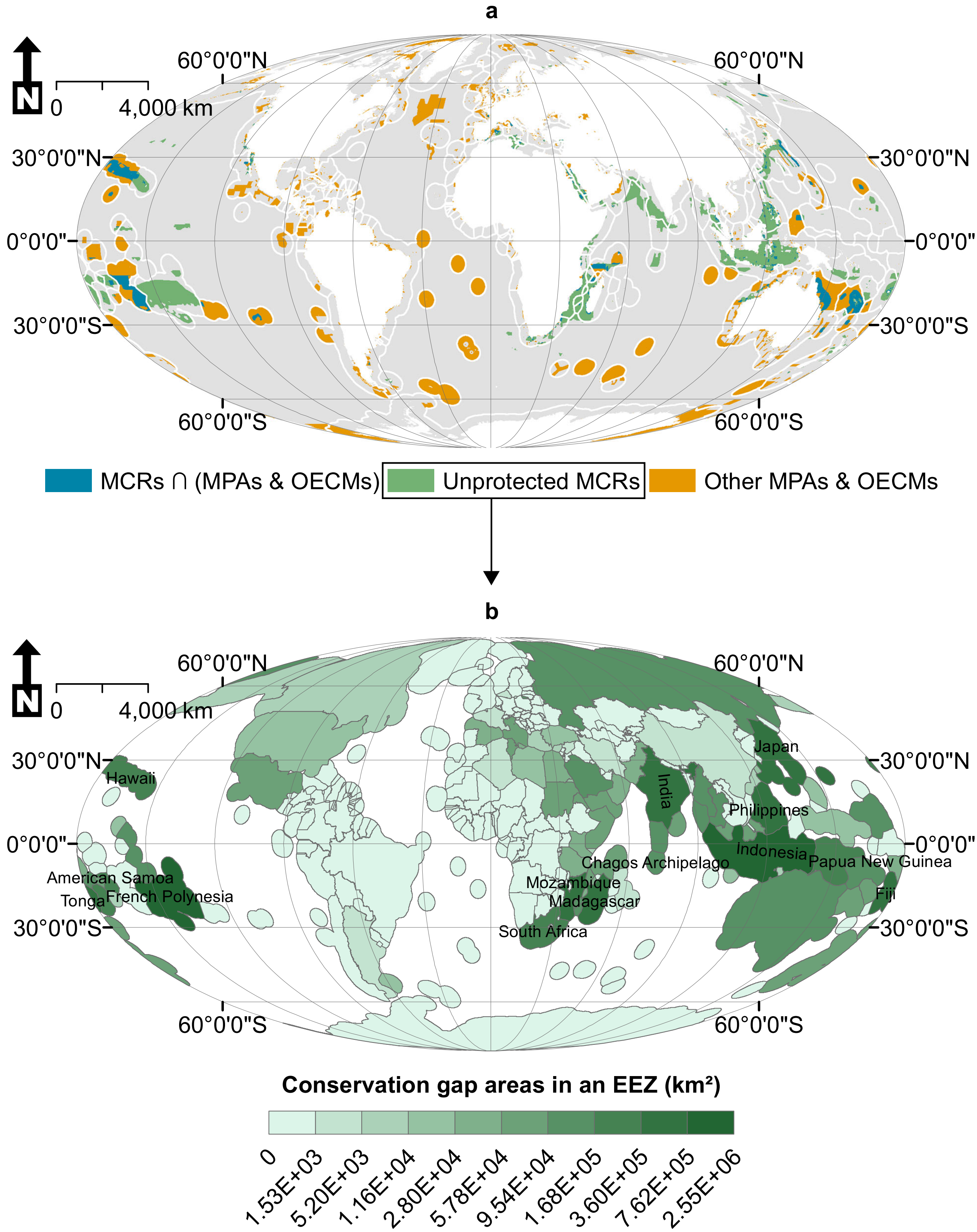

Fig. 4 | The current status of in-situ conservation for global marine climate refugia. **a** Conservation gaps in marine climate refugia (MCRs) and **b** distribution patterns of conservation gaps in exclusive economic zones (EEZs) based on area statistics. The white lines in **a** represent the boundaries of EEZs. Unprotected MCRs in **a** represent a conservation gap. MPAs represent marine protected areas. OECMs represent other effective area-based conservation measures. The names marked in **b** are the EEZs with conservation gap areas exceeding 160,000 square kilometres.

Furthermore, we calculated the total area and grid cells of the zonal distributions of the sensitive zones and stability zones, including latitudinal, horizontal, and vertical zonality. Additionally, summary statistics were generated for five latitudinal zones: the North Frigid Zone (66.5°N-90°N), North Temperate Zone (23.5°N-66.5°N), Torrid Zone (23.5°N-23.5°S), South Temperate Zone (23.5°S-66.5°S), and South Frigid Zone (66.5°S-90°S); four horizontal zones: Exclusive Economic Zone (< 200 nautical miles), Near Sea (200-350 nautical miles), Mediterranean Sea (350-600 nautical miles), and Far Sea (> 600 nautical miles); and five depth zones: the Epipelagic Zone (< 200 metres), Mesopelagic Zone (200-1000 metres), Bathypelagic Zone (1000-4000 metres), Abyssopelagic Zone (4000-6000 metres), and Hadal Zone (> 6000 metres). This study primarily focused on conducting statistical analyses of surface climate change across sea areas at varying depths, without delving into stratified analyses of climate change based on different depth levels.

Determination of marine climate refugia

We conducted a spatial meta-analysis of four global marine conservation priority areas (CPAs), including the Species–Genetic–Phylogenetic Diversity CPA[65]; Global 200 Ecoregions[66]; Ecologically or Biologically Significant Marine Areas (www.cbd.int/ebsa); and Key Biodiversity Areas (www.keybiodiversityareas.org) (Table S3). The CPA layers were then overlaid based on the number of times the zone was identified by different CPA layers. Areas covered by two or more CPA layers were defined as conservation consensus area (CCA) with multiple benefits.

These CPAs were selected based on the following criteria: (i) they were globally representative and highly important for marine conservation and were not restricted to specific taxa or ecological functions, (ii) they possessed widespread appeal, as relevant areas had received support from the United Nations, international conventions, or been funded by global foundations, and (iii) their boundaries were clear and transparent. Global 200 Ecoregions, Ecologically or Biologically Significant Marine Areas, and Key Biodiversity Areas all satisfy these three criteria. Although the Species–Genetic–Phylogenetic Diversity CPA is a recent development that does not yet fully satisfy criterion (ii), it represents the first global examination that reveals marine biodiversity conservation priority areas from the perspectives of species, genetic, and phylogenetic diversity; consequently, it was included in this analysis. Owing to differences in the selection of surrogates, emphasis on criteria, and designation methods, these CPAs demonstrate significant variation from one another. Species–Genetic–Phylogenetic Diversity CPA emphasizes genetics and phylogeny, whereas Global 200 Ecoregions and Ecologically or Biologically Significant Marine Areas focus on ecoregions, and Key Biodiversity Areas focuses on species and ecosystems. Clearly, no single CPA is sufficient for comprehensive marine biodiversity conservation; thus, overlay analysis is necessary. The CCA areas located in stability zones were designated the marine climate refugia (MCR). We further conducted an analysis of MCR distribution patterns across exclusive economic zones and generated area cumulative curves by analyzing the sizes of independent MCR patches (including large-scale patches, ≥150,000 square kilometres).

Assessment of existing in situ conservation networks

For the marine in situ conservation network, we utilized August 2024 data from the World Database on Protected Areas, which includes marine protected areas (MPAs) and other effective area-based conservation measures (OECMs) (www.protectedplanet.net). We exclusively employed marine area data and implemented a conservative approach to select the in situ conservation network for inclusion in our analysis. After excluding land portions, the total area of MPAs and OECMs was 36,947,863 square kilometres (using the Mollweide projection). We initially assessed the potential risks posed by climate change to the existing in situ conservation network by overlaying sensitive zones and stability zones. To enhance the existing in situ conservation network, we conducted a gap analysis by identifying areas currently within MCR that were not covered by existing MPAs and OECMs.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data supporting the findings of this study are available with this paper. The layer data for the sensitive zone, stability zone, and marine climate refugia generated in this study have been deposited in the Figshare database under accession code: https://doi.org/10.6084/m9.figshare.29307197. The global land basemaps in Fig. 1a, and Supplementary Figs. S1–S4 were obtained from the publicly available GitHub database of a published paper (https://github.com/fanhuizhong/Marine-biodiversity/tree/main/03.map/SHP)[65]. The global ocean basemaps in Fig. 1a, Fig. 3a, and Fig. 4a were obtained from the public database of Marine Regions (https://www.marineregions.org/download_file.php?name=GOaS_v1_20211214.zip)[67]. The exclusive economic zones basemaps in Fig. 3, Fig. 4, and Supplementary Figs. S3, S4 were obtained from the public database of Marine Regions (https://www.marineregions.org/download_file.php?name=EEZ_land_union_v3_202003.zip)[68].

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Author contributions

H.Z., Z.Z., and L.Y. conceived and designed the study. H.Z. and L.Y. performed the analyses to identify the MCR. L.Z. and Z.W. conducted the gap analyses. H.Z. and L.Y. created the figures. H.Z., L.Z., and L.Y. drafted the initial manuscript, while Z.W. and Z.Z. contributed to the writing and revision of the manuscript.

Competing interests

The authors declare no competing interests.

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