

Climate Change Impacts on Marine Invaders: Analyzing Future Distribution and Ecological Niche Shifts of *Pterois Miles* and *Pterois Volitans*

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Abstract: Invasive lionfish species, *Pterois miles* and *Pterois volitans*, are poised for significant range expansion due to environmental changes and their intrinsic adaptability. Utilizing Species Distribution Models (SDMs), this study predicts a marked increase in the future spread of these species, particularly as non-suitable areas transform into highly suitable habitats under projected climate change scenarios. Our findings indicate that both species are expanding their ecological niches in invaded territories, where they increasingly occupy more dominant ecological positions. This shift is likely facilitated by rising sea temperatures and alterations in marine ecosystems, which enable these invasive species to exploit new areas and outcompete native fauna. The projected movement towards higher latitudes represents a significant ecological threat, with potential severe impacts on biodiversity and the functionality of marine ecosystems. This study highlights the urgent need for proactive strategies to monitor and manage the spread of lionfish, aiming to mitigate the substantial risks associated with their future expansion and dominance in new marine environments.

Keywords: climate change, invasive alien species, ecological niche shift, ensemble model, *Pterois* spp.

1. Introduction

In the era of globalization, human activities, including international trade, tourism, transportation and infrastructure construction, increase the risk of biological invasion. The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) Assessment Report found that more than 37,000 established alien species have been introduced by human activities across all regions and biomes, with new alien species presently being recorded at an unprecedented rate of approximately 200 annually [1]. Among these alien species, about 3,500 species are categorized as invasive alien species (IAS), which have negative impacts on nature and human society [1]. Consequently, the establishment and spread of non-indigenous species are important drivers for biodiversity loss and disorders of ecosystem structure and function. Besides the ecological impacts, IAS pose a significant threat to production in many sectors, such as agriculture, forestry, animal husbandry, and fisheries. Although this issue has attracted increasing attention from both scholars and the general public, policies and their implementation toward the prevention and control of IAS are still insufficient in most countries [2]. In addition, the number of IAS and their negative impacts are likely to increase

due to the amplification of multiple drivers including but not limited to demographic, economic and land- and sea-use change [1, 3]. Climate change can cause shifts in species distribution in some areas leading to a reduction in species diversity and the exposure of vacant ecological niches, making the ecosystem more vulnerable to IAS and enhancing the success rate of invasive species population establishment.

Alien marine fish are mainly introduced through maritime transportation and canal construction. However, few worldwide fish invasions of similar magnitude are documented as the introduction of lionfish (*Pterois volitans* Linnaeus, 1758; *Pterois miles* Bennett, 1828) in the western Atlantic Ocean, which is one of the fastest and most ecologically harmful marine fish invasions to date [4]. *P. volitans* is a Pacific Ocean species while *P. miles* is native to the Indian Ocean from the Red Sea to eastern South Africa, Arabian Sea, Persian Gulf, Andaman Sea and Sumatra, the eastern extreme of its distribution, where populations of *P. miles* and *P. volitans* overlap [5]. The invasive lionfish was first documented along Florida coasts in 1985 due to either intentional or accidental aquarium release. In less than 30 years, they have expanded their distribution range to the Caribbean Sea, the Gulf of Mexico and recently there are new records of lionfish for the Brazilian coast, in the southwestern Atlantic [6]. Studies about invasive lionfish in the western Atlantic indicated that they are opportunistic generalist carnivores, consuming at least 167 vertebrate and invertebrate prey species across multiple trophic guilds [7]. Within their invaded range, lionfish have reached densities up to ten times that of their native range [8]; on the individual level, they have larger average body lengths with growth rate of 1.25 to 2.25 times faster than lionfish in the Pacific [9]. As the dominant predator on coral reefs with a great impact on native coral reef fishes, lionfish have reduced the abundance of small native reef fishes by up to 95% at some invaded site [10]. Female lionfish are capable of spawning every 3.6-4.1 days throughout the year after getting matured at about 1 year of age, and produce around two million buoyant gelatinous eggs per year [11, 12]. During the pelagic larval phase, which is estimated to be 25-40 days, lionfish larvae can float with the ocean currents and be dispersed across great distances [13]. These reproductive characteristics (i.e. rapid growth, early sexual maturity, and frequent spawning ability) of lionfish would contribute to their rapid expansion and sustained population levels in invaded ranges [12, 14-15]. In addition, the successful invasion of lionfish also results from other biological traits, including their generalist feeding habits, antipredator defense and wide ecophysiological tolerance [4]. In recent years, lionfish has spread rapidly through the eastern and central Mediterranean. Following the typical pattern of Lessepsian migration, it progressively moved toward the northwest and spread in the Ionian Sea [16] and the Adriatic Sea [17]. With ongoing climate change, sea warming is favoring the spread of such tropical fish [18], enabling them to survive and reproduce in previously thermically inhospitable ecosystems, and therefore further expand westwards and northwards.

To the best of our knowledge, most research on the lionfish invasion focus on its biological and ecological traits, and tracking the invasion history to date, with little attention given to the correlation between its distribution patterns and environmental parameters. Therefore, it is necessary to strengthen our understanding of how climate change will influence lionfish distribution in order to mitigate the negative impacts of this species. Predictions of the effects of rising temperatures on invasive alien species (IAS) typically include observational studies of population dynamics under climate change, mechanistic studies in controlled settings [19-21], and climate modeling [22], often integrating these methods [23]. Recently, species distribution models (SDMs) have emerged as a powerful tool for analyzing the effects of climate change on invasive alien species populations [24, 25]. SDMs are commonly used to predict species' potential geographic distributions and migration trends under varying climate conditions. Popular models include MAXENT, CLIMEX, GLMs, GARP, and Biomod2 [26-28]. Among these, Biomod2 is an R-based platform that supports various modeling methods like ANN, GAM, GLM, MAXENT, and XGBOOST, which can be combined into

a single integrated model [29]. Compared to single models, ensemble models (EMs) enhance accuracy by reducing noise through multi-model integration, which is vital for accurate species prediction [30-32], thus are more reliable than single models [33-35].

To effectively investigate the temporal and spatial distribution of *P. volitans* and *P. miles*, we applied the Biomod2 integrated model. This approach enables integrated analysis of environmental factors, enhancing our understanding and management of *P. volitans* and *P. miles* invasions. Our strategy prioritizes identifying key environmental factors for prevention and control in areas climatically similar to those invaded. Considering the significant impacts of *P. miles* and *P. volitans* on marine ecology, this study focuses on exploring their potential distribution and ecological niche changes across the global ocean. We will conduct an in-depth analysis of their environmental adaptations to reveal the dynamics and drivers of their invasion, providing a scientific basis for effective biosecurity and management strategies. The approach includes: (1) selecting top single models for Biomod2 integration to find the most effective model; (2) using the best integrated model to predict suitable and overlapping distribution areas of *P. volitans* and *P. miles* under SSP1-2.6 and SSP5-8.5 scenarios for 2050 and 2090; (3) examining the environmental adaptability and ecological niche dynamics; (4) analyzing environmental similarities in suitable areas using multivariate environmental similarity surfaces (MESS) and ANOVA.

2. Materials and Methods

2.1. Species geographical distribution data

We obtained occurrence records for *P. miles* and *P. volitans* from the Global Biodiversity Information Facility (GBIF, <https://www.gbif.org/>) and the Ocean Biodiversity Information System (OBIS, <https://obis.org/>) [36]. To align with the resolution of our environmental variables, we optimized our occurrence data using the ENMtools [37]. We filtered the data to maintain only one distribution point per 10×10 arcminute grid, significantly reducing spatial autocorrelation. If unaddressed, spatial autocorrelation could skew results by clustering data points [38, 39]. Following this screening, we compiled 1,077 and 3,543 valid distribution points for *P. miles* and *P. volitans* respectively. This dataset forms the foundation for our predictive modeling, enabling a robust analysis of the relationship between species distributions and environmental factors.

2.2. Environmental variables

Based on previous studies, we selected 36 ocean climate variables for both current and future periods (2050s: 2050-2060; 2090s: 2090-2100) [40, 41]. We obtained climate data for both periods from the Bio-Oracle database (accessed on June 5, 2024, <https://bio-oracle.org/>), selecting future projections from the BCCSM2-MR model of the CMIP6 program. This selection represents a shift from the Representative Concentration Pathways (RCPs) of CMIP5, which integrated socio-economic pathways (SSPs) with RCPs to model future socio-economic scenarios [42]. To ensure accurate predictions, these diverse variables included temperature, pH, velocity, oxygen, primary productivity and bathymetry, whose data were at various resolutions. However, previous research has indicated that higher spatial resolution does not necessarily enhance SDM predictive performance [43]. Therefore, we standardized the spatial resolution of all environmental variables across the models to minimize prediction uncertainty. We analyzed these bioclimatic factors using Pearson correlation and assessed their intercorrelations and significance with the variance inflation factor (VIF) [44]. Employing the R programming language, we performed Spearman's correlation and multicollinear VIF assessments on the interpolated data from our occurrence points. Our selection criteria for relevant factors were a correlation coefficient <0.8 and VIF values <10 [45]. The variance inflation factor (VIF), the inverse of tolerance, quantifies the extent of multicollinearity among variables.

Specifically, a VIF value below 10 suggests no multicollinearity, values between 10 and 100 suggest multicollinearity, and values above 100 indicate severe multicollinearity [46]. This methodology aids in identifying the most relevant and independent bioclimatic variables, ensuring our ecological niche model's robustness. The filtered modeling factors are presented in Table 1.

Table 1: Environment variables involved in modeling.

Parameter code	Description	Parameter code	Description
ben_b_max	Maximum benthic bathymetry	surf_ph	Mean surface pH
ben_b_mean	Mean benthic bathymetry	surf_pp	Mean surface primary productivity
ben_o	Mean benthic oxygen	surf_s_range	Surface salinity range
ben_pp	Mean benthic primary productivity	surf_t_max	Maximum surface temperature
ben_s_range	Benthic salinity range	surf_t_range	Surface temperature range
ben_t_range	Benthic temperature range	surf_v	Surface velocity

2.3. Model accuracy assessment

We modeled the current and future geographic distributions of *P. miles* and *P. volitans* using global occurrence data and environmental variables, utilizing the Biomod2 package in RStudio (version 3.1.0, 2014) [35]. By integrating multiple models, we leverage their unique sensitivities and explanatory capabilities to enhance the diversity, robustness, and accuracy of our predictions. This method balances model biases, reduces errors, and merges outputs to improve forecast accuracy and assess uncertainty more effectively [30]. Research shows that integrating multiple models typically yields higher prediction accuracy compared to using a single model, thereby enhancing the reliability and practicality of the scientific research [33]. Within Biomod2, we utilized twelve diverse modeling algorithms: artificial neural networks (ANN), classification tree analysis (CTA), flexible discriminant analysis (FDA), generalized additive models (GAM), generalized boosting models (GBM), generalized linear models (GLM), multivariate adaptive regression splines (MARS), maximum entropy (MAXENT), MAXNET, random forest (RF), XGBOOST, and species range envelope (SRE). To refine the models, we employed a BioModel tuning command to optimize the parameters. We designated 75% of the data as the training set, ensuring equal weighting for both distribution and pseudo-absence data to maintain model balance. We iterated the modeling process five times to enhance reliability, producing 60 simulation models. From these, we selected single models with a True Skill Statistic (TSS) greater than 0.8 and Area Under the Curve (AUC) greater than 0.9 for further consideration, indicative of high predictive accuracy and reliability [47]. We constructed an Ensemble Model (EM) to simulate the potential distribution areas of *P. miles* and *P. volitans* using several methods, including EMmean, EMcv, EMci, EMmedin, EMca, and EMwmean. EM demonstrated superior performance, with TSS and AUC values exceeding 0.85 and 0.95, respectively. This comprehensive approach allowed for thorough evaluation of the models, ensuring selection of the best integrated model for predicting and analyzing the potential distribution of *P. miles* and *P. volitans*.

2.4. Ecological niche quantification

The ecological niche of *P. miles* and *P. volitans* was analyzed using the ecospat package in RStudio 4.2.3, integrating PCA-env and COUE schemes [48, 49]. This analysis encompassed gathering species distribution and climatic data, defining geospatial and environmental parameters on a two-dimensional grid, and applying kernel smoothing to estimate climatic densities. Statistical methods, including stochastic tests, were used to compare the climatic ecological niches of the original and invasion areas [50]. Additionally, a stochastic test was used to quantify the differences in niche dynamics, specifically vacancy, stability, and shifts, between these areas [51].

2.5. Analysis of MESS and MoD

Using environmental variables from the current potential distribution area of *P. miles* and *P. volitans* as a reference layer, we employed MESS to assess climatic anomalies in suitable habitats for *P. miles* and *P. volitans* under the projected climate change scenarios. The most divergent variable was then analyzed to identify the key factors influencing shifts in *P. miles* and *P. volitans* potential geographic distribution.

The MESS calculation quantifies the similarity between the predictive variables ($V_1, V_2, V_i \dots$) and reference points. For any environmental variable, V_i , in the reference layer, mini and maxi represent the minimum and maximum values, respectively. The variable ϕ denotes the V_i value at a specific point P during a defined period and ϕ is the proportion of points in the study area where $V_i < \Pi$ [52]. The MESS calculation varies based on the percentage (ϕ) of points where the environmental variable ϕ is less than its value π at point P . Specifically: when $\phi = 0$, $\text{MESS} = 100 (p - \text{mini}) / (\text{maxi} - \text{mini})$; when $0 < \phi \leq 50$, $\text{MESS} = 2\phi$; when $50 < \phi < 100$, $\text{MESS} = 2(100 - \phi)$; when $\phi = 100$, $\text{MESS} = 100 (\text{maxi} - p) / (\text{maxi} - \text{mini})$. The MESS at point P represents the minimum similarity across variables, which is termed the MoD [53]. A negative MESS indicates that one or more variable values fall outside the environmental range of the reference points, thereby identifying a climate anomaly point. Conversely, a MESS of 100 suggests complete consistency with the reference climate, indicating normal climatic conditions. The variable with the greatest anomaly, or the MoD, is critical for understanding potential geographic shifts in species distribution. The density.tool.novel tool was incorporated into the MaxEnt model for this analysis [52, 54].

3. Results

3.1. Current geographical distributions and further migration of *P. miles* and *P. volitans*

The current (1979-2013) geographical distributions of *P. miles* and *P. volitans* are shown in Figure 1. The current distribution area of *P. miles* include the Arafura Sea, Timor Sea, Flores Sea, East China Sea, and Gulf of Mexico; for *P. volitans*, these are in the Coral Sea, Indian Ocean, South Atlantic Ocean, and Gulf of Mexico. The overlapping areas for both species currently include the Flores Sea, South China Sea, East China Sea, Caribbean Sea, and Gulf of Mexico. At present, *P. miles* occupies a total habitat area of $1,590.02 \times 10^4 \text{ km}^2$, *P. volitans* occupies $2,359.23 \times 10^4 \text{ km}^2$, with an overlapping area of $311.74 \times 10^4 \text{ km}^2$. (Table 2)

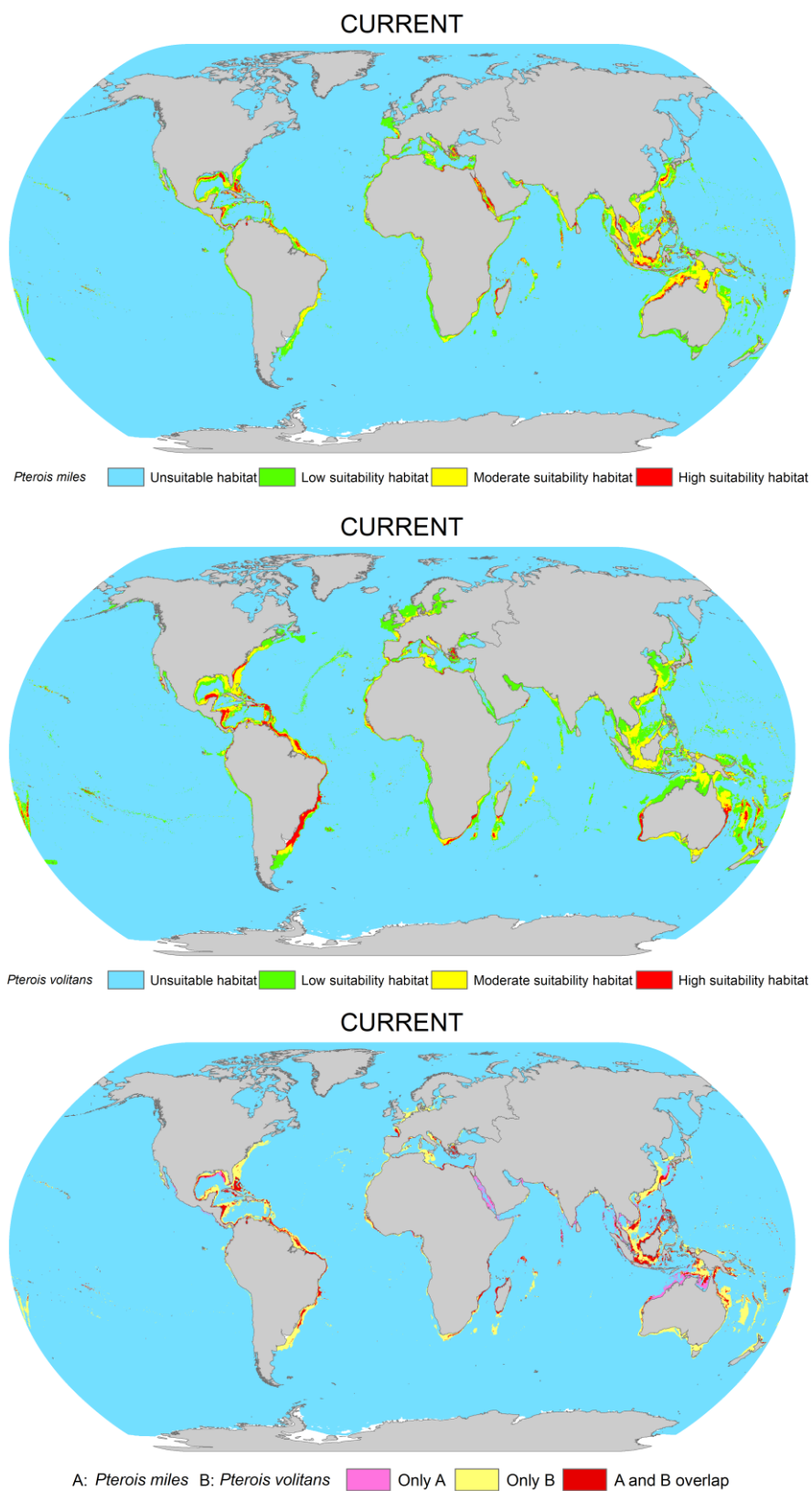


Figure 1: Current geographic distribution of *P. miles* and *P. volitans*.

Table 2: Current global area ($\times 10^4 \text{ km}^2$) of suitable habitat of *P. miles* and *P. volitans*.

Species	Unsuitable	Habitat type		
		Low	Moderate	High
<i>P. miles</i>	34409.98	767.71	613.54	208.75
<i>P. volitans</i>	33640.76	1277.64	840.52	241.06

The optimal prediction of the Biomod2 model, Emwmean, was transformed into raster data to calculate the suitable area for *P. miles* and *P. volitans* under different climate scenarios. The results indicated a substantial increase in suitable areas compared to the current climate scenario (Fig2, Tab3). For *P. miles*, the total area of suitable habitats is projected to expand under most future scenarios. Under the SSP585 climate scenario, the expansion of the high-fitness zone is the most significant, with the area of the high-fitness zone growing from $213.31 \times 10^4 \text{ km}^2$ in 2050 to $382.50 \times 10^4 \text{ km}^2$ in 2090, mainly in the Mediterranean Sea, the Red Sea, the Timor Sea, the Coral Sea and other seas. The non-fitness zones will gradually transform into the fitness zones, and the low and medium-fitness zones in the current period will gradually transform into the high-fitness zones. For *P. volitans*, the total area of suitable zone reaches the maximum under SSP126 scenario in 2050, which is about $2,668.49 \times 10^4 \text{ km}^2$, while it seems to shrink from then. In 2090, the area of high suitable zone under SSP585 scenario expands to the maximum, which is mainly distributed in the Gulf of Mexico, Sargasso Sea, South China Sea, East China Sea, Timor Sea, and Coral Sea, etc., and the high suitable zone is gradually expanding under each future scenario.

Table 3: Area of habitat suitability class under future climate scenarios ($\times 10^4 \text{ km}^2$).

Species	Climate scenario	Unsuitable	Low	Moderate	High	All
<i>P. miles</i>	2050s_SSP126	34314.15	758.33	634.33	293.18	1685.84
	2050s_SSP585	34441.84	699.83	645.00	213.31	1558.15
	2090s_SSP126	34304.30	764.27	663.34	268.07	1695.69
	2090s_SSP585	34349.90	633.55	641.69	382.50	1657.75
<i>P. volitans</i>	2050s_SSP126	33331.50	1305.97	618.08	744.43	2668.49
	2050s_SSP585	33495.25	1244.87	698.23	561.63	2504.74
	2090s_SSP126	33405.30	1239.81	615.12	739.75	2594.69
	2090s_SSP585	33660.91	1044.88	445.04	856.84	2346.77

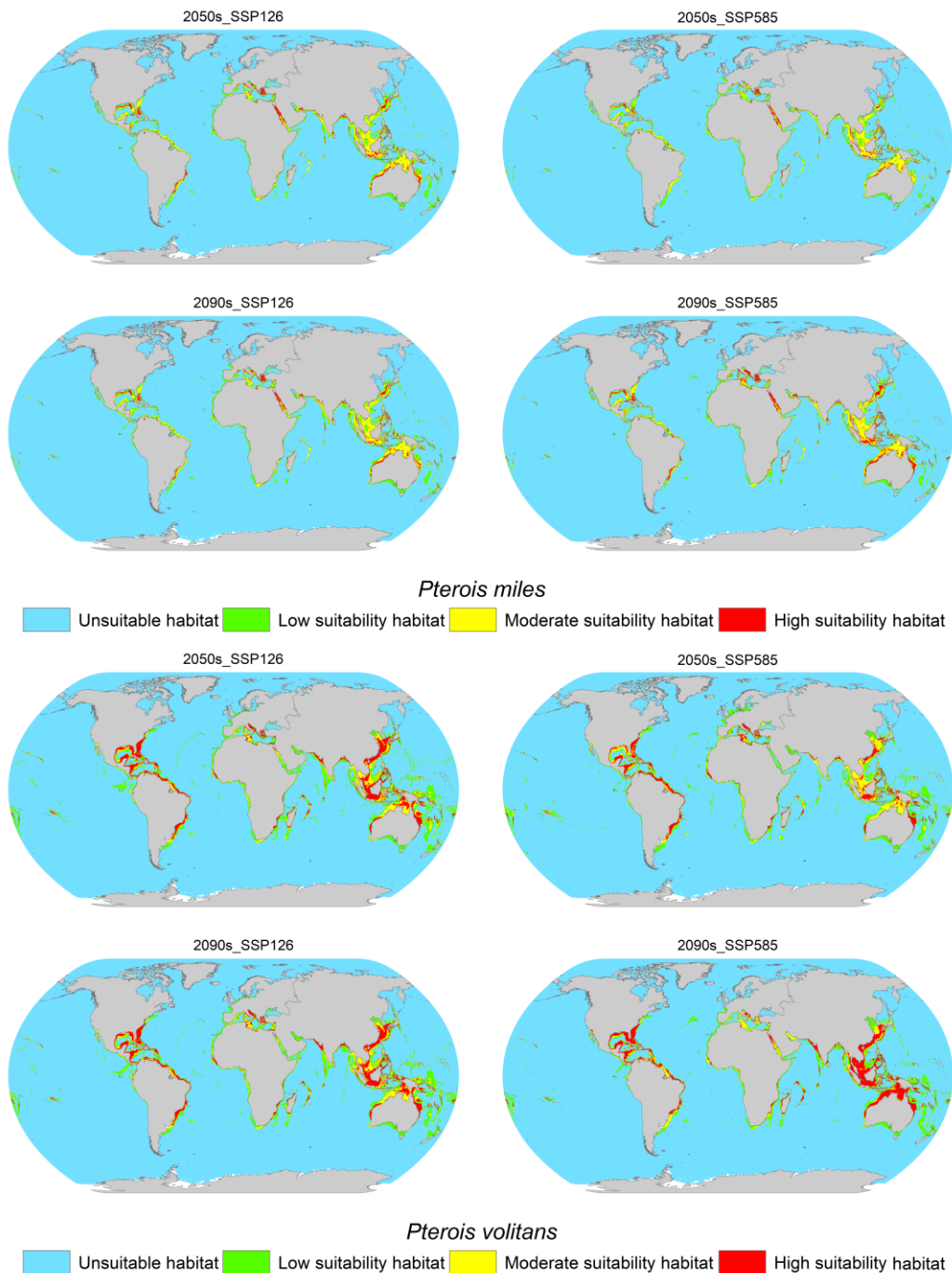


Figure 2: Future potential geographic distribution of *P. miles* and *P. volitans*.

3.2. Differentiation and overlapping of their ecological niches

Visualizing the ecological niches of *P. miles* and *P. volitans* offers intuitive insights into their adaptability to future climate change scenarios. Figure 3 demonstrates the significant ecological niche drift for *P. miles* and *P. volitans* under future climate scenarios. For *P. miles*, ecological niche differences between future periods were marked, with maximum and minimum overlaps of 0.77 (2050s_SSP585) and 0.69 (2090s_SSP585) respectively. For *P. volitans*, the maximum overlap is 0.74 (2050s_SSP126), and the minimum is 0.24 (2090s_SSP585). The ecological niche overlap of the two species varies over time and climate scenarios, with niche drift intensifying and overlap

decreasing as radiation intensity increased. The significant ecological niche overlaps suggest that *P. miles* and *P. volitans* are highly resilient to future climate changes. Additionally, the ecological niche overlap under the 2090 climate scenario was notably lower than under the 2050 scenario, indicating that the risk of dispersal and invasion by *P. miles* and *P. volitans* may increase over time.

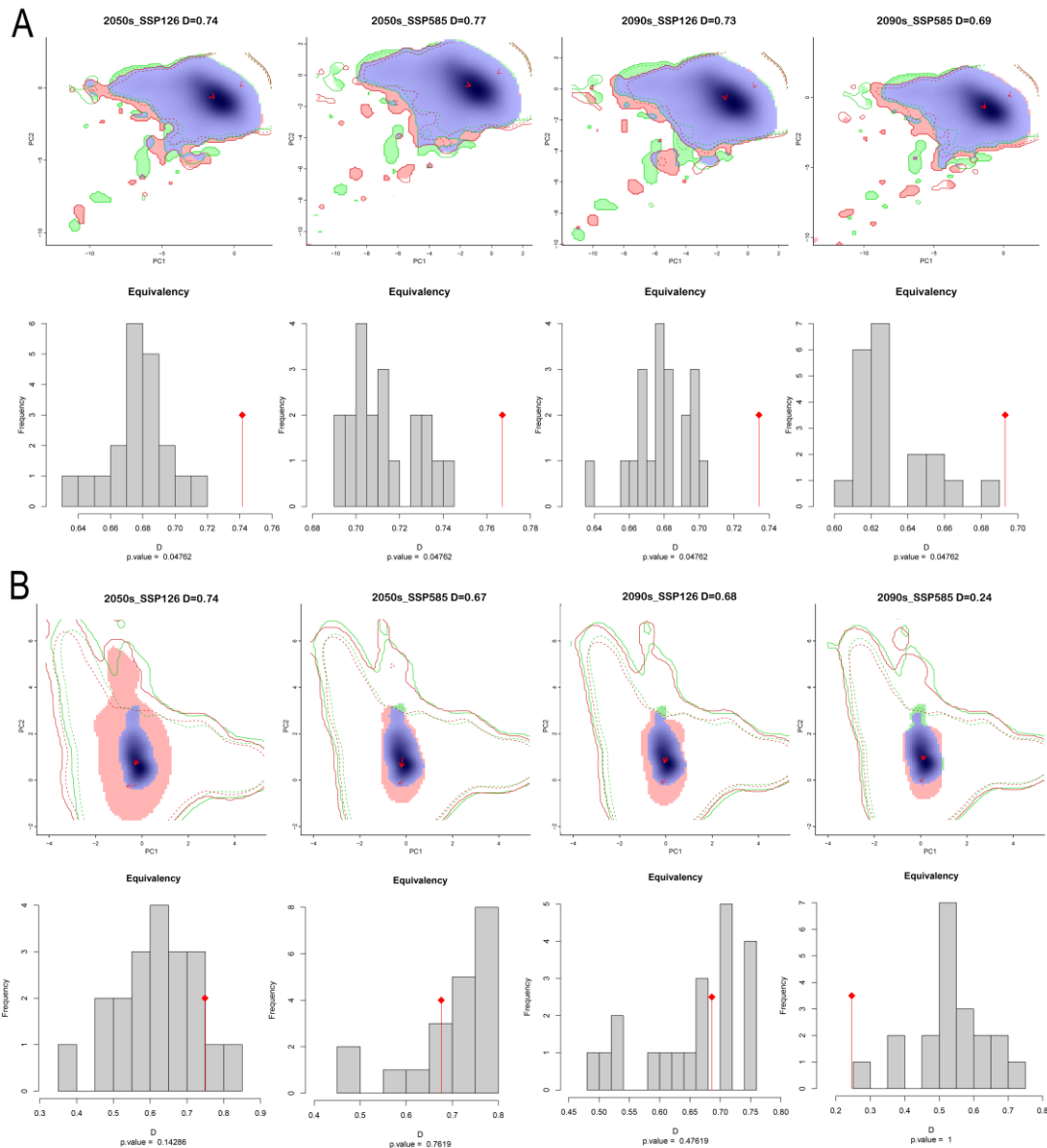


Figure 3: Niche differences of *P. miles* and *P. volitans* in different climatic backgrounds in the future. D: ecological niche overlap value. A: *P. miles* B: *P. volitans*

As depicted in Figure 4 and Table 4, the future overlapping geographic distribution of these two invasive species generally exhibits an expansion trend. Under the 2050s_SSP585 scenario, a reduction in overlap, approximately $100.83 \times 10^4 \text{ km}^2$, will occur primarily in the Gulf of Mexico, Sargasso Sea, Caribbean Sea, South China Sea, Java Sea, East China Sea, and Arafura Sea. For other periods and climate scenarios, the largest overlapping area occurs under the 2050s_SSP126 scenario, approximately $1,035.50 \times 10^4 \text{ km}^2$. The smallest increase is observed in the 2090s_SSP126 scenario, with an expansion of about $214.18 \times 10^4 \text{ km}^2$ compared with current scenario. Expansion predominantly occurs in the nearshore areas of the Gulf of Mexico, Sargasso Sea, Caribbean Sea,

South Atlantic Ocean, Mediterranean Sea, Red Sea, Arabian Sea, East China Sea, South China Sea, Java Sea, Timor Sea, Arafura Sea, and Coral Sea. This trend mirrors the expansion of the habitable zones of the two species under future scenarios.

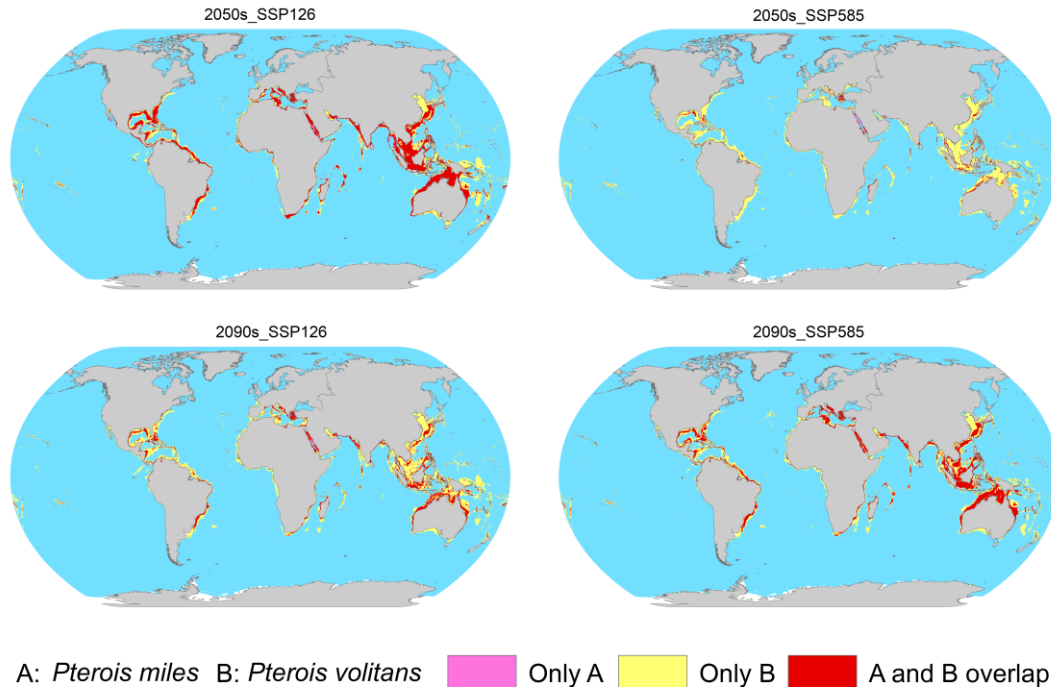


Figure 4: Predicted overlapping geographic ranges of *P. miles* and *P. volitans* in the 2050s and 2090s under SSP126 and SSP585.

Table 4: Area of overlap between *P. miles* and *P. volitans* ($\times 10^4 \text{ km}^2$).

Climate scenario	Only A	Only B	A and B overlap
2050s SSP126	16.34	976.70	1035.50
2050s SSP585	8.55	1395.74	210.91
2090s SSP126	3.85	1421.93	525.92
2090s SSP585	0.54	1064.35	835.77

3.3. MESS and MoD variable analysis

Under the SSP126 and SSP585 scenarios, the mean environmental similarity at 719 effective distribution points of *P. miles* is 2.59 and 0.78 in 2050, and 2.54 and -0.10 in 2090, respectively (see Fig.5). The scenarios with significant variability and decreasing anomalies in climate similarity are SSP585 and SSP126 in both 2050 and 2090. For *P. volitans*, the mean environmental variable similarity at 2887 effective distribution sites under the SSP126 and SSP585 scenarios is 1.22 and 0.42 in 2050, and 1.47 and 0.04 in 2090, respectively. The scenarios with the most climate variability and decreasing anomalies are SSP126 in 2090, SSP585 in 2050, and SSP585 in 2090. The dominant variables remain ben_pp (mean benthic primary productivity) and surf_t_max (maximum surface temperature), which exhibit significant variability in future periods. The expansion of both species may vary due to differences in changes in surf_t_max.

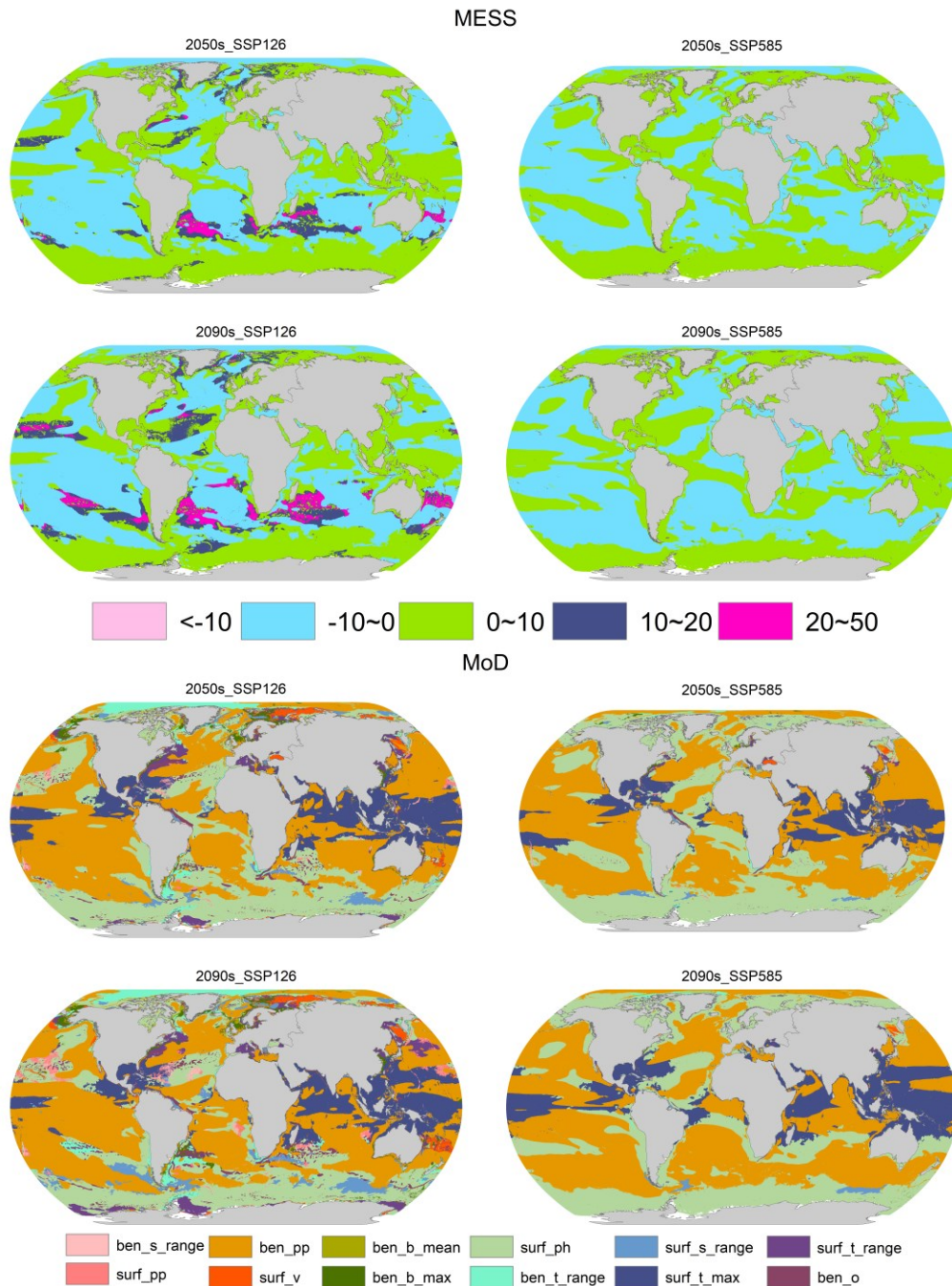


Figure 5: MESS and MoD analysis of *P. miles* and *P. volitans* under future climate scenarios.

3.4. Analysis of dominant environmental factors

From Figure 6, the First Principal Component (Dim1) accounts for 55.8% of the variance and is closely associated with factors such as *ben_b_max* (maximum benthic bathymetry), *ben_b_mean* (mean benthic bathymetry), *ben_t_range* (benthic temperature range), and *ben_s_range* (benthic salinity range). The closeness of these factor directions suggests a positive correlation, significantly impacting the model's explanatory power. The Second Principal Component (Dim2) accounts for 36.5% of the variance and is significantly influenced by factors such as *surf_t_max* (maximum surface temperature) and *surf_pp* (mean surface primary productivity), highlighting their impact on

species distribution along a dimension distinct from major chemical or physical factors. This PCA analysis reveals that *ben_b_max* (maximum benthic bathymetry) is one of the most influential environmental factors affecting the distribution of these species, suggesting that bathymetry might be critical limiting factors. Additionally, the temperature and salinity ranges play a crucial role, potentially related to the species' adaptation to environmental stability.

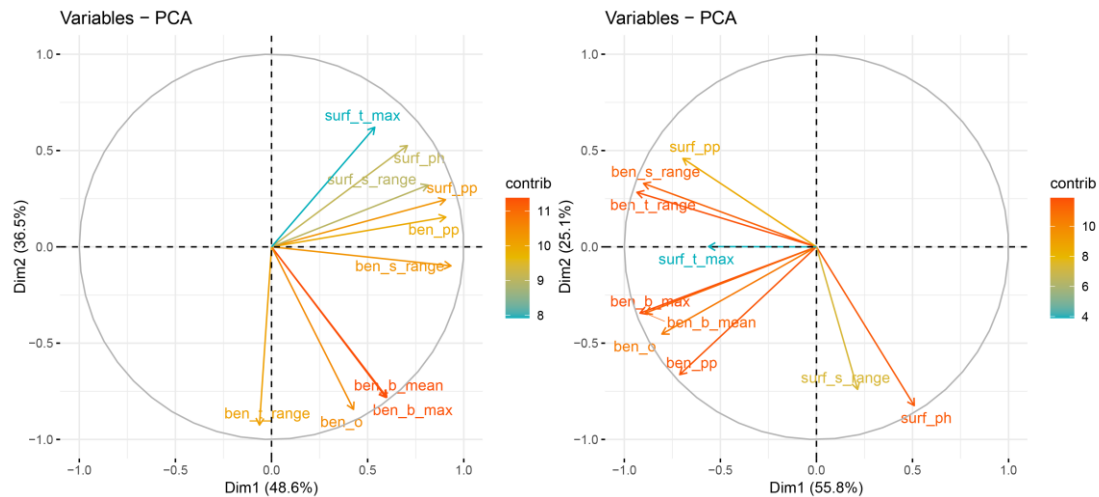


Figure 6: Dominant environmental factors. A: *P. miles* B: *P. volitans*

4. Discussion

4.1. The ecological niche dynamics of *P. miles* and *P. volitans*

Our study has employed Species Distribution Models (SDMs) to project the global potential geographical distribution and analyze the ecological niches of two invasive lionfish species, *Pterois miles* and *Pterois volitans*. The results of this analysis strongly support the ecological niche shift hypothesis, suggesting that these species have undergone significant changes in their ecological preferences and tolerances after establishing populations in non-native regions. In comparing the ecological niches of these species in their native versus invaded ranges, our findings reveal that both *P. miles* and *P. volitans* have not only expanded their habitat preferences but also exhibit distinct patterns of resource utilization and environmental resistance. Such shifts are indicative of an evolutionary response to novel selection pressures in invaded ecosystems, potentially including changes in prey availability, absence of natural predators, and new competitive dynamics [11, 55-56]. The potential for further invasion and spread remains high, which suggest that vast areas of the world's oceans are climatically suitable but not yet colonized by these lionfish. This ongoing threat underscores the need for continued monitoring and development of management strategies aimed at mitigating the impact of lionfish on local marine biodiversity and fisheries [4, 10, 57].

4.2. Potential geographical distribution shifts of the *P. miles* and *P. volitans* under climate change

The impact of global climate change on IAS such as *Pterois miles* and *Pterois volitans* is of critical concern, as shifts in temperature and sea conditions can significantly alter their potential geographical distributions. Our research supports the hypothesis that global warming is driving the latitudinal migration of these invasive lionfish species, potentially enhancing their range expansion into previously unsuitable areas. Consistent with prior studies [40, 58], our findings suggest that rising sea temperatures and altered ocean currents are facilitating the northward and southward expansion of *P.*

miles and *P. volitans*. This trend towards higher latitudes corresponds with the predicted shifts in suitable habitats caused by warming waters, which extend the thermal niche boundaries that previously constrained the distribution of these tropical and subtropical species. Furthermore, models developed by Poursanidis D [36, 59] and other researchers have projected significant range expansions for numerous marine species, including invasive ones like lionfish, under various climate change scenarios. These models underline that *P. miles* and *P. volitans* may exploit new regions as their thermal habitats shift poleward, potentially leading to new ecological challenges for the native marine communities in these higher latitudes. Our study adds to the evidence that climate change acts as a catalyst for the spread of IAS by altering their geographical range limits. The predicted expansion of suitable habitats for *P. miles* and *P. volitans* into higher latitudes not only confirms the adaptive flexibility of these species but also highlights the urgency for enhanced monitoring and management strategies in these new potential invasion fronts. In summary, the shifting geographical distribution of *P. miles* and *P. volitans* under climate change scenarios emphasizes the dynamic nature of ecological niches and the profound implications of environmental changes on invasive species distribution. This knowledge is crucial for developing predictive models and proactive strategies to mitigate the ecological impacts of these expanding invasive populations.

5. Conclusions

This study utilized Species Distribution Models (SDMs) to evaluate the global potential distribution and ecological niche dynamics of two invasive lionfish species, *Pterois miles* and *Pterois volitans*. The analysis provided significant insights into the adaptability and potential spread of these species under current and projected environmental conditions. Our findings reveal that both *P. miles* and *P. volitans* have successfully expanded their ecological niches beyond their native ranges, exhibiting considerable adaptability to varying marine environments. This adaptability underpins their invasive success and poses a substantial threat to biodiversity and local ecosystems across their potential distribution zones. The study supports the hypothesis that global warming could further facilitate the expansion of these invasive species by making higher latitude marine environments more hospitable. This potential shift in geographical distribution due to climate change highlights the urgent need for robust monitoring and management strategies. Proactive measures are essential to mitigate the ecological and economic impacts of these invasions, which threaten marine ecosystems globally. In conclusion, our research underscores the critical importance of utilizing advanced modeling techniques to predict and prepare for the spread of invasive species. Effective management and conservation efforts must be informed by continuous scientific research to adapt to the dynamic challenges posed by species like *P. miles* and *P. volitans* in a rapidly changing world.

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