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The global network of Marine Protected Areas is not ready to face projected climate change

Masterado em Biologia Marinha

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The global network of Marine Protected Areas is not ready to face projected climate change

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English abstract

A current challenge of climate change adaptation is determining how resource management and conservation programs are designed to comprehensively protect biodiversity under present and future conditions. Marine protected areas (MPAs) are primary management tools aiming to reduce localized anthropogenic impacts on marine biodiversity but their implementation has neglected future climate change resilience, potentially reducing their performance in the years to come. Here, we ask if the global network of MPAs is ready to face future climate change by estimating its degree of exposure to novel climates (i.e., future conditions non-existent today) and by testing if its distribution inside each country's Exclusive Economic Zones is optimal. Our analyses were based on climatic analogs (sigma dissimilarity) using four biologically meaningful variables (temperature, oxygen, pH and primary productivity) from present-day conditions to the end of the 21st century, under contrasting Shared Socioeconomic Pathways (SSP) scenarios (SSP1-1.9 and SSP5-8.5). Our results show 8.59% of the MPAs exposed to novel climate under SSP1-1.9 in contrast to 81.05% under SSP5-8.5 (average sigma dissimilarity of MPAs: 0.7 and 4.40 with SSP1-1.9 and SSP5-8.5, respectively). Such novel conditions, particularly aggravated in tropical and polar regions, will likely produce local population extinctions and range shifting, while species search for climatic analogs. The four variables considered had a similar contribution on projected novel climates, reinforcing their role in driving range shifts at global scales. Moreover, only 9.6% and 4.7% of MPAs (SSP1-1.9 vs. SSP5-8.5) were estimated to be located in regions of national EEZs with reduced novel climates, suggesting the importance of considering climate change resilience during implementation phases. Overall, we show that broad compliance to the Paris Agreement expectations is key to increasing global MPA resilience and achieving international conservation targets like the post-2020 framework of the Convention on Biological Diversity, which considers expanding global MPA coverage up to 30% by 2030.

Key words: Marine Protected Areas; Climate Change; Climate analogs; Climate resilience; Shared Socioeconomic Pathways

Portuguese abstract

Um desafio atual da adaptação às alterações climáticas é determinar como os programas de gestão e conservação de recursos marinhos foram concebidos para proteger a biodiversidade sob condições ambientais do presente e futuro. Os impactos das alterações climáticas nos ecossistemas marinhos estão entre os desafios mais difíceis que a nossa sociedade enfrenta hoje e no próximo século. Em algumas regiões, a temperatura dos oceanos aumentou de 1 a 3 ºC devido à absorção de mais de 90% do calor adicional retido pelos gases com efeito de estufa. Este aquecimento, associado à crescente estratificação das águas pouco profundas, pode ainda levar à desoxigenação, potencialmente afetando a produção primária, entre outros processos físicos e geoquímicos. Além disso, a absorção de dióxido de carbono antropogénico leva à acidificação do oceano, o que já desencadeou uma queda no pH de 0,3 a 0,5 unidades, tornando difícil a calcificação de organismos marinhos que formam conchas ou esqueletos de carbonato de cálcio. Juntos, o efeito sinergético do aquecimento, desoxigenação, pH e declínio da produtividade levou a múltiplas mudanças na biodiversidade e habitats marinhos. As áreas marinhas protegidas (AMP) são ferramentas de gestão primária que visam reduzir os impactos antropogénicos na biodiversidade marinha, mas a sua implementação negligenciou a resiliência às alterações climáticas futuras, potencialmente reduzindo o seu desempenho nos anos vindouros. Por conseguinte, muitos países costeiros comprometeram-se a designar uma proporção significativa das suas Zonas Económicas Exclusivas Marinhas (ZEE) como AMP (por exemplo, acordo pós-2020 que pretende conservar 30% até 2030). Atualmente, aproximadamente 8% do oceano global é coberto por AMP, mas uma localização ótima pode ser crucial para aumentar a resiliência das AMPs face às alterações climáticas, uma vez que algumas regiões dentro das Zonas Económicas Exclusivas do país podem vir a mudar menos do que outras. Falta, no entanto, uma visão integrada e global da exposição global das AMPs às alterações climáticas. Aqui, perguntamos se a atual rede global de AMP está pronta para enfrentar as alterações climáticas futuras. Estimámos o seu grau de exposição à dissimilaridade climática futuro e testámos se a sua distribuição dentro das ZEEs é óptima. As nossas análises foram baseadas em análogos climáticos (sigma dissimilaridade) utilizando quatro variáveis com significado biológico (temperatura, oxigénio, pH e produtividade primária) desde as condições atuais até ao final do século XXI, sob cenários contrastantes de Shared Socioeconomic Pathways (SSP1-1,9 e SSP5-8,5). Estas variáveis foram escolhidas considerando que estão abertamente disponíveis (fontes de dados climáticos mostradas nos métodos) e que são biologicamente importantes, conduzindo à adequação do habitat das

espécies marinhas (Zhao et al., 2020, McHenry et al., 2019; Kroeker et al., 2019; Lauchlan & Nagelkerken, 2020; Kroeker et al., 2013). A metodologia de análogos climáticos quantifica a semelhança do clima de um local relativamente às condições de outro local e/ou período de tempo (Beniston et al., 2014). Utiliza uma Distância Euclidiana Normalizada (SED) de locais/períodos climáticos para determinar a distância Mahalanobis (M_D), da qual se extrai a dissimilaridade de Sigma, uma métrica normalizada e independente das escalas de variabilidade das variáveis climáticas. Globalmente, esta métrica pode ser entendida como o número de desvios padrão de variabilidade climática (ICV) num determinado local (Lotterhos et al., 2021). Além disso, também estimámos a contribuição das variáveis para a dissimilaridade climática. As análises de análogos climáticos do clima têm sido largamente utilizadas para projetar os impactos das alterações climáticas nas APs terrestres (por exemplo, Graham et al., 2019; Hoffman et al., 2019), mas apenas um estudo foi realizado no domínio marinho. Este centrou-se em AMPs muito grandes, não abrangendo as zonas costeiras, e estimou que 97% destas estarão sujeitas a novos climas até 2100, ou seja, a condições inexistentes no presente (Johonson & Watson, 2021).

O presente estudo fornece linhas de base sobre a exposição das AMPs às alterações climáticas, abordando a avaliação dos impactos na biodiversidade que será crucial para a futura gestão e implementação de AMPs. Por conseguinte, ao realizar dos análises análogos climáticos baseadas em variáveis biologicamente significativas, fornecemos pela primeira vez uma visão global da exposição de AMP a futuras alterações climáticas sob cenários contrastantes de emissões de SSP. Os resultados sugerem várias implicações para as ações de conservação, dando informação para a designação inteligente de uma rede de AMP, desde a gestão de AMP a nível local (localizados de forma óptima) até à extensão global (oceano global). O amplo cumprimento do Acordo de Paris parece crucial para a futura resiliência e funcionamento dos AMP face a climas futuros, uma vez que os resultados foram altamente dependentes do cenário SSP, com maior grau de novidade (ou seja, condições inexistentes na linha de base atual) no pior cenário considerdado. Os valores moderados e extremos dos novos climas foram três vezes superiores para a SSP5-8,5, causando a deslocação de análogos em distâncias mais longas. Além disso, parece haver áreas adicionais dentro das ZEEs que podem proporcionar melhores condições climáticas no futuro do que a atual rede de AMPs. As quatro dimensões do clima consideradas tiveram o mesmo impacto na dissimilaridade climática, reforçando o seu potencial papel como agentes de alterações das distribuições de espécies à escala global. No entanto, para SSP1-1.9, as variáveis mostraram algum grau de padrão espacial. Em geral, o

oxigénio dissolvido e a produtividade contribuíram para a novidade climática em regiões tropicais do Sul, como o Indo-Pacífico. Por outro lado, para a SSP5-8.5, o Ártico e a Antárctica apresentaram contribuições mais elevadas de pH e temperatura máxima na determinação de novas condições. Além disso, apenas 9,6% e 4,7% das AMPs (SSP1-1,9 vs. SSP5-8,5) foram estimadas em regiões de ZEE nacionais com reduzida alteração do clima (mas não-análogo), o que sugere a importância de considerar a resiliência às alterações climáticas durante as fases de implementação. O estudo mostra que a eficácia global da AMP e a própria implementação do acordo pós-2020 poderão ser reduzidas face a futuras alterações climáticas. Toda a informação é fornecida em acesso aberto para que os países tenham acesso às nossas estimativas e preencham as suas lacunas no que diz respeito à gestão de AMPs.

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List of abbreviations, acronyms, and symbols

MPAs	Marine Protected Areas
WDPA	World Database on Protected Areas
MPAtlas	Atlas of Marine Protection
EEZ	Economic Exclusive Zones
IPCC	Intergovernmental Panel on Climate Change
UNCLOS	United Nations Convention on the Law of the Sea
CBD	Convention on Biological Diversity
IUCN	International Union for Conservation of Nature
PA	Protected Areas
OECMs	Other effective area-based conservation measures
WCPA	World Commission on Protected Areas
PP	Primary productivity
SST	Sea Surface Temperature
SSP	Shared socio-economic pathway scenarios
SED	Standardized Euclidean Distance
ICV	Interannual climate variation
PCA	Principal component analysis
$\mathbf{M_D}$	Mahalanobis Distance
$\sigma_{\mathbf{D}}$	Sigma dissimilarity

1. State of the art: General Introduction

1. Climate change

Climate Change is expected to become the most serious threat to biodiversity in the coming decades (Pecl et al., 2017). Different authors have already proven the consequences that these changes have caused in ecological systems from individual organisms to biomes (Bellard et al., 2012) impacting over eighty percent of all biological processes (Scheffers et al., 2016). One of the main biological effects of climate change is the global redistribution of species. To avoid extinction, organisms exposed to a changing climate can respond by conforming to the new conditions within their current range or by stoutly tracking their climatic niches in space (distribution shifts) or time (phenological shifts) (García Molinos et al., 2016). Hence, adaptation of local populations and ecosystems mainly rely on the inbound dispersal of novel gens and species better suited to the new environment. Although the evolutionary potential of marine organisms to cope with climate change is not entirely clear, distribution shifts are extensively observed and reported (Chen et al., 2011; Pinsky et al., 2013). Apart from organisms that can actively track suitable climates, other authors also focused on the importance of dispersal in the face climatic changing conditions (Kling & Ackerly, 2020). Given the expected intensification of current climate changing rates, species shifts will probably become increasingly important (Peters et al., 2013).

Considering that the current distribution of climatic conditions will change globally, some climates may disappear entirely, while new climates appear in wide regions (Williams et al., 2007). Climate change effects have been observed from the poles to the equator; however, research and literature reviews have focused on biotic impacts where temperatures are predicted to increase the most, meaning mid and high latitude sites (Feeley at al., 2017). Nevertheless, impacts of climate change highly depend on species' sensitivity to change which is expected to be greater in the tropics although most studies do not focus on that area. The first assessment report by the United Nations' Intergovernmental Panel on Climate Change (IPCC 1990) determined that at-risk species included poor dispersers, specialized organisms, and species less tolerant of ecological changes. Subsequent reviews indicated that changes would be concentrated in areas where temperature changes were largest, for instance higher latitudes, and for changes to be less noticeable elsewhere (Root et al., 2003). However, they did not consider that the very traits identified as risk factors by the IPCC (poor dispersal ability, specialization, and low tolerance for ecological changes) characterize tropical species which will therefore be more affected by climatic changes (Sheldon et al., 2019). In addition, other studies also pointed to the importance of the polar regions as the ones that will show the fastest change serving as a bellwether of climate change. Polar marine ecosystems are experiencing large shifts in species size and spatial range that will directly affect the local marine fauna such as marine mammals or seabirds (Doney et al., 2012). Therefore, adequate conservation tools will be required to guarantee long-term protection of marine biodiversity.

2. Marine Protected Areas

One of the most effective tools for mitigating threats to marine biodiversity are marine protected areas (Edgar et al., 2014). These are geographically defined areas where natural resources are given greater protection than the surrounding waters. Currently, spatial conservation prioritization is the most common approach to support the designation of these protected areas for conservation and socio-economic purposes (Moilanen et al., 2009). Climate change and its impacts are rarely incorporated into spatial conservation prioritizations (Álvarez-Romero et al., 2018) despite affecting marine and coastal environments. The disruption of threatened marine species may also shift within, into or out of an MPA. Populations or species that move outside of an MPA may lose the valuable protection that it provides. A recent study of Frazão Santos et al. (2020) pointed to the importance of the inclusion of climate change in marine spatial planning and to anticipate climate change effects in the zonation of MPAs as a key point for future ocean conservation. Thus, predicting how climatic conditions would be in the future will help countries to establish a sufficiently optimally located MPA network.

Despite MPAs help species within their boundaries to adapt to a changing climate, species shift their distributions to track their preferred thermal niches as climate change. They potentially move across the boundaries of existing protected areas causing an impact on the existing ecological interactions and creating new ones. Pecl et al. (2017) determined MPAs that could facilitate connectivity for climatic trajectories as the key to improve conservation efficiency. They proved the MPAs found in the Southern Hemisphere were subjected to lower velocity and climatic exposure values, indicating relative shorter, less exposed paths. Conversely, Northern Hemisphere MPAs were subjected not only to increasing rates of warming, but also climatic barriers in tracking shifting isotherms.

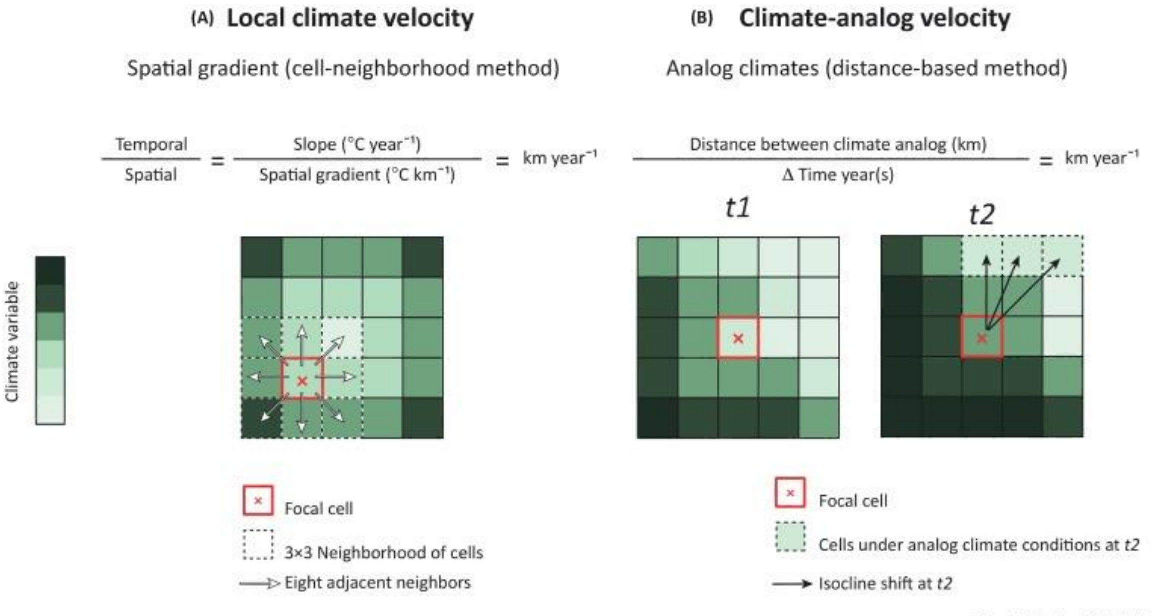
Historically, marine and terrestrial protected areas have been established and managed to protect particular resources of biological, historical or cultural significance and enhance biodiversity. Management of ecological networks in the ocean requires coordination among and between MPAs and numerous jurisdictions and authorities they represent (Cannizzo et al., 2021). These networks have the potential to be key mechanisms for long-term ecosystem management. Optimal distribution of the global MPA network can also help species and ecosystems adapt to climate change by protecting climate refugia or providing a safe landing space for species undergoing range shifts (Balbar & Metaxas, 2019). These climatic stable areas, named refugia, are habitats that components of biodiversity retreat to, persist in, and potentially expand from under changing climatic conditions (Keppel et al., 2012) and therefore, areas that exhibit persistent conditions that reduce vulnerability of species to climate change. Two different types of refugia can be considered: spatial refugia and adaptative refugia. The first one is understood as areas where changes are occurring more slowly, giving species time to adapt or evolve to changing conditions. On the other hand, adaptative refugia is where conditions are already similar to projected future conditions which contain populations that are pre-adapted to change (Cannizzo et al., 2021). While the importance of ecological connectivity to MPAs is now increasingly recognized, the marine conservation community is still far from fully applying this knowledge to enhance conservation outcomes. The understanding and implementation of ecologically optimal MPAs lags behind that of their terrestrial counterparts. In short, MPAs will be more effective when connected into networks of protected areas through ecological refugia and incorporated into an integrated approach to improve conservation outcomes.

3. Climate landscape metrics

Most species lack detailed physiological, ecological, and evolutionary data, especially in the tropics and much of the world’s ocean, and the current priorities in research make it increasingly difficult to collect such data (Costello et al., 2010). Thus, conservation and management agencies will use whatever tools they have available to them for making decisions. Climate landscape metrics provide simple, direct measures of the magnitude of change and shifts in local climatological conditions. For example, the velocity of climate change, or in simpler terms, climate velocity, is a solution that preserves generality while conveying more ecologically relevant information (Loarie et al., 2009). As recent evidence suggests this measure is a useful and simple predictor of the rate and direction of shift across a wide variety of marine taxa (Pinsky et al., 2013; Poloczanska et al., 2013). Linked to this concept, there is a newer promising metric called climate analogs. This metric identifies where sites with climate conditions comparable to those of the present day are likely to be found in the future (Williams & Jackson, 2007). Thus, climate landscape metrics will be key to making further progress in future species distribution research.

Climate velocity

Climate velocity is a simple predictive metric of range shifts that do not require extensive knowledge or data on individual species. This metric describes the speed and direction of climate movement at any point in space. In other words, climate velocity estimates the speed at which species must migrate over the earth’s surface to maintain constant climatic conditions (Loarie et al., 2009). Ecologically speaking, climate velocity can be seen as an indicator of how vulnerable an organism may be to climate change if the climate moves beyond the physiological tolerance of a local population. Although climate velocity appears to have ecological relevance, it is based exclusively on an environmental variable rather than species data (Brito-Morales et al., 2018). This expression of climate velocity represents the local rate of movement of climate isocline across a spatially varying climate gradient (Ordonez et al., 2013). Overall, climate velocity interpretation will be the speed at which hypothetical species will need to move to stay within current environmental conditions (i.e., changes in local climate conditions) or exploit new environments that will become suitable for the species in the future (i.e., changes in neighboring conditions).



Trends in Ecology & Evolution

Fig. 1.1: Graphical map from Brito-Morales et al., 2018 where they presented the differences between local and analog climate velocities.

There are two ways to calculate climate velocity: local climate velocity or climate-analog velocity, as graphically presented in Figure 1.2. In 2009, Loaire et al. proposed the original metric, the local climate velocity. To be able to calculate it at a location – how far and in which direction the isoline would move – only the rate of change of a variable through time and the corresponding spatial gradient of that variable are needed. This velocity has a dependence on neighboring (local) cells for the estimation of the spatial gradient in climate. On the other hand, climate-analog velocity emerged as an extension of the climate analog concept (Ordonez et al., 2013). Basically, it considers the distance between points at a particular point in time and their future climate analogs, divided by the time difference. To summarize, local climate velocity can be limited by species' preferences for habitat features, for instance, being limited to coastal marine regions by the need for light on the sea bottom, or substratum types for reef formation, or intertidal zones (Molinos et al., 2016). Instead, climate-analog velocity has usually been used with multiple variables and therefore, it has greater ecological realism in complex environments. Together, analog and local velocity analyses provide simple, yet powerful, tools for assessing how climate change could affect species distribution.

Climate velocity present various characteristics that might make the results less realistic, one of which is the fact of being univariate, based on sea surface temperature (SST) profiles only. However, the distribution of marine organisms is shaped by additional biological meaningful drivers that might change in the future such as dissolved oxygen, pH, limiting nutrients' concentration… (Assis et al., 2018). Recent developments in terrestrial climate change ecology open the possibility for more realistic estimates of climate projections using other metrics (e.g., climate analogs) and better integration with oceanographic connectivity (Assis et al., 2021).

Climate analogs

As climate changes, the currently realized climate could shrink, expand, or disappear; and in some cases, could emerge entirely new (no-analog) climatic conditions. Climate analogs are a statistical technique that quantifies the similarity of a location's climate relative to the climate of another place (i.e., between locations) and/or time (i.e., with past or future climates) (Beniston, 2014). For instance, if the given place of interest is Faro (Portugal), we can locate where in the world are today's climate analogous to Faro's predicted future climate (in *n* year), or vice versa. Hence, climate analog analyses can be used to identify the direction and bearing of future analogs, providing a measure of spatial displacement (Veloz et al., 2012) making it becoming more important as a means of communicating climate change effects (Kellett et al., 2015). This method is multivariate and so its estimates of climate displacement will be jointly influenced by fast-changing and slow-changing climate variables, as well as by the chosen variables.

Climate analogs define similar conditions by reference to a fixed, common climatic threshold and assume that resident biota is equally sensitive and exposed to the same change in climatic conditions. Regions above this threshold will be defined as non-analog conditions area. Such definition emphasizes on the role of climatic variability in shaping the physiological plasticity of populations via adaptation and acclimatation; as well as the assumption that responses to climate change are increasingly likely as conditions move beyond those that local biota are adapted to (García Molinos et al., 2017).

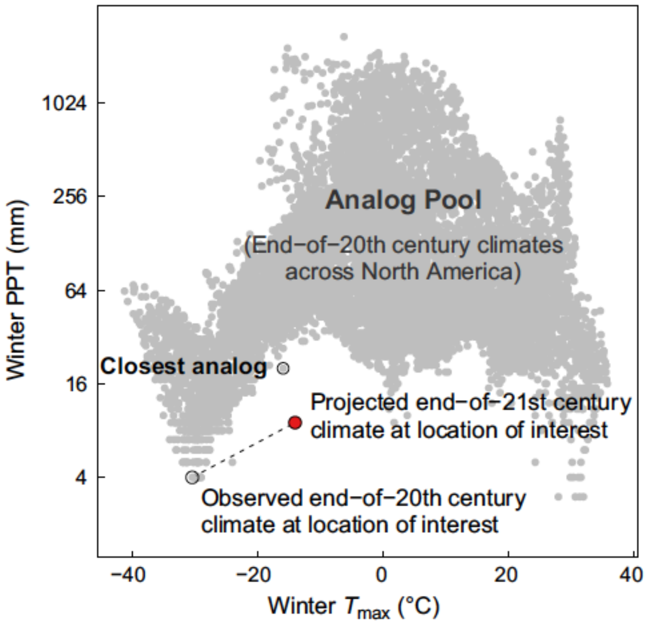


Fig. 1.2: Illustration from Mahony et al. (2017) of the novelty assessment from the observed end-of-20th century climate and the projected end-of-21st century climate. They used maximum winter temperature and total winter precipitation as variables.

Mahony et al. (2017) improved the climate analogs methodology using sigma dissimilarity to measure the novelty (new climatic conditions). As can be schematically seen in figure 1.2, novelty is the distance between the projected future climate of a location of interest and its closest analog in the observed climates of the study area. Ordonez & Williams (2013) used this metric to compare the similarity between 20th-centruy and late-21st-century climate by calculating the minimum Standardized Euclidean Distance (SED_{min}). Further, they estimated it against two alternative SED thresholds used to assess when SED_{min} were large enough to represent a truly novel climate.

Climate analogs has been more applied in terrestrial areas to assess novel terrestrial climates (Fitzpatrick & Dunn, 2019; Mahony et al., 2017) or to assess connectivity areas (Caroll et al., 2017) mostly in North America. In addition, other authors also used this metric to predict the impacts of climate change on terrestrial PA at local scale (e.g., Graham et al. (2019) in Autralia) or worldwide (Hoffman et al., 2019). However, less studies have been focussed on the marine environment to study MPAs. To this day, some authors used climate analogs to assess marine novel conditions worldwide (Johonson & Watson 2021, Lotterhos et al., 2021) or to assess connectivity and range shifts (Petsas et al., 2022). On the other hand, other studies have focused on local scales to identify future climatic stability and connectivity of MPAs (Garcia-Molinos et al., 2017, Kyprioti et al., 2021). García Molinos et al. (2017) used this metric to estimate future climatic connectivity between each focal cell and its corresponding future analog by using a randomized shortest path analysis based on circuit theory and random walks.

4. *Economic Exclusive Zones*

On the other hand, another important concept regarding MPAs distribution is the Economic Exclusive Zones (EEZ) of each country. These zones are marine areas that were prescribed by the United Nations Convention on the Law of the Sea (UNCLOS) and stretching from the baseline out to 200 nautical miles from the coast; and is regulated by each state. EEZs appear to be important areas to focus on the development of legal protection of endangered marine species as they are national jurisdiction areas. Therefore, a coastal approach to study MPAs within EEZs would be useful for the governments to address the challenge of optimal distributed MPAs. The World Database on Protected Areas (WDPA) is a global database that identify, monitor, and advocate for fully and highly protected marine areas. Extracted from this database, figure 1.3 depicts the world situation of MPAs in 2020 showing implemented and not implemented MPAs. According to this database, currently, 8.1% of the ocean is protected and 2.4% of the ocean is fully or highly protected from fishing impacts.

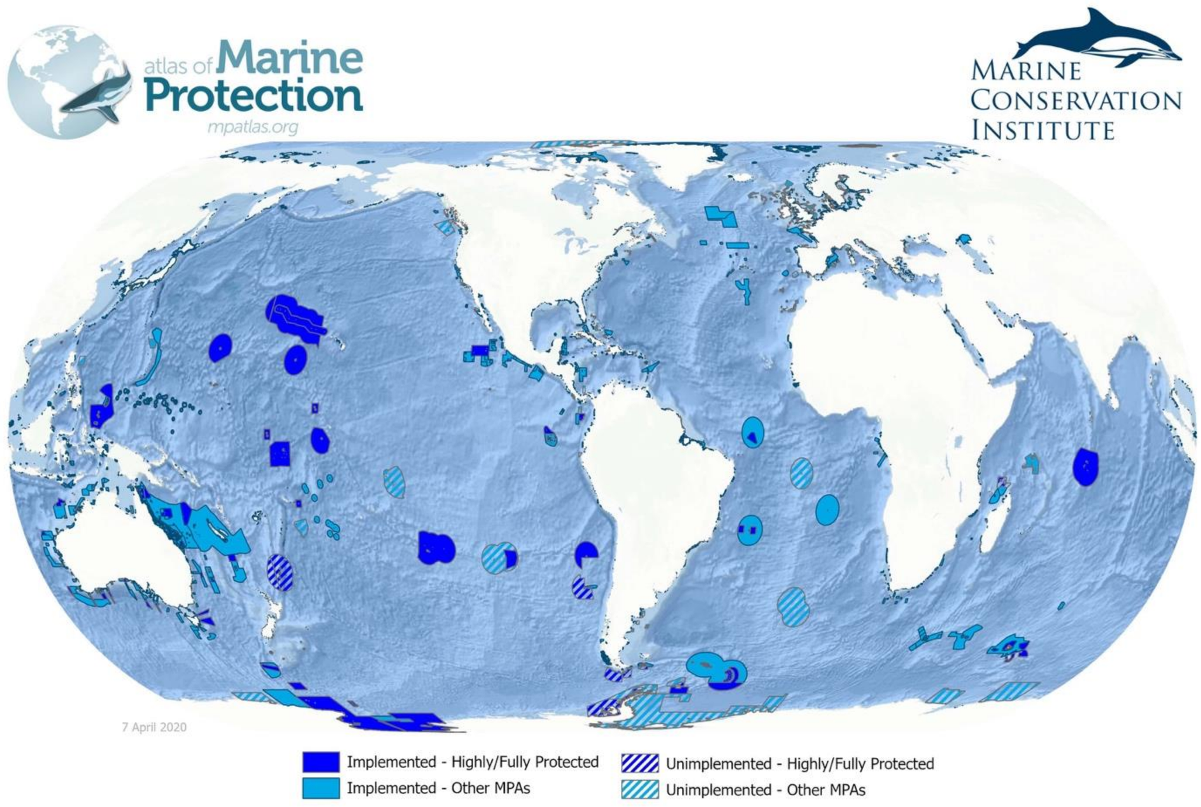


***Fig. 1.3*:** Illustration from MPAtlas.org (02/2020) representing the world current situation of MPA, data extracted from World Database of Protected Areas (WDPA).

5. *Post-2020 – 30% protection*

The modern movement to designate protected areas (PAs) started in the mid-1800, even if the drive to protect "spatial places" goes back millennia. Currently, PAs are the main tool on which hopes for stemming the relentless decline in the global diversity largely rest. The current vision of PAs as an international cooperation endeavor goes back to the early years of the International Union for Conservation of Nature (IUCN), through the work of its World Commission on Protected Areas (WCPA) created in 1960. Later on, in 1992, it was consolidated the United National Convention on Biological Diversity (CBD) aiming to stablish a PAs' system. They are currently operating with conservation plans such as CBD 2011-2020 Strategic Plan for Biodiversity, and the post-2020 Global Biodiversity Framework.

Since Aichi target was adopted in 2010 (which agreed a 10% of marine area protected by 2020), MPAs have multiplied along with the tools and information to ensure their effectiveness. The increase in coverage was necessary but has been insufficient to conserve global biodiversity and therefore, marine ecosystem health has continued to decline (Díaz et al., 2019). Currently, the world conservation community is on the verge of a formal commitment to protect 30% of our lands and waters by 2030. Scientists have unequivocally said that increasing management, conservation and restoration of natural systems is a must to preserve global biodiversity, regulate our climate, and provide a host of other benefits. However, in order to reach beyond the numerical target of protection to achieve desired conservation outcomes, MPAs must be optimally located in the global network.

6. Climate resilience – optimal MPAs distribution

Overall, rapid global warming over the past few decades has had consequences for weather, climate, ecosystems, and human society. Marine ecosystems are critical components of the global environment. They have a limited ability to adapt according to climate change which has already been proven to be altering the distribution and abundance of marine ecosystems (Prakash, 2021). The capacity of an ecosystem to foresee, prepare for, and react to sudden climate changes or disturbances is known as climate resilience. Therefore, fully protected MPAs will be a key mechanism to increase climate resilience of ecosystems in it as all the natural resources in it will be protected. Although we can implement measures to regulate direct human impacts to biodiversity, ecological interactions and food webs changes due to changing climatic conditions are harder to predict. Climate change drivers (e.g., warming, heat waves, ocean acidification) will have large scales impacts where MPAs borders might not be necessarily respected. Hence, MPAs' capacity to protect marine ecosystems from future climate change remains unclear and it is an unanswered question (Roberts et al., 2017). Until recently, climate change drivers had not been considered when designing the global network of MPAs. However, with those landscape metrics explained above, it has been possible to carry out studies taking some of these biologically meaningful drivers into consideration. There are no past studies about optimal location of MPAs regarding climate, nevertheless, Arafeh-Dalmau et al. (2021) used climate velocity to propose a climate-smart network of MPAs. They selected slow-moving climate velocity areas to protect climate refugia in the Mediterranean Sea. However, this metric is univariate and therefore, they only considered sea surface temperature values for the MPAs network analyses. In brief, there is no studies about the optimal climate location of global network of MPAs that can guide towards a proper implementation of the post-2020.

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2. Manuscript Thesis Project

The global network of Marine Protected Areas is not ready to face projected climate change beyond the Paris Agreement expectations

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Abstract

A current challenge of climate change adaptation is determining how resource management and conservation programs are designed to comprehensively protect biodiversity under present and future conditions. Marine protected areas (MPAs) are primary management tools aiming to reduce localized anthropogenic impacts on marine biodiversity but their implementation has neglected future climate change resilience, potentially reducing their performance in the years to come. Here, we ask if the global network of MPAs is ready to face future climate change by estimating its degree of exposure to novel climates (i.e., future conditions non-existent today) and by testing if its distribution inside each country's Exclusive Economic Zones is optimal. Our analyses were based on climatic analogs (sigma dissimilarity) using four biologically meaningful variables (temperature, oxygen, pH and primary productivity) from present-day conditions to the end of the 21st century, under contrasting Shared Socioeconomic Pathways (SSP) scenarios (SSP1-1.9 and SSP5-8.5). Our results show 8.59% of the MPAs exposed to novel climate under SSP1-1.9 in contrast to 81.05% under SSP5-8.5 (average sigma dissimilarity of MPAs: 0.7 and 4.40 with SSP1-1.9 and SSP5-8.5, respectively). Such novel conditions, particularly aggravated in tropical and polar regions, will likely produce local population extinctions and range shifting, while species search for climatic analogs. The four variables considered had a similar contribution on projected novel climates, reinforcing their role in driving range shifts at global scales. Moreover, only 9.6% and 4.7% of MPAs (SSP1-1.9 vs. SSP5-8.5) were estimated to be located in regions of national EEZs with reduced novel climates, suggesting the importance of considering climate change resilience during implementation phases. Overall, we show that broad compliance to the Paris Agreement expectations is key to increasing global MPA resilience and achieving international conservation targets like the post-2020 framework of the Convention on Biological Diversity, which considers expanding global MPA coverage up to 30% by 2030.

Key words: Marine Protected Areas; Climate Change; Climate analogs; Climate resilience; Shared Socioeconomic Pathways

Introduction

Climate change impacts on global marine ecosystems are among the hardest challenges our society faces today and in the coming century. In some regions, ocean temperature has risen by 1 to 3 ºC (IPCC, 2013) caused by the absorption of more than 90% of the additional heat trapped by anthropogenic greenhouse gasses. Such warming, coupled with increasing shallow-water stratification can lead to deoxygenation, potentially affecting primary production among other physical and geochemical processes (Bruno et al., 2018). Additionally, the uptake of anthropogenic carbon dioxide, termed ocean acidification, has triggered a pH drop of 0.3-0.5 units (Lotterhos et al., 2021) making it harder for calcifying marine organisms to form calcium carbonate shells or skeletons (Lemasson et al., 2017). Together, the synergetic effect of deoxygenation, warming, pH and productivity declines has led to multiple changes in species biodiversity and habitats. Numerous biotic responses have already been reported, including local and global extinctions and shifts in phenology, distribution, abundance, calcification, and demography (Poloczanska, 2013, Keeley et al., 2018). For marine taxa, the mean rate of expansion at range edges was estimated to be 72.0 ± 13.5 km dec^{-1} (Poloczanska, 2013). Changes in oxygen, temperature, pH and productivity are projected to accelerate until the end of the 21st century, particularly under the business as usual scenario of greenhouse gas emissions, reflected in the Shared Socioeconomic Pathway (SSP) 5-8.5 (Bruno et al., 2018; Schmidtko et al. 2017) further impacting life on Earth, posing major challenges for biodiversity, ecosystem functioning, and people to adapt.

A current challenge of climate change adaptation is determining how resource management and conservation programs are designed to protect biodiversity under future conditions. Marine protected areas (MPAs) are primary management tools aiming to reduce localized anthropogenic impacts on marine biodiversity (Watson et al., 2014), but their implementation has neglected future climate change resilience (Bates et al., 2019), potentially reducing their performance in the years to come. Currently, approximately 8% of the global ocean is covered by MPAs (Marine Conservation Institute, 2021; UNEP-WCMC & IUCN, 2022), but optimal location may be crucial to increase MPA resilience in the face of climate change, as some regions within country's Exclusive Economic Zones may change less than others. Such regions could work as refugia for biodiversity, providing more stable conditions in time and allowing species to persist locally and cope with global change (Micheli et al., 2012).

The few attempts to address MPA exposure to climate change have been done using climate metrics as direct proxies of potential biodiversity responses (Arafeh-Dalmau et al., 2021).

Climate velocity is a pioneer metric that describes the speed and direction at which species shift distributions to remain within suitable climatic conditions (Loarie et al., 2009). Using such a metric, Arafeh-Dalmau et al. (2021) proposed a climate-smart network of MPAs by selecting slow-moving climate velocity areas to protect climate refugia in the Mediterranean Sea. However, this metric is univariate, considering warming (e.g., sea surface temperature), and neglecting important drivers structuring the distribution of species like oxygen, pH and primary productivity. To overcome this, multivariate approaches have been recently developed and implemented. One of which, the climate analogs, quantifies the similarity of a location's climate, relative to the conditions of another place and/or period in time (Beniston et al., 2014). This uses a standardized Euclidean Distance (SED) of climate locations/periods to determine the Mahalanobis distance (M_D), from which Sigma dissimilarity is extracted as a standardized metric independent of the scales of variability of the climate variables. Overall, this metric can be understood as the number of standard deviations of climate variability at a given place (Lotterhos et al., 2021). Climate analog analyses have been largely used to project the impacts of climate change on terrestrial PA (e.g., Graham et al., 2019; Hoffman et al., 2019), yet only one study has been conducted in the marine realm. This focused on very large MPAs and estimated that 97% of them will be subjected to novel climates by 2100, i.e., to non-existing conditions in the present (Johonson & Watson, 2021).

An overall view of the global MPA exposure to climate change is still missing. We aim to fill this gap by answering the major question "is the global network of MPAs ready to face future climate change?". We answer the question using climate analogs analyses to estimate the degree of exposure to novel climates and to test if MPA location inside each country's Exclusive Economic Zones is optimal. The concept of climate "optimal location" links to how a particular MPA may be subject to lower degree of novel climates, compared to the surroundings of a countries' EEZ. We estimated the amount of resilient MPAs, ready to face future climate conditions, and the ones not to be, which may be a key precedent for countries aiming to achieve the new target of the Convention on Biological Diversity proposing an expansion of conservation areas to 30% by 2030 (the "30% target"; CBD 2020). We performed the study using a high performance computational framework feeding on multi-model ensemble from the Coupled Model Intercomparison Project phase 6 (CMIP6) and the World Database of Protected Areas, which documents the status and spatial extent of MPAs globally. Analyses used four biologically meaningful variables (temperature, oxygen, pH and primary productivity) from present-day conditions to the end of the 21^{st} century under contrasting Shared Socioeconomic Pathways (SSP) scenarios (SSP1-1.9 and SSP5-8.5).

Material and Methods

In the present study, exposure to climate change was estimated as the dissimilarity in climate conditions between the projected end-of-21st-century climate of a location of interest and its best analogue compared to observed current climates (years 2000-2020). The approach was based on the standardized Euclidean distance (SED) metric (Williams et al., 2007), which scales climate variables relative to the local range of interannual climate variation (ICV), with the modifications of Mahony et al. (2017) as SED is susceptible to variance inflation due to correlations in the raw variables and do not account for the effect of the number of variables on the statistical meaning of distance. This transforms SED into Mahalanobis distances, and subsequently, metric interpretation of distances as percentiles of the chi distribution. Mahalanobis distance is understood as a multivariate distance between a single grid point at one point in the time and its closest analogue (nearest neighbor) in the global climate baseline data from another time point. By using chi distribution in its interpretation, the effect of dimensionality is accounted for by the statistical meaning of distance. This approach is named 'sigma dissimilarity' and we have used it in climatic analog analyses.

Using Sigma dissimilarity, any given climate variable contribution is weighted according to how closely it correlates with all other variables, and it is expressed as a statistical measure of distance. The impact of dimensionality on expected distances is an important factor to consider when interpreting distances as dissimilarity. The chi-square distribution describes the probability distribution of squared Mahalanobis distances in multivariate normal data, with degrees of freedom corresponding to the number of dimensions (meaning the number of climate variables) in which the distance is measured. Hence, sigma dissimilarity is a multivariate z-score metric representing the percentile of a given Mahalanobis distance within this chi distribution.

Distances must be translated into probabilities to account for the effect of dimensionality on their statistical significance. We express the chi percentile as 4σ (sigma) to describe 99th normal percentile instead of using a threshold analogue dissimilarity level for defining novelty. Past studies, such as Williams et al. (2007) used a threshold of SEDt = 3.22 to define novel climates. However, we followed Mahony et al. (2017) who measured SEDt in a 4-dimensional climate space, considered 2σ analogue dissimilarity (the 95th percentile of local ICV) associating it to a moderate degree of climate novelty, and 4σ analogue dissimilarity to extreme climate novelty. Therefore, we divided novelty in non-novel climates (σ<2), moderate novel climates (2<σ>4) and extreme novel climates (σ>4).

Our climate analog analyses used four variables (meaning four dimensions): maximum temperature, average dissolved oxygen, average pH and primary productivity (PP) – total phytoplankton. These were chosen considering that they are openly available (see below climate data sources) and are biologically meaningful, driving habitat suitability of marine species (Zhao et al., 2020, McHenry et al., 2019; Lauchlan & Nagelkerken, 2020; Kroeker et al., 2013). Marine data for present and future conditions of the four variables were acquired from pre-processed global ocean re-analyses at regular spatial grids available from the Global Ocean Ensemble Reanalysis provided by the E.U. Copernicus Marine Service Information and from multiple Atmospheric-Ocean General Circulation Models provided by the Coupled Model Intercomparison Project Version 6.0. Data defining the present and future conditions of the ocean's surface were produced from 2000 to 2020 and from 2080 to 2100 using the pipelines of Bio-ORACLE (Assis et al., 2017). Data for the future were produced for the new SSP: the SSP1-1.9, a scenario of low greenhouse gas concentration levels matching the Paris Agreement expectations and the SSP5-8.5 of increasing emissions over time. These data, produced at the sea surface levels, allows comparisons with the past studies of Petsas et al., 2022; Kyprioti et al., 2021 or Ding et al., 2018.

We use a principal component analysis (PCA) at the cell level to simplify the complexity in high-dimensional data and to create new uncorrelated variables that successively maximize variance. Subsequently, we standardized them by the multivariate ICV at the focal station. The principal component analyses express climate variables as standardized anomalies of the nearest climate station (meaning the pool of analogs around a specific grid cell) and rotates data space axes into alignment with the principal components of local ICV. As a result, principal components with variances lower than 0.01 will be discarded by applying the PCA, therefore, this will reduce the dimensionality of the data space. After generating this area around a focal cell, we extract the principal components of reference interannual variability to be able to identify the best analog using the Mahalanobis distance in the principal component space. Therefore, the nearest neighbor in the principal component space is the geographical location in the global baseline climate data with most similar present-day climate to that of the focal station’s future projected, meaning their closest analog. In addition, regarding the number of dimensions, Mahony et al. (2017) have demonstrated that variable selection is a critical consideration in novel climate detection, therefore, we perform the analyses with the four variables listed above carefully selected to cover the maximum range of species.

We also assessed the contribution of each variable to future climatic dissimilarity. To do so, we run the analyses multiple times, by sticking climate conditions of one variable at the time to its present-day conditions. These interactions allowed determining the impact of each variable to the overall climatic dissimilarity estimated for the future. We represented their contribution as a percentage.

Finally, the distribution of each MPA was tested inside each country's Exclusive Economic Zones to assess if their location is optimal to cope with future climate change. This was performed by 10.000 randomizations comparing future novel climates of each MPA with virtual MPA of the same size randomly located inside corresponding EEZs. In particular, we counted the number of times future climate conditions were better in MPAs, i.e., lower climate dissimilarity, when compared to random locations of the same size inside EEZ. An estimate of significance for optimally located was inferred when 99.5% of the times future climates of MPAs were less dissimilar than in their surroundings.

Marine protected areas data were obtained from The World Database on Protected Area (www.protectedplanet.net) which includes data from PA and OECMs updated monthly with submissions from governments, NGOs, landowners, and communities. On the other hand, EEZs data was obtained from Marine Regions (www.marineregions.org) which is an integration of the VLIMAR Gazetteer and the VLIZ Maritime Boundaries Geodatabase that depends on data and knowledge sharing from global, European, regional, and national data providers and relevant experts.

Results

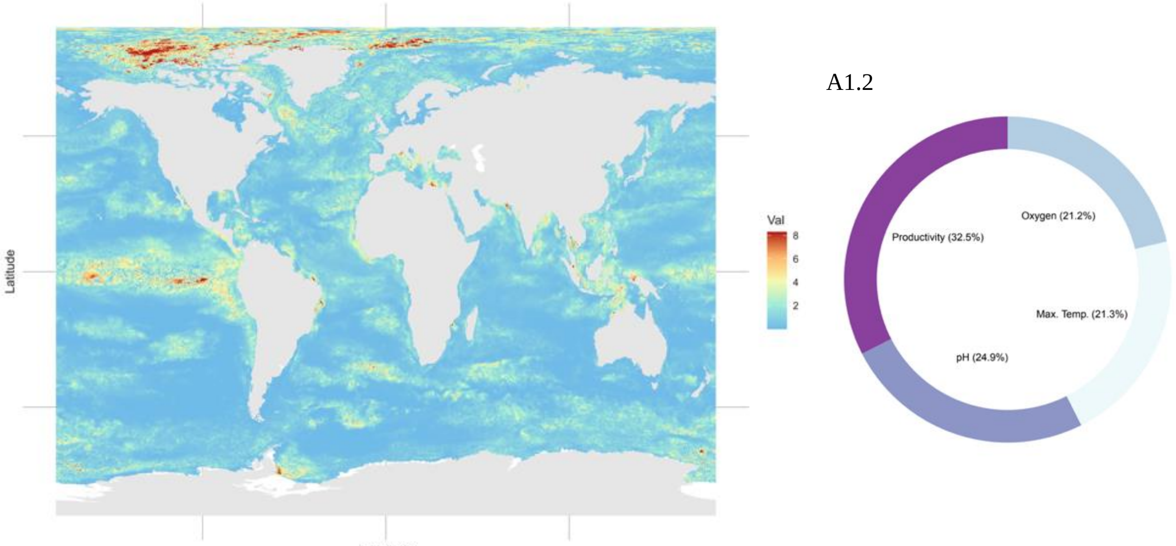
Global ocean exposed to future climate dissimilarity

Our estimates of global exposure to novel climate conditions revealed that the Arctic and the tropical regions might be the most affected areas in the future (Figure 2.1A). For SSP1-1.9, besides the Arctic, the novelty in tropical areas was particularly obvious in the eastern Pacific region between Perú and Ecuador latitudes. Besides, smaller regions with novel climates also appear in the Mediterranean Sea. The SSP5-8.5 scenario follows the same pattern, however, experiencing much harsher conditions and novel climates (Figure 2.1B). When considering SSP1-1.9, the proportion of the ocean experiencing moderate and extreme novel climates were 0.11 and 0.03, respectively, which contrast with SSP5-8.5, with moderate and extreme climates of 0.41 and 0.32. Future disappearing climates show the same pattern (Supplementary Figure 3.1A). Disappearing climates refer to those cells that will not have any analogs of their conditions in the future, thus, corresponding to future climatic conditions that do not exist anywhere in the present. Refugial areas proportion, where climate analogs were not displaced, were verified in SSP1-1.9 and almost non-existent in SSP5-8.5. In opposition to refugial areas, the Arctic and the western Pacific were the regions where analogs traveled most (Supplementary Figure 3.1B). Overall, over 80% of the global ocean analogs will travel distances shorter than 500 km to find its analogue (Figure 2.1C).

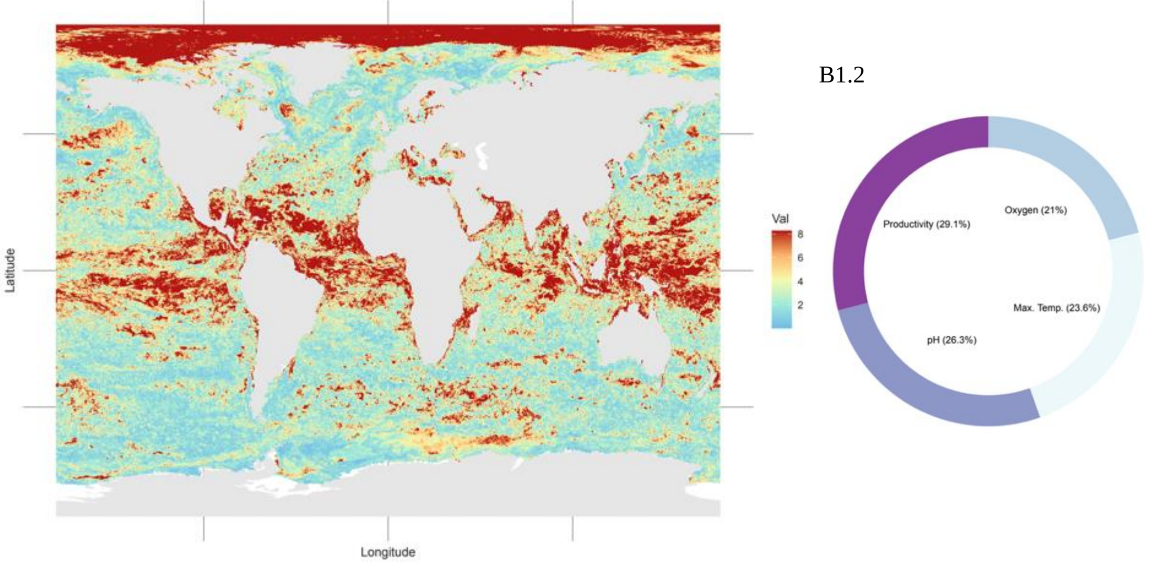
Similar contributions to global climate dissimilarity were inferred for the 4 variables considered: maximum temperature, dissolved oxygen, pH, and productivity, for both scenarios (Figure 2.1: A1.2, B1.2). Besides, there were no clear patterns in the global ocean maps of the relative importance of each variable. However, for SSP1-1.9 some spatial patterns could be detected (Supplementary Figure 3.2); and for SSP5-8.5 pH and temperature contribution values were higher in the Arctic and Antarctic (Supplementary Figure 3.3).

Focusing on global exposure to climate dissimilarity per latitudinal bin, allowing to better understand the impacts of climate change as an area of exposure, for SSP5-8.5, moderate climates might be found in temperate latitudes whereas extreme climates might be in the Arctic and tropical latitudes. For SSP1-1.9, the total area of moderate and extreme climate is far lower than for SSP5-8.5. The area in the Arctic is smaller than the Antarctic, thus, maps per latitudinal bin will show that the Southern Ocean, in area, may be more affected (Figure 2.2).

A. Novel climates – SPP1-1.9



B. Novel climates – SPP5-8.5



C. Distance to analogue (km)

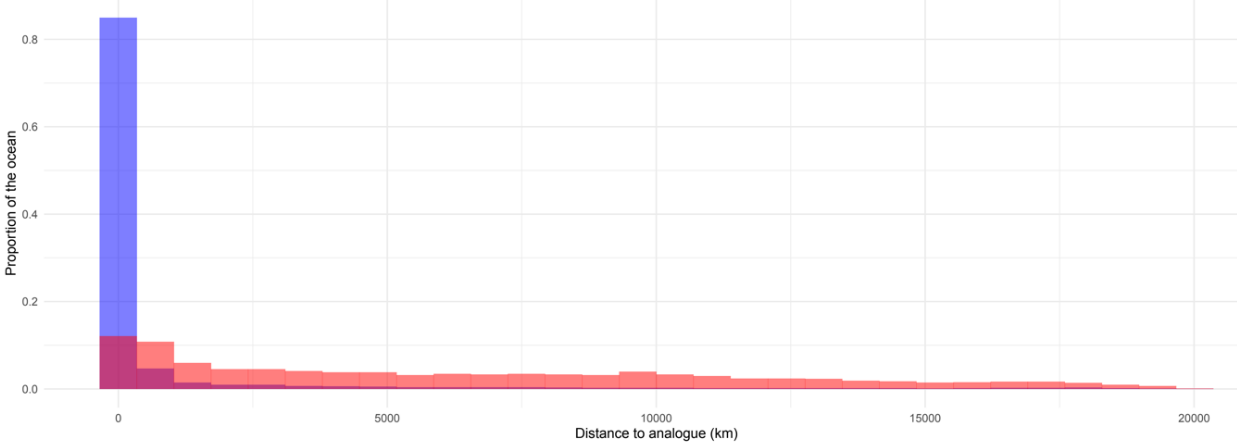


Figure 2.1: Novel climates (sigma dissimilarity) for both scenarios (A and B) with their variable contribution (A1.2 and B1.2). Distances to analogs (km) for the whole ocean including both scenarios can be seen bellow C (blue: non-novel conditions, pink: moderate conditions, orange: extreme conditions).

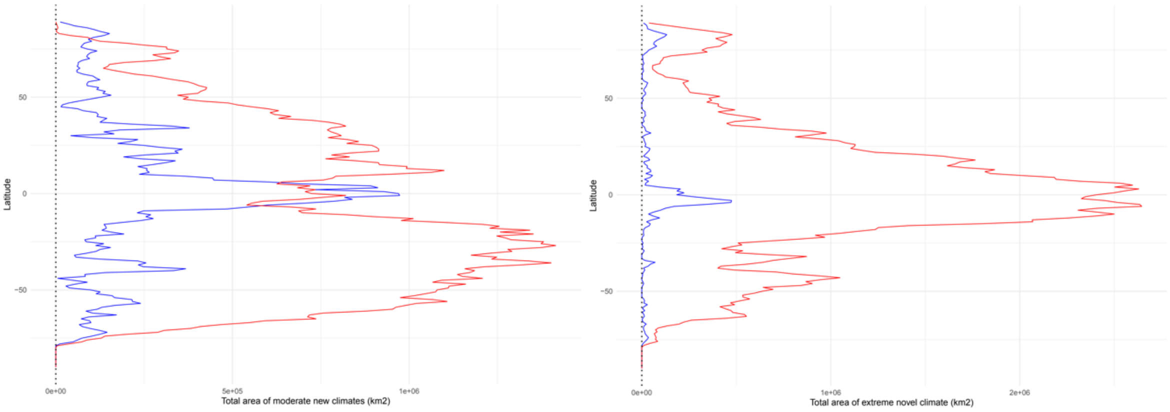


Figure 2.2: Moderate (left) and extreme (right) novel climates per latitude (km^2) are presented for both scenarios (blue line: SPP1-1.9; red line: SPP5-8.5).

Economic exclusive zones exposed to future climate dissimilarity

The average values of climatic dissimilarity per EEZs follow the same pattern described for the global ocean, with novel and disappearing climates values nearly the same. For the SSP5-8.5 scenario, novel and disappearing climates were approximately four times higher (Table 2.1). On average, analogs travel over 5.500 km more in SSP5-8.5 than in SSP1-1.9. Consequently, estimates of refugia were higher for SSP1-1.9 (average refugia proportion: 0.80); while SSP5-8.5 will hardly offer refugia areas.

	NC (Sigma Mean)	NC (Sigma Max)	DC (Sigma Mean)	DC (Sigma Max)	ECP	AD Mean	RP
SSP 1-1.9	1,23	3,32	1,23	3,33	0,03	679,33	0,8009
SSP 5-8.5	4,88	7,82	4,86	7,81	0,58	6223,88	0,0025

Table 2.1: Average values for the analyses per EEZs considering novel climates (NC), disappearing climates (DC), extreme climates proportion (ECP), average distance to the closest analog (AD) and refugia proportion (RP) for both SSP scenarios. Values for all EEZs are presented in the Supplementary information.

According to SSP5-8.5, the ten EEZ exposed to worst conditions in the future are located in temperate and tropical areas, agreeing also with Figure 2.1B; mostly in the Mediterranean Sea (e.g., Monégasque, Slovenian and Croatia EEZs), Caribbean Sea (e.g., Sint-Maarten, or Saint

Matin EEZs) and the Persian Gulf (e.g., Iraqi EEZ). Therefore, semi-enclosed areas/seas might be more affected than open-ocean areas. All of them are under extreme novel climate conditions, with average sigma dissimilarity values above 4 (Table 2.2). However, the distribution of the best EEZs were mostly distributed in temperate and high latitudes. For instance, the northern and southern Atlantic Ocean (e.g., Faeroe, Irish, Dutch or Tristan Da Cunha EEZ). Under the SSP1-1.9, 84% of EEZ present non-novel conditions whereas under the SSP5-8.5 there are only three EEZ that contain non-novel climatic conditions, the rest have moderate to extreme climates (Supplementary Table 3.1). The same table with the best and the worst EEZs for the SSP1-1.9 is presented in the supplementary information as a tool for the countries for future management, as well as novel and disappearing values for all EEZs.

TOP10: WORST EEZ SPP5-8.5	NC (Sigma Mean)	NC (Sigma Max)	DC (Sigma Mean)	DC (Sigma Max)	ECP	AD Mean	RP	Climate
Monégasque Exclusive Economic Zone	7,05	8,29	7,34	8,29	1	17319	0	Ext.
Slovenian Exclusive Economic Zone	8,29	8,29	6,28	6,28	1	148,4	0	Ext.
Joint regime area Croatia / Slovenia	8,29	8,29	7,76	8,29	1	19,54	0	Ext.
Iraqi Exclusive Economic Zone	8,29	8,29	8,29	8,29	1	46,26	0	Ext.
Overlapping claim: Puerto Rico / Dominican Republic	8,29	8,29	4,48	8,29	1	330,9	0	Ext.
Saint-Martin Exclusive Economic Zone	7,81	8,29	5,95	8,29	1	178,8	0	Ext.
Joint regime area Guyana / Barbados	8,29	8,29	8,29	8,29	1	87,34	0	Ext.
Overlapping claim Peñón de Vélez de la Gomera: Spain / Morocco	4,53	4,83	1,36	2,13	1	4026	0	Ext.
Sint-Maarten Exclusive Economic Zone	8,29	8,29	8,21	8,21	1	348,7	0	Ext.
Joint regime area Colombia / Dominican Republic	5,96	7,65	8,22	8,29	1	902,6	0	Ext.
TOP10: BEST EEZ SPP5-8.5								
Overlapping claim Qatar / Saudi Arabia / United Arab Emirates	1,04	1,04	7,52	7,52	0	8684	0	Non-N
Joint regime area United Kingdom / Denmark (Faeroe Islands)	1,51	3,8	6,72	8,29	0	10683	0	Non-N
Joint regime area United States / Russia	1,97	4,08	2,86	4,92	0,05	4237	0	Non-N
Faeroe Exclusive Economic Zone	2,01	6,64	2,47	8,29	0,07	8213	0	Mod.
Overlapping claim Liancourt Rocks: Japan / South Korea	2,02	3,01	0,22	0,27	0	13954	0	Mod.
Norwegian Exclusive Economic Zone	2,02	7,98	2,84	8,29	0,07	8232	0	Mod.
Overlapping claim Falkland / Malvinas Islands: UK / Argentina	2,03	8,29	2,48	8,29	0,06	5843	0	Mod.
Dutch Exclusive Economic Zone	2,03	4,81	1,1	3,31	0,07	8646	0	Mod.
Tristan Da Cunha Exclusive Economic Zone	2,1	8,29	2,7	8,29	0,09	7870	0	Mod.
Irish Exclusive Economic Zone	2,14	6,71	2,59	8,29	0,08	10630	0	Mod.

Table 2.2: Analyses TOP10 worst and best EEZs considering novel climates (NC), disappearing climates (DC), extreme climates proportion (ECP), average distance to the closest analog (AD) and refugia proportion (RP) for the worst-case scenario (SSP 5-8.5). Climate: Non-Novel (0-2), Moderate (2-4) and Extreme (>4). Values for all EEZs are presented in the Supplementary information.

Marine protected areas exposed to future climate dissimilarity

Globally, novel and disappearing climates for MPAs follow the same pattern of four times higher under the worst-case scenario (Table 2.3). The total of 5.365 MPAs extracted from the WDPA were divided into very large MPA (>10.000 km^2), large MPA (10.000-1.000 km^2) and medium MPA (<1.000 km^2), obtaining a total of 155, 434, and 4.776 MPAs, respectively. Sigma values, both for novel and disappearing, do not show striking differences between the MPAs categories. Yet, the maximum sigma value for very large MPAs was around 2.3 for SSP1-1.9; and 7.5 for SSP5-8.5 (Table 2.3). Extreme novel climate proportion, as well as refugia proportion, do not show significant differences between MPAs areas. Nonetheless, large MPAs present the highest average distances meaning that the analogs need to travel longer distances than in the case of very large or medium MPAs.

In terms of the distribution of MPAs, 9.6% of them were estimated to be climatic optimally located under SSP1-1.9, whereas 4.7% under SSP5-8.5. Importantly, a MPA can be optimally located (in regions of EEZs facing better conditions in the future than its surroundings) but may still have to cope with moderate or even extreme novel climates. Considering MPAs facing non-novel climatic conditions, the percentage of optimally located remains practically the same: 9.4 and 4% respectively. Yet, under the SSP1-1.9, all MPAs under moderate/extreme novel climates (505 MPAs) were estimated as non-optimally located. Under the SSP5-8.5, 0.3% of all MPAs were found optimally located for moderate climates and 0.2% for extreme climates.

Scenario	**NC (Sigma Mean)**	**NC (Sigma Max)**	**DC (Sigma Mean)**	**DC (Sigma Max)**	**ENCP**	**AD Mean (km^2)**	**RP**
SSP 1-1.9	0,70	0,80	0,70	0,80	0,01	478,97	0,88
SSP 5-8.5	4,40	4,93	4,20	4,70	0,49	6047,77	0,01

MPA Category	**NC (Sigma Mean)**	**NC (Sigma Max)**	**DC (Sigma Mean)**	**DC (Sigma Max)**	**ENCP**	**AD Mean (km^2)**	**RP**
Very Large (SSP 1-1.9)	1,03	2,38	1,04	2,42	0,03	695,67	0,81
Large (SSP 1-1.9)	1,06	1,38	1,07	1,40	0,03	929,78	0,82
Medium (SSP 1-1.9)	0,79	0,85	0,79	0,85	0,01	715,81	0,87
Very Large (SSP 5-8.5)	4,11	7,56	4,01	7,25	0,45	6842,45	0,00
Large (SSP 5-8.5)	4,33	5,62	3,94	5,23	0,47	7343,97	0,01
Medium (SSP 5-8.5)	4,42	4,78	4,23	4,57	0,49	5904,36	0,01

		SSP 1-1.9			**SSP 5-8.5**	
	Num. MPAs	**optimally located MPAs**	**% optimally located**	**Num. MPAs**	**optimally located MPAs**	**% optimally located**
Global optimally-located MPAs (**regardless of climate**)	5367	513	**9,6**	5367	251	**4,7**
Optimally located MPAs, **non-novel** climate (s < 2)	4852	503	**9,4**	1017	213	**4,0**
Optimally located MPAs, **moderate** climate (s 2-4)	436	0	**0**	1748	18	**0,3**
Optimally located MPAs, **extreme** climate (s > 4)	69	0	**0**	2592	10	**0,2**

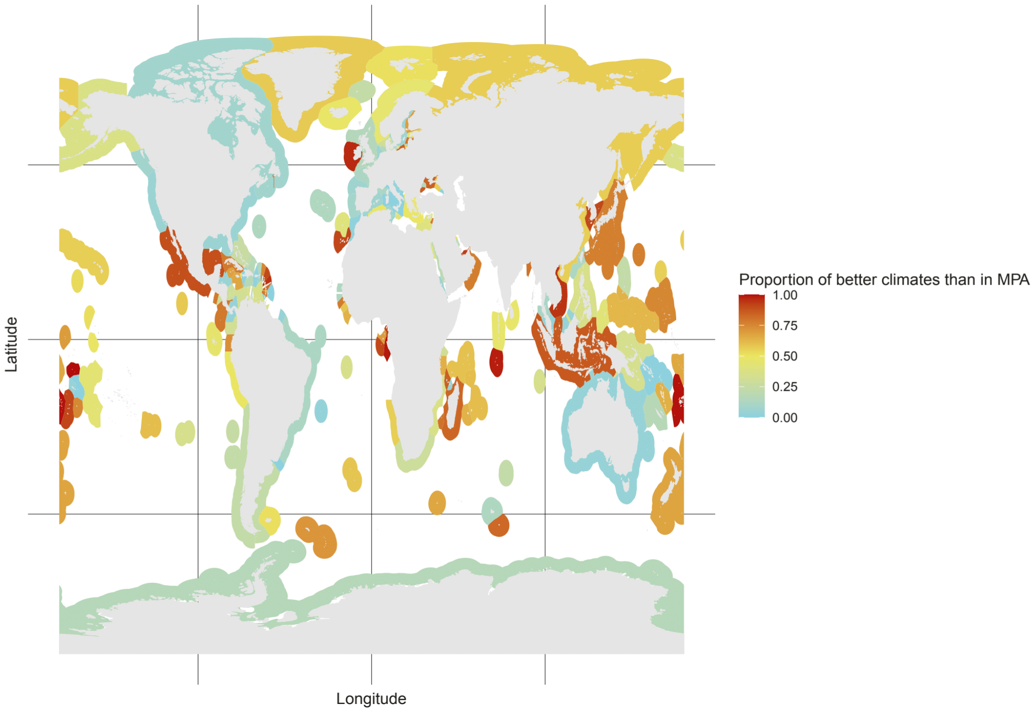
Table 2.3: Average values for the MPAs analyses considering novel climates (NC), disappearing climates (DC), extreme novel climates proportion (ENCP), average distance to the closest analog (AD) and refugia proportion (RP) for both SSP scenarios. Averages are also calculated classifying MPAs according to very large (> 10.000 km^2), large (1.000 – 10.000 km^2) and medium (0-1.000 km^2). Climatic optimally located percentages for the global MPAs is presented as a function of sigma dissimilarity

values. In blue the percentage of optimally located MPAs for SSP1-1.9 and in orange for SSP5-8.5. Further, all values for climate dissimilarity for each MPA are presented in the supplementary information.

In general, east Europe, Australia, and North America MPAs there might not be areas with better climate than the current MPAs as for SSP1-1.9 conditions, followed by South America and Antarctica (proportions around 0.25). Conversely, tropical areas such as part of Central America (Mexico, Barbados, Santa Lucia, and Dominica), Canary Islands, Fiji Islands, Ireland, The Maldives, Gabon, and part of Indonesia might be the worst-located MPAs with proportions around 1 (Figure 2.3A). Looking at the SSP5-8.5, this distribution is maintained but worsens in certain areas, for instance, north Europe and Asia with values around 0.75-1. Besides, North America will also experience an increase in the proportion of better climates than in MPAs going from 0.10 to 0.50 values (Figure 2.3B).

Overall, under SSP1-1.9, the majority of MPAs will be exposed to non-novel conditions whereas for SSP5-8.5 there will be a higher percentage of exposed MPAs to moderate novel conditions (Figure 2.4). Those MPAs facing moderate conditions might be found in more temperate latitudes and mostly in the Southern Ocean while exposed MPAs to extreme climatic conditions, might be in polar and tropical latitudes (Figure 2.4B, 2.4C).

A.



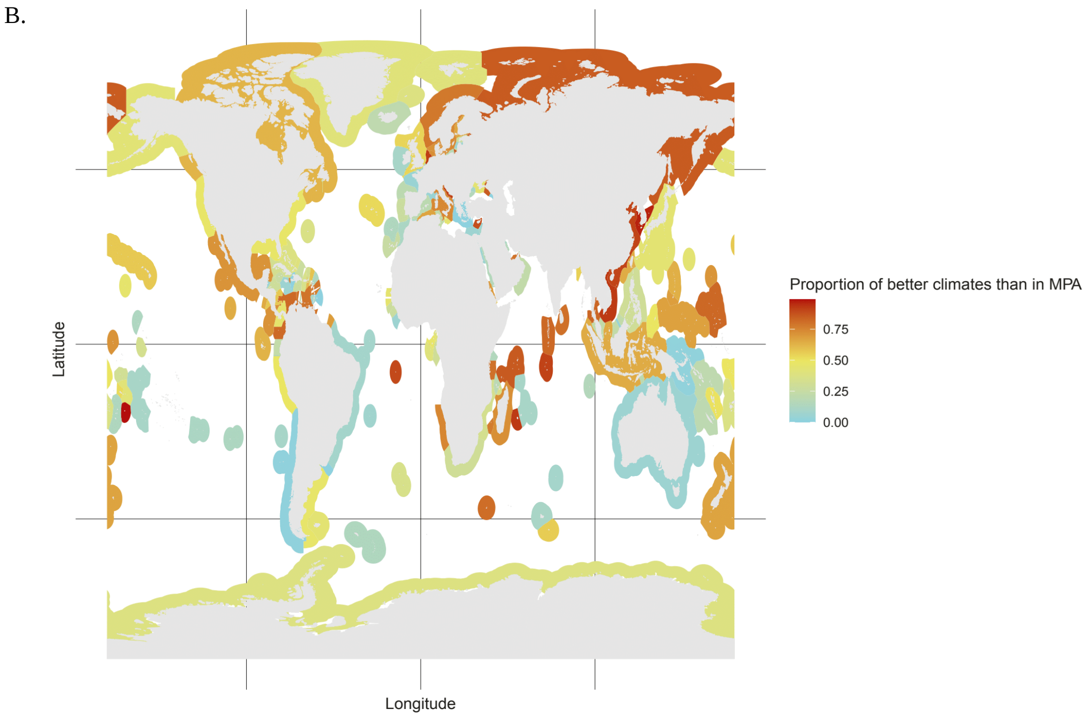


Figure 2.3: Proportion of better climates than in MPA for both scenarios: SSP 1-1.9 (A) and SSP 5-8.5 (B).

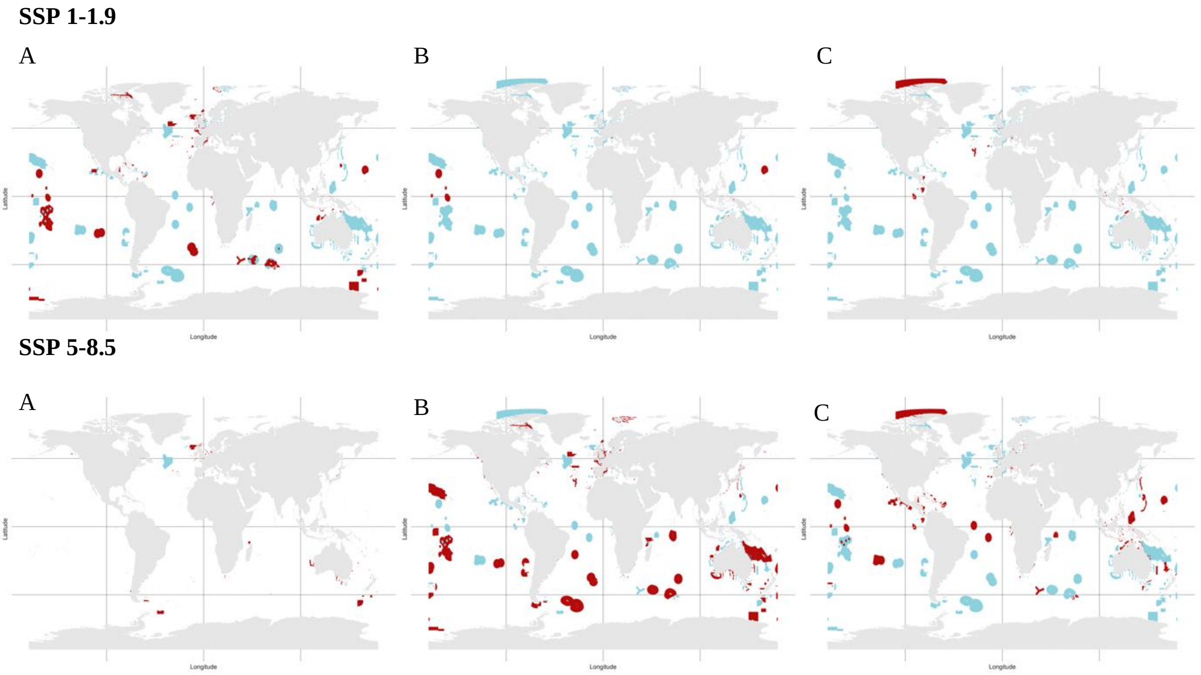


Figure 2.4: Exposed MPAs in red to non-novel climates (A), moderate novel climates (B) and exposed to extreme novel climates (C) for both SSPs.

The Arctic part of the Canadian EEZ, a small area of the Australian and Palau EEZ and an area of Hawaii were estimated to be optimally located MPAs under both scenarios. Besides, for the SSP5-8.5, two more islands (Tristan da Cunha and Gough Island) and a small spot in the Seychelles EEZ will also be optimally located.

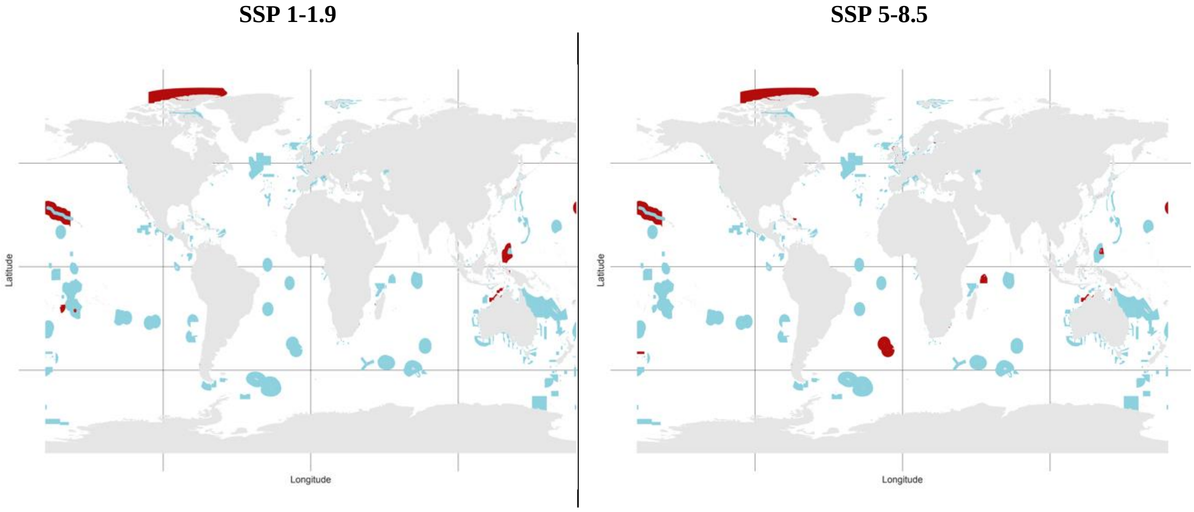


Figure 2.5: Climatic optimal located MPAs for both SSPs. Blue are the current MPAs within the EEZs and red corresponds to the MPAs that are climatic optimally located (ready) regardless the novel climates.

Discussion

By conducting climate analogue analyses based on biologically meaningful variables, we provide for the first time an overall view of MPA exposure to future climate change under contrasting SSP emissions scenarios. We show that MPA exposure to climate change is highly dependent on SSP anticipation, with the proportion of the ocean experiencing novel climates far much higher for the worst-case scenario. Moderate and extreme novel climates values were three times higher for SSP5-8.5, causing analogs to be displaced on longer distances. Under SSP1-1.9, non-novel climates prevailed, allowing a higher proportion of refugia. We further show that most MPAs (9.6% and 4.7%; SSP1-1.9 vs. SSP5-8.5) are located in regions of national EEZs with higher degree of novel climates than their vicinities, highlighting the importance of considering climate change resilience during implementation phases. Overall, we provide new baselines for well-informed IPCC impact assessments, conservation, and management. Importantly, broad compliance to the Paris Agreement expectations seems key to increasing global MPA resilience and achieving international conservation targets like the post-2020 framework of the Convention on Biological Diversity, which considers expanding global MPA coverage up to 30% by 2030.

Global exposure to future climate dissimilarity (from the global ocean to MPAs)

Our study projects from the global ocean, to local MPAs, exposure to climate change can be severe, particularly if countries do not comply with the Paris Agreement. Climatic analog analyses based on sigma dissimilarity allowed us to estimate that the Arctic and the eastern Pacific might be the most affected regions regardless of the SSPs. This goes in line with past studies which also found that climate novelty was particularly pronounced in the tropics (Lotterhos et al., 2021) and Arctic (Johnson & Watson, 2021) regions. Even though both the regions are affected, in terms of the overall area, Arctic impacts are much less (around 10^4 orders of magnitude) as detailed in the analyses per latitudinal bin. Furthermore, the low degree of global novelty in northern temperate regions found by Lotterhos et al. (2021) is in line with our results (Figure 2.1B for the SSP5-8.5). Apart from those regions, for the Paris Agreement expectation, some novelty spots were found in the Mediterranean Sea. This area, together with the eastern Pacific, are considered to be important areas for conservation considering their high species richness (Jefferson et al., 2021). The fact that they present novel climates underlines the importance of MPAs management at these broad regions to preserve biodiversity. Besides, for SSP1-1.9, the percentage of the ocean experiencing novel conditions is not as high as for the worst-case scenario, where more than 50% of the ocean is affected by novelty. These are expected results since increasing emissions will lead to higher sigma dissimilarity values meaning more extreme novel conditions. Past studies stated that 60%-80% of the ocean surface is expected to contain novel climates by 2100 regarding three different climatic scenarios (SSP2-4.5; SSP5-8.5 and SSP3-7.0) (Johnson & Watson, 2021; Lotterhos et al., 2021).

Climate analog analyses allowed determining for the first time novel and disappearing climates, for both EEZs and MPAs. While for the EEZs novelty was estimated as 4 times in average higher for SSP5-8.5, for MPAs this was up to 6 times higher, meaning that the impacts might be greater in these areas. Our findings suggest a worrying outlook for marine environments if stringent climate policy is not undertaken. There are no past studies of coastal MPAs using climate analogs, nonetheless, studies about very large (offshore) MPAs stated that most of them could be significantly impacted by 2060 (Johnson & Watson, 2021). Regarding the distances to analogs, for the worst-case scenario, these were, in average, around 5.500 km longer than for the SSP1-1.9. The greater these distances are, the greater species may shift ranges while migrating to find suitable conditions. Analogues will likely transpose boundaries, and species range shifts may occur across countries; thus, it will be necessary to take measures at a global level and to communicate between countries to ensure good management of MPAs and marine resources (e.g., fisheries).

Drivers of exposure

The analog analyses of the present study considered maximum temperature, dissolved oxygen, productivity, and pH. A crucial step in our study was the choice of predictors since it could affect the outcomes. Mostly, past climate studies focussed on temperature as it is known to be an important driver of biodiversity in the marine environment (Tittensor et al., 2010). For instance, Lotterhos et al (2021) assessments were conservative as they only include temperature and carbon chemistry predictors. However, they mention the importance of other variables such as primary productivity, specifically in coastal areas, or dissolved oxygen as warming reduces its solubility. Hence, we include multiple stressors, listed above, in M_D and sigma dissimilarity calculations to improve the estimations and fill this gap. Along with, an important consideration when analyzing general novelty is to balance the definition of climate between not sufficient climate variables (too broadly) and too many variables (too specifically). Mahony et al. (2017) affirmed that the 4-variable definition of climate used by Williams et al. (2007) ensures a method with a low risk of false novelty and therefore, improves the results.

Our results of drivers' exposure to climate change for SSP1-1.9 showed some degree of spatial patterns. In general, dissolved oxygen and productivity contributed to climate novelty in tropical-temperate southern regions like the Indo-Pacific. This region is known to be a critical hotspot for endemic biodiversity and coral reefs (Burke et al., 2012), and past studies have claimed it to be one of the areas with the highest climate novelty (Lotterhos et al., 2021). Besides, the contribution of productivity was mostly pronounced in the southeastern tropical Pacific and sub-Antarctic area. South America is one of the most biologically productive areas in the world driven by the highly productive Peruvian coastal upwelling. Beneath these productive waters there is an oxygen-deficient zone due to the respiration of these sinking particles and characterized by low temperatures (Kadko, 2017); both features are reflected in our predictors' maps. Further, evaluations from other studies pointed to an increase of productivity in the Southern Ocean (Steinacher et al., 2010). On the other hand, for SSP5-8.5, the Arctic and Antarctic presented higher contributions of pH and maximum temperature in determining novel conditions. Johnson & Watson (2021) proved that both pH and temperature conditions will emerge throughout the century and emphasized the importance of considering ocean acidification in biodiversity impact assessments. Other past studies also projected an increase in productivity in the Arctic due to sea-ice melting (Yool & Coward, 2015). In addition, for both emissions scenarios, variable contribution plots show similar values for the 4 predictors (Figure 2.1: A1.2 and B1.2). Consequently, the overall lack of striking patterns indicates that potential species range shifts might be the combination of all 4 predictors. As a result, any change in one of the predictors' conditions will lead to stressful conditions for biodiversity, therefore, all of them are biologically meaningful drivers for marine biodiversity distributions in our study

Projected consequences of novel climates (sigma-dissimilarity)

Novel and disappearing climate conditions involve novel and disappearing habitat conditions (Hoffman et al., 2019). Our results claim that all MPAs are expected to experience novelty in SSP5-8.5. Hence, those MPAs experiencing novel climates will facilitate the potential migration of invasive species into them (Walther et al., 2009) and the tendency of current resident species to migrate out of MPAs (Wessely et al., 2017). Therefore, these projected consequences will impact biodiversity by range shifting and many populations' survival might be determined by their capacity to disperse and colonize new habitats (Carrol et al., 2018). Tropical areas (emphasizing the Pacific Ocean) and the Arctic are expected to be the more detrimental areas in terms of novelty (sigma-dissimilarity). Species might shift to non-novel areas to avoid changing conditions. Poloczanska et al. (2013) stated that 38% of leading-edge expansions, where populations expand following climate change, were from latitudes warming strongly (>40ºN) which are in line with our novelty maps. Additionally, they pointed to highly dispersive pelagic organisms as the ones with the fastest migration rates. Conversely, range shifts will be aggravated for low dispersive organisms which can be key structuring species (e.g., corals, seagrass and marine forests of large algae). However, if dispersal will not be an option, these species may need to resort to evolutionary adaptation, plasticity, acclimatization, and/or epigenetic processes (Munday et al., 2013). In this case, connectivity among MPAs will be crucial as MPAs may be subjected to network fragmentation (Assis et al., 2021); highlighting the need to create a strong network of MPAs with an optimal distribution.

Optimally located MPAs

Climate analogue analyses allowed us to test which MPAs might be optimally located to face future climate conditions. As novel conditions emerge, MPAs will definitely play an important role in ongoing ocean conservation thanks to their numerous socio-environmental benefits (Ban et al., 2019). Our results prove that MPAs will face higher novel/disappearing climates for the worst-case scenario, following the pattern of EEZs and the global ocean. Past studies have been performed for large MPAs (Jonson & Watson, 2021), missing an important region of coastal areas. Those areas are known to experience large temperature and carbonate chemistry fluctuations caused by upwelling processes and freshwater input (Chan et al., 2017). Lotterhos et al. (2021) did not include coastal areas in their study, however they mentioned the need to include them in future research. Therefore, our study fills this gap by also presenting the analysis of the coastal MPAs within the EEZs. Our results proved that MPAs exposed to moderate conditions might be found in temperate latitudes, specifically in the Southern Ocean. Otherwise, MPAs exposed to extreme climatic conditions will probably be found in more polar and tropical latitudes.

Globally, 9.6% in number of the total MPAs had climatic optimal locations following the Paris Agreement scenario while only 4.7% for the worst-case scenario, meaning that most areas inside EEZ may provide better climates in the future than where MPAs are located. In particular, nearly half of all MPAs (2.592 out of a total of 5.367 MPAs) might be facing extreme novel conditions under SSP5-8.5, and only 0.2% of these are optimally located. Solutions could consider moving current MPAs (Cashion et al., 2020), expanding their size to include regions with reduced novel climates (Brander et al., 2020), or being aware that these MPAs will not act as a refugia, but rather as stepping-stones for species to migrate safely. Nevertheless, past studies proved a lack of connectivity corridors between MPAs, stressing that isolation could limit marine conservation and cause cascading effects to entire ecosystems (Assis et al., 2021, 2022). In addition, no correlation between MPA area and the optimal location was found, as well as no significant differences between climate dissimilarity between contrasting MPAs areas. Therefore, MPAs' networks will be highly affected by climate change, however, the post-2020 agreement may shed light on this problem by enhancing the increase of MPAs.

Issues unresolved

While our approach explores the exposure of MPAs according to two SSPs emissions scenarios, there are some uncertainties that should be acknowledge. Firstly, our results are delimited to surface conditions as all predictors used were surface layers to make it simple and comparable to past studies. Thus, climatic effects on the demersal sea and seafloor, due to changing conditions or anthropogenic impacts (e.g., fisheries or mining activity), were not considered (Kroodsma et al., 2018). Further, the deep sea has warmed faster than the surface layer (Brito-Morales et al., 2020), hence obtaining the entire ocean structure will be interesting for future research to climate optimal distribution of MPAs within the global network. Secondly, oversimplification and uncertainties about climate change estimations may also influence the results, for instance, other potentially meaningful variables apart from those used in our study. Thirdly, it is not necessarily true that species within a MPA will lose their entire habitat due to novel climatic conditions, as species niches may be broader than the MPA area and/or species may be able to adapt and so, not shift ranges (Hoffman et al., 2019). At the same time, there may even be positive effects due to novel climate conditions such as species migrating into MPAs (Johnston et al., 2013). Finally, another unresolved issue is climate data resolution, which could underestimate some habitats (e.g., micro-refugia, local habitats), although most of the world's MPAs are smaller than the 1º grid resolution cells (Johnson & Watson, 2021), and our data has 0.25º resolution. Further, climate may not be the only factor determining species' habitat distribution. Anthropogenic impacts can also be a cause of habitat degradation or species' range shifts, particularly in coastal areas (He & Silliman, 2019). Despite all this, MPAs remain a promising biodiversity conservation tool, therefore, future research should focus on integrating and improving these aspects.

Conclusion

The present study provides baselines of MPA exposure to climate change, addressing biodiversity impacts assessment that will be crucial for future MPA management and implementation. The outcomes suggest several implications for conservation actions, giving information for climate-smart designation of MPAs network, as well as management from local (optimally located MPAs) to the global extent (global ocean). In particular, broad compliance with the Paris Agreement seems crucial for future MPA resilience and functioning in the face of future climates, as results were highly dependent on the SSP scenario, and driven by the combination of multiple biologically meaningful drivers (temperature, oxygen, pH and productivity). Also, there seem to be additional areas within EEZs that may provide better climatic conditions in the future than the current network of MPAs. Importantly, less than 10% of MPAs were estimated as optimally located, emphasizing the potential effect of climate change disrupting MPAs' functioning. Conservation planning guides efforts across nations to protect marine environments and to fulfill the objectives of the convention (e.g., 30% by 2030) should consider climate resilience during implementation phases, contrarelly to the past, as evidenced here. All information is provided open access for the countries to get access to our estimates and fill their gaps regarding management integrating climatic optimally located MPAs

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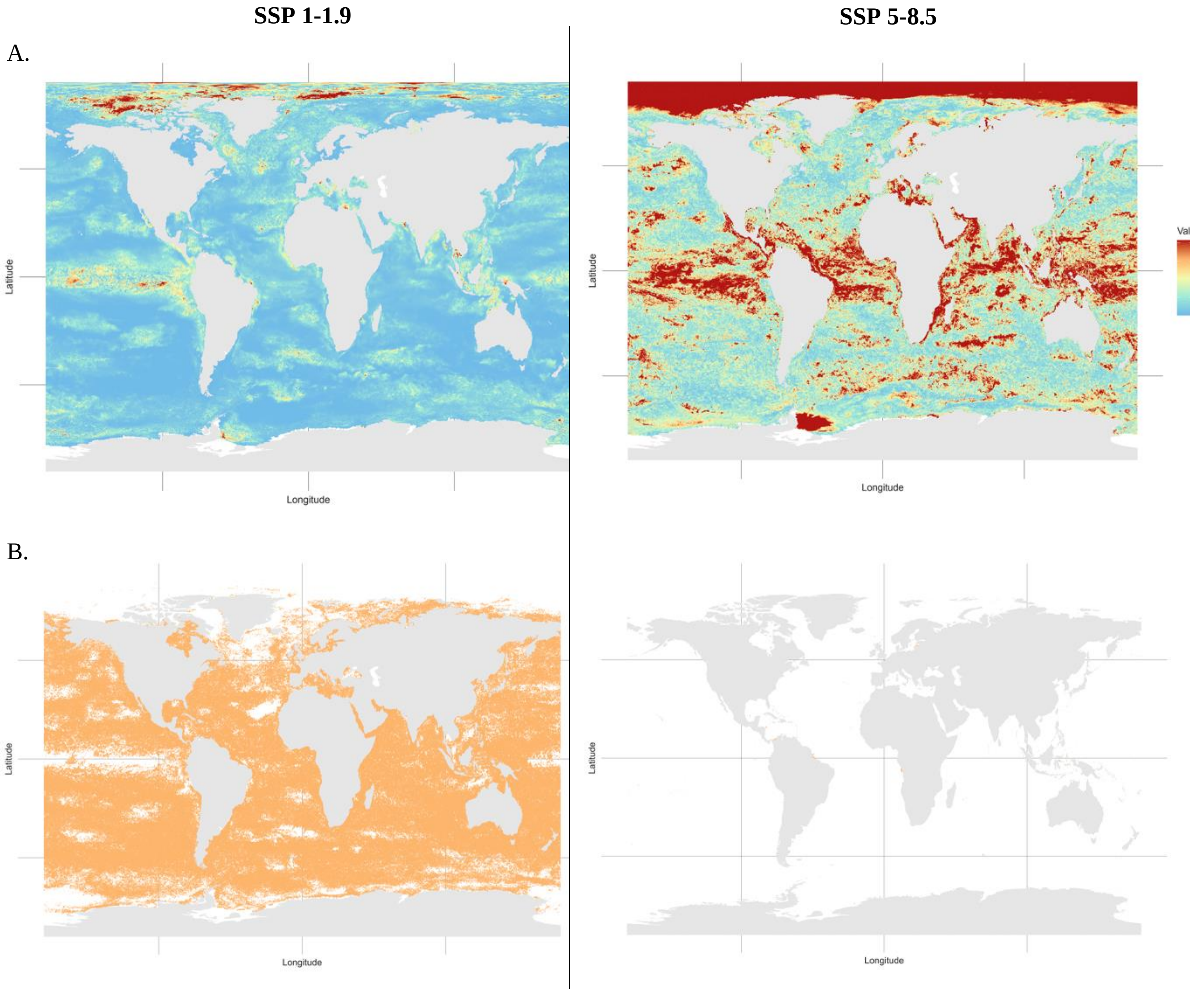
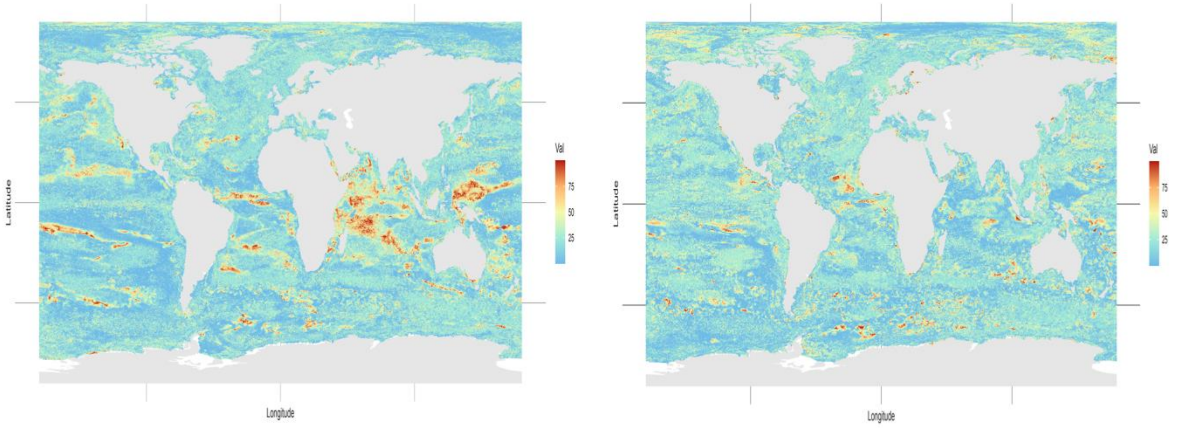
3. Supplementary information



Supplementary Figure 3.1: Disappearing climates (sigma dissimilarity) for both scenarios (A), along with the global proportion of refugia (B)

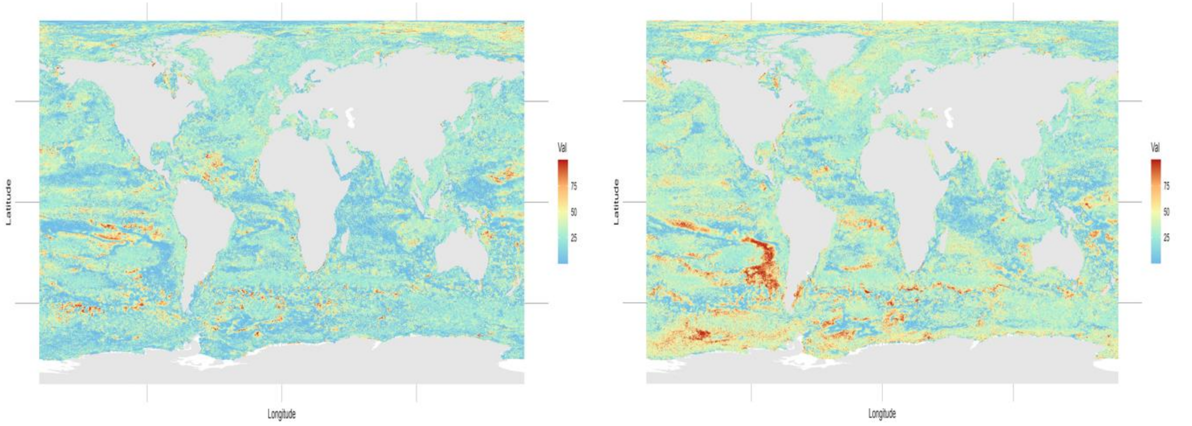
Dissolved Molecular Oxygen Mean

Maximum Temperature



pH Surface Mean

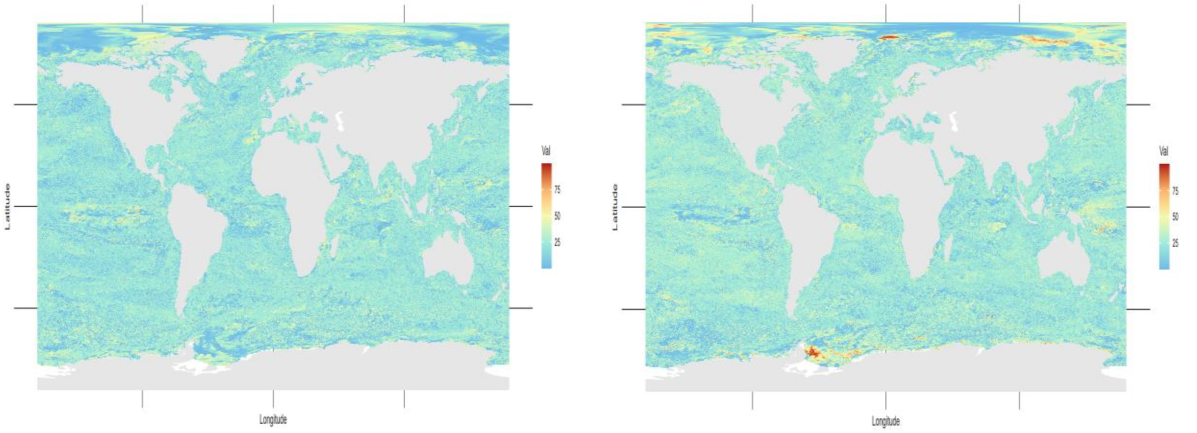
Productivity (Total Phytoplankton Mean)



Supplementary Figure 3.2: Global Ocean relative importance of predictors for SSP1-1.9

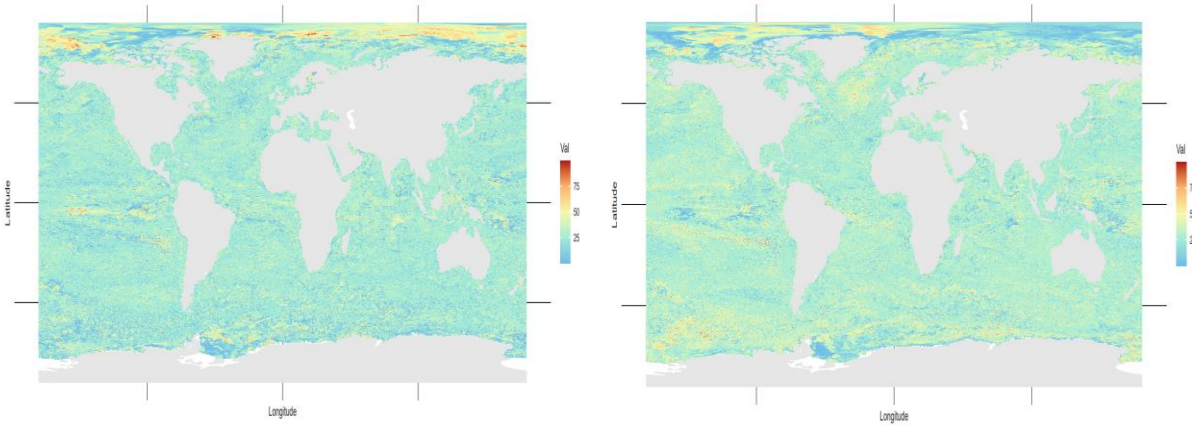
Dissolved Molecular Oxygen Mean

Maximum Temperature



pH Surface Mean

Productivity (Total Phytoplankton Mean)



Supplementary Figure 3.3: Global Ocean relative importance of predictors for SSP5-8.5

TOP10: WORST EEZ SPP1-1.9	NC (Sigma Mean)	NC (Sigma Max)	DC (Sigma Mean)	DC (Sigma Max)	ECP	AD Mean	RP	Climate
Monégasque Exclusive Economic Zone	6,43	7,01	6,74	7,42	1	11886	0	Ext.
Jarvis Island Exclusive Economic Zone	4,87	7,96	5,01	7,97	0,77	1158	0,58	Ext.
Cambodian Exclusive Economic Zone	4,42	8,29	5,45	8,29	0,55	2010	0,13	Ext.
Montenegrin Exclusive economic Zone	4,57	6,76	3,99	6,76	0,5	25,49	0,8	Ext.
Albanian Exclusive Economic Zone	4,13	5,97	4,39	6,14	0,48	1232	0,76	Ext.
Joint regime area Costa Rica / Ecuador (Galapagos)	3,54	5,69	3,75	5,31	0,36	2428	0,36	Mod.
East Timorian Exclusive Economic Zone	3,48	6,67	3,51	7,05	0,34	2897	0,29	Mod.
Pakistani Exclusive Economic Zone	2,52	8,29	2,53	8,29	0,19	535,4	0,93	Mod.
Ecuadorian Exclusive Economic Zone (Galapagos)	2,89	5,88	2,94	5,82	0,19	1928	0,43	Mod.
Canadian Exclusive Economic Zone	2,07	8,29	2,2	8,29	0,18	1757	0,31	Mod.
TOP10: BEST EEZ SPP1-1.9								
Samoan Exclusive Economic Zone	0,06	0,12	0,06	0,12	0	0	1	Non-N
Overlapping claim Matthew and Hunter Islands: New Caledonia / \	0,07	0,21	0,07	0,21	0	86,82	0,99	Non-N
Lithuanian Exclusive Economic Zone	0,09	0,19	0,09	0,19	0	0	1	Non-N
American Samoa Exclusive Economic Zone	0,09	0,33	0,09	0,33	0	0,1	1	Non-N
Slovenian Exclusive Economic Zone	0,12	0,12	0,12	0,12	0	0	1	Non-N
New Caledonian Exclusive Economic Zone	0,13	0,83	0,13	0,83	0	34,38	0,98	Non-N
Polish Exclusive Economic Zone	0,13	0,34	0,13	0,35	0	17,94	0,88	Non-N
Wallis and Futuna Exclusive Economic Zone	0,14	0,43	0,14	0,43	0	0,31	0,99	Non-N
Joint regime area Sweden / Norway	0,15	0,15	0,15	0,15	0	0	1	Non-N
Brazilian Exclusive Economic Zone (Trindade)	0,15	0,44	0,15	0,44	0	18,04	0,98	Non-N

Supplementary Table 3.1: Analyses per EEZs considering novel climates (NC), disappearing climates (DC), extreme climates proportion (ECP), average distance to the closest analog (AD) and refugia proportion (RP) for the worst-case scenario (SSP 1-1.9). TOP10 for the worst and the best EEZs are presented above. Climate: Non-Novel (0-2), Moderate (2-4) and Extreme (>4).

TIOP10 WORST LOCATED MPAs

EEZ Designation	Country	EEZ Area	Average Sigma EEZ	Sd Sigma	Number of MPAs	Average Sigma of MPAs	MPAs Area (P)	Num. MPAs Moderate (P)	Num. MPAs Extreme (P)	Num. of MPAs Ready	Num. of MPAs Ready (P)	Area of Ready MPAs (P)	Better Climate than MPAs
Joint regime area Italy / France	France	67041302,89	2,434	0,024	1	NA	1303,272	NA	NA	0	0	0	1
Saint-Martin Exclusive Economic Zone	France	1109029192	0,775	0,088	1	0,837	129,223	0	0	0	0	0	1
Tokelau Exclusive Economic Zone	New Zealand	3,20491E+11	0,254	0,170	1	0,546	1,275	0	0	0	0	0	1
Fijian Exclusive Economic Zone	Fiji	1,28398E+12	0,400	0,434	54	0,791	0,010	0,074	0	11	0,204	0,425	0,994
Gabonese Exclusive Economic Zone	Gabon	2,01956E+11	1,099	0,279	27	1,177	0,276	0	0	4	0,148	0,021	0,989
Chagos Archipelago Exclusive Economic Zone	Mauritius	6,50052E+11	0,595	0,424	6	0,369	0,983	0	0	0	0	0	0,982
Irish Exclusive Economic Zone	Ireland	4,26926E+11	1,198	0,790	47	1,092	0,023	0,191	0	2	0,043	0,023	0,967
Guadeloupean Exclusive Economic Zone	France	90592036516	1,178	0,565	16	1,691	1,56E-05	0,375	0	2	0,125	0,080	0,951
Vietnamese Exclusive Economic Zone	Vietnam	7,51303E+11	1,349	1,132	7	2,801	0,002	0,571	0,143	2	0,286	0,654	0,948
United Arab Emirates Exclusive Economic Zone	United Arab Emirates	51640077170	0,814	0,455	7	1,339	0,046	0	0	0	0	0	0,932

TOP10 BEST LOCATED MPAs

EEZ Designation	Country	EEZ Area	Average Sigma EEZ	Sd Sigma	Number of MPAs	Average Sigma of MPAs	MPAs Area (P)	Num. MPAs Moderate (P)	Num. MPAs Extreme (P)	Num. of MPAs Ready	Num. of MPAs Ready (P)	Area of Ready MPAs (P)	Better Climate than MPAs
Barbados Exclusive Economic Zone	Barbados	1,846E+11	0,500	0,248	1	0,242	1,23E-05	0	0	0	0	0	0
Belizean Exclusive Economic Zone	Belize	3,433E+10	0,946	0,143	30	0,905	0,120	0	0	0	0	0	0
Georgian Exclusive Economic Zone	Georgia	2,290E+10	3,018	0,712	5	NA	2,774	NA	NA	0	0	0	0
Haitian Exclusive Economic Zone	Haiti	1,035E+11	0,648	0,342	1	0,632	0,00072	0	0	0	0	0	0
Singaporean Exclusive Economic Zone	Singapore	7,373E+08	1,441	0	1	NA	8,75E-05	NA	NA	0	0	0	0
Sint-Maarten Exclusive Economic Zone	Netherlands	4,793E+08	0,938	0	2	0,938	0,070	0	0	0	0	0	0
Uruguayan Exclusive Economic Zone	Uruguay	1,426E+11	0,495	0	1	0,372	0,000	0	0	0	0	0	0
American Samoa Exclusive Economic Zone	United States	4,054E+11	0,092	0,047	10	0,048	0,258	0	0	0	0	0	0,004
Italian Exclusive Economic Zone	Italy	5,360E+11	2,032	1,511	144	2,308	0,078	0,479	0,111	10	0,069	0,010	0,004
Solomon Islands Exclusive Economic Zone	Solomon Islands	1,605E+12	0,485	0,330	25	0,206	0,000	0	0	0	0	0	0,006

Supplementary Table 3.2: TOP10 worst and best located MPAs analyses for SSP1-1.9

	SSP 1-1.9							**SSP 5-8.5**						
EEZ	Novel Climate Sigma Mean	Novel Climate Sigma Max	Disappear Climate Sigma Mean	Disappear Climate Sigma Max	Extreme Climate Proportion	Analog Distance Mean	Refugia Proportion	Novel Climate Sigma Mean	Novel Climate Sigma Max	Disappear Climate Sigma Mean	Disappear Climate Sigma Max	Extreme Climate Proportion	Analog Distance Mean	Refugia Proportion
Albanian Exclusive Economic Zone	4,13	5,97	4,39	6,14	0,48	1231,53	0,76	4,76	8,29	7,84	8,29	0,57	9036,17	0
Algerian Exclusive Economic Zone	1,63	4,05	1,73	4,11	0	2163,44	0,67	3,33	8,29	4,52	8,29	0,29	7615,88	0
American Samoa Exclusive Economic Zone	0,09	0,33	0,09	0,33	0	0,1	1	4,01	8,29	4,97	8,29	0,46	11997,33	0
Amsterdam Island & St, Paul Island Exclusive Economic Zone	0,75	2,67	0,73	2,38	0	1197,53	0,81	2,45	7,75	2,2	8,29	0,14	7330,63	0
Angolan Exclusive Economic Zone	0,88	3,19	0,9	3,7	0	598,48	0,94	5,73	8,29	4,88	8,29	0,72	6774,77	0,02
Anguilla Exclusive Economic Zone	0,37	0,83	0,37	0,83	0	3,33	0,93	6,85	8,29	4,08	8,29	0,9	1443,27	0
Antarctic 200NM zone beyond the coastline	1,05	8,29	1,08	8,29	0,02	1304,05	0,45	2,39	8,29	3,22	8,29	0,14	6424,47	0
Antigua and Barbuda Exclusive Economic Zone	0,86	2,05	0,87	2,17	0	117,51	0,84	6,1	8,29	4,07	8,29	0,81	1666,11	0
Argentinean Exclusive Economic Zone	0,17	1,14	0,17	1,14	0	76,83	0,97	2,38	8,29	2,38	8,29	0,16	8415,43	0
Aruban Exclusive Economic Zone	0,71	1,94	0,78	2,2	0	2,62	0,9	5,7	8,29	6,42	8,29	0,71	4370,38	0
Ascension Exclusive Economic Zone	0,96	2,17	0,96	2,17	0	140,82	0,87	4,36	8,29	6,38	8,29	0,53	3699,26	0
Australian Exclusive Economic Zone	0,44	8,29	0,44	8,29	0,01	264,55	0,95	3,3	8,29	3,3	8,29	0,3	8800,04	0
Australian Exclusive Economic Zone (Macquarie Island)	0,96	5,35	0,94	5,54	0,01	695,63	0,79	2,49	8,29	3,25	8,29	0,15	6122,2	0
Bahamas Exclusive Economic Zone	0,74	3,07	0,73	3,07	0	163,7	0,92	6,21	8,29	3,49	8,29	0,78	5226,52	0
Bahraini Exclusive Economic Zone	0,33	0,48	0,33	0,48	0	0	1	4,76	8,29	6,1	8,29	0,75	13711,18	0
Bangladeshi Exclusive Economic Zone	2,16	4,63	2,13	4,63	0,03	291,39	0,97	6,97	8,29	5,47	8,29	0,85	7475,92	0,02
Barbados Exclusive Economic Zone	0,5	1,67	0,5	1,67	0	7,41	0,94	5,12	8,29	6,05	8,29	0,66	1729,33	0
Bassas da India Exclusive Economic Zone	1,04	6,23	0,98	5,48	0,04	165,06	0,9	5,96	8,29	7,34	8,29	0,78	6203,55	0

Belgian Exclusive Economic Zone	0,95	1,64	0,81	1,28	0	4590,4	0,38	2,86	5,07	1,35	2,66	0,25	10343,61	0
Belizean Exclusive Economic Zone	0,95	1,34	0,94	1,34	0	0	1	7,63	8,29	6,53	8,29	0,95	2879,75	0
Beninese Exclusive Economic Zone	1,03	1,98	1,04	1,98	0	397,67	0,98	6,51	8,29	5,7	8,29	0,84	6224,27	0
Bermudian Exclusive Economic Zone	0,39	1,25	0,39	1,25	0	165,69	0,95	3,24	8,29	2,44	7,77	0,31	6750,03	0
Bonaire Exclusive Economic Zone	0,47	1,4	0,5	1,4	0	1,43	0,95	5,42	8,29	4,59	8,29	0,74	8841,8	0
Bosnian and Herzegovinian Exclusive Economic Zone	3,76	3,88	3,76	3,88	0	0	1	4,46	5,61	7,38	8,29	0,5	996,13	0
Brazilian Exclusive Economic Zone	1,3	8,29	1,27	8,29	0,05	698,33	0,83	5,21	8,29	5,48	8,29	0,63	9186,07	0,01
Brazilian Exclusive Economic Zone (Trindade)	0,15	0,44	0,15	0,44	0	18,04	0,98	3	6,94	3,22	8,29	0,22	8402,89	0
British Virgin Islands Exclusive Economic Zone	0,3	0,83	0,31	0,83	0	12,1	0,94	7,57	8,29	3,81	8,29	0,93	1317,19	0,01
Bruneian Exclusive Economic Zone	1,12	1,83	1,09	1,83	0	68,41	0,93	4,19	7,2	4,67	8,29	0,58	4017,35	0
Bulgarian Exclusive Economic Zone	1,8	3,38	1,68	3,76	0	302,21	0,49	5,25	8,29	2,24	4,09	0,75	4574,75	0
Cambodian Exclusive Economic Zone	4,42	8,29	5,45	8,29	0,55	2009,94	0,13	4,23	8,29	8	8,29	0,38	5685,68	0
Cameroonian Exclusive Economic Zone	0,59	1,18	0,59	1,18	0	0	1	6,27	8,29	5,18	8,29	0,86	11500,58	0
Canadian Exclusive Economic Zone	2,07	8,29	2,2	8,29	0,18	1756,67	0,31	4,84	8,29	4,72	8,29	0,56	6036,96	0
Cape Verdean Exclusive Economic Zone	1,29	4,31	1,27	4,74	0	255,48	0,93	6,32	8,29	4,94	8,29	0,8	4793,18	0
Cayman Islands Exclusive Economic Zone	1,55	3,03	1,57	3,06	0	21,92	0,71	6,48	8,29	5,2	8,29	0,82	721,16	0
Chagos Archipelago Exclusive Economic Zone	0,59	2,43	0,6	2,44	0	345,37	0,89	4,01	8,29	3,83	8,29	0,46	7440,6	0
Chilean Exclusive Economic Zone	0,6	5,72	0,6	5,72	0	710,84	0,9	3,09	8,29	2,81	8,29	0,26	7335,23	0
Chilean Exclusive Economic Zone (Easter Island)	1,88	6,28	1,78	5,17	0,03	2729,14	0,45	3,08	8,29	2,48	7,72	0,26	5388,17	0
Chilean Exclusive Economic Zone (San Felix and San Ambrosio islands)	0,23	1,92	0,23	1,92	0	177,35	0,97	2,54	8,29	2,49	8,29	0,16	7482,69	0
Chinese Exclusive Economic Zone	1,37	7,13	1,38	6,59	0,02	1475,27	0,77	4,12	8,29	3,13	8,29	0,47	8172,9	0
Christmas Island Exclusive Economic Zone	1,31	2,64	1,31	2,7	0	762,06	0,64	3,85	8,29	3,27	8,29	0,45	9940,51	0
Clipperton Exclusive Economic Zone	0,75	1,56	0,74	1,56	0	52,65	0,91	6,45	8,29	4,92	8,29	0,83	6735,33	0
Cocos Islands Exclusive Economic Zone	0,76	2,24	0,77	2,24	0	419,38	0,83	3,48	8,29	4,6	8,29	0,35	9280,31	0
Colombian Exclusive Economic Zone	2,33	4,92	2,35	5,28	0,06	1011,71	0,74	5,28	8,29	5,9	8,29	0,66	6279,76	0,01
Colombian Exclusive Economic Zone (Bajo Nuevo)	3,8	3,8	0,63	0,63	0	0	1	6,77	6,77	6,68	6,68	1	750,52	0
Colombian Exclusive Economic Zone (Quitasueño)	1,99	3,14	2,8	4,63	0	170,86	0	6,78	8,29	8,27	8,29	0,75	634,83	0
Colombian Exclusive Economic Zone (Serrana)	2,19	3,39	2,16	3,51	0	29,42	0	3,91	8,06	8,29	8,29	0,4	552,29	0

Colombian Exclusive Economic Zone (Serranilla)	1,86	2,94	1,9	2,31	0	53,6	0	5,07	5,63	7,59	7,74	1	806,41	0
Comoran Exclusive Economic Zone	0,42	0,99	0,41	0,99	0	37,17	0,99	4,43	8,29	6,89	8,29	0,61	7150,05	0
Congolese Exclusive Economic Zone	1,3	2,27	1,3	2,27	0	0	1	6,94	8,29	5,48	8,29	0,9	7757,77	0
Cook Islands Exclusive Economic Zone	0,71	3,09	0,72	3,2	0	811,5	0,8	4,39	8,29	4,56	8,29	0,54	8449,66	0
Costa Rican Exclusive Economic Zone	1,97	5,41	2,06	5,34	0,07	1173,79	0,76	5,9	8,29	5,64	8,29	0,75	5563,66	0
Croatian Exclusive Economic Zone	2,12	5,77	2,19	5,87	0,13	952	0,86	4,89	8,29	6,14	8,29	0,62	7895,79	0
Crozet Islands Exclusive Economic Zone	0,86	2,78	0,86	2,58	0	98,31	0,95	5,09	8,29	5,05	8,29	0,61	5214,76	0
Cuban Exclusive Economic Zone	0,83	2,1	0,83	2,26	0	227,53	0,92	5,13	8,29	3,63	8,29	0,66	4320,58	0
Curaçaoan Exclusive Economic Zone	0,71	1,93	0,78	1,93	0	4,35	0,84	4,86	8,29	5,51	8,29	0,61	4014,71	0
Cypriote Exclusive Economic Zone	1,01	2,08	1,03	2,08	0	1026,56	0,89	3,22	8,29	3,44	8,29	0,29	9467,95	0
Danish Exclusive Economic Zone	0,2	0,8	0,19	0,8	0	302,3	0,9	2,93	8,29	2,81	8,21	0,27	4879,73	0
Democratic Republic of the Congo Exclusive Economic Zone	0,44	0,92	0,44	0,92	0	0	1	6,62	8,29	4,54	8,29	0,82	6482,16	0,24
Djiboutian Exclusive Economic Zone	1,11	1,38	1,18	1,38	0	610,01	0,92	5,48	8,29	6,26	8,29	0,75	11811,14	0
Dominican Exclusive Economic Zone	1,63	2,52	1,76	2,69	0	17,93	0,69	6,87	8,29	6,64	8,29	0,92	1385,6	0
Dominican Republic Exclusive Economic Zone	1	3,69	1	3,74	0	30,42	0,87	7,73	8,29	4,92	8,29	0,95	1243,13	0,01
Dutch Exclusive Economic Zone	0,56	1,35	0,54	1,54	0	2001,88	0,67	2,03	4,81	1,1	3,31	0,07	8645,54	0
East Timorian Exclusive Economic Zone	3,48	6,67	3,51	7,05	0,34	2897,04	0,29	5,5	8,29	5,2	8,29	0,74	10792,46	0
Ecuadorian Exclusive Economic Zone	2,46	5,43	2,49	5,43	0,02	674,14	0,78	4,72	8,29	5,2	8,29	0,59	4335,3	0
Ecuadorian Exclusive Economic Zone (Galapagos)	2,89	5,88	2,94	5,82	0,19	1928,37	0,43	4,32	8,29	5,23	8,29	0,51	6412,1	0
Egyptian Exclusive Economic Zone	2,58	8,29	2,51	8,29	0,18	701,28	0,85	6,13	8,29	5,82	8,29	0,78	6808,64	0
El Salvador Exclusive Economic Zone	1,79	5,06	1,78	5,06	0,13	99,4	0,96	5,86	8,29	4,82	8,29	0,73	5843,93	0
Equatorial Guinean Exclusive Economic Zone	0,79	2,12	0,78	2,12	0	44,18	0,92	6,88	8,29	5,86	8,29	0,89	6907,69	0
Eritrean Exclusive Economic Zone	0,86	1,39	0,87	1,39	0	138,71	0,98	6,15	8,29	7,19	8,29	0,78	7543,19	0
Estonian Exclusive Economic Zone	0,32	2,48	0,32	2,48	0	5,95	0,93	6,24	8,29	3,58	8,29	0,8	372,78	0,07
Faeroe Exclusive Economic Zone	1,47	4,04	1,52	4,74	0	5429,33	0,25	2,01	6,64	2,47	8,29	0,07	8213,08	0
Fijian Exclusive Economic Zone	0,4	2,35	0,4	2,61	0	160,08	0,96	4,05	8,29	2,9	8,29	0,43	7240,71	0
Finnish Exclusive Economic Zone	0,29	1,36	0,32	1,47	0	7,69	0,78	5,47	8,29	6,43	8,29	0,72	280,33	0,02
French Exclusive Economic Zone	1,49	8,29	1,47	7,42	0,04	2002,4	0,69	3,5	8,29	3,7	8,29	0,34	9250,96	0

French Guiana Exclusive Economic Zone	2,69	5,61	2,72	5,51	0,08	349,22	0,82	6,29	8,29	7,55	8,29	0,84	7721,71	0
French Polynesian Exclusive Economic Zone	0,61	4,27	0,61	5,29	0	234,22	0,9	3,98	8,29	4,1	8,29	0,43	5819,71	0
Gabonese Exclusive Economic Zone	1,1	1,85	1,1	1,85	0	82,69	0,96	6,85	8,29	5,63	8,29	0,88	6225,33	0
Gambian Exclusive Economic Zone	2,29	5,11	2,42	5,11	0,11	36,18	0,79	6,78	8,29	5,56	8,29	0,89	1534,37	0
Georgian Exclusive Economic Zone	3,02	4,52	2,8	4,52	0,05	615,18	0,79	6,64	8,29	4,54	8,29	0,92	2688,63	0
German Exclusive Economic Zone	0,19	0,45	0,2	0,42	0	180,19	0,83	3,33	8,29	1,92	8,29	0,27	6506,36	0,02
Ghanaian Exclusive Economic Zone	1,08	1,98	1,08	1,98	0	343,88	0,94	5,59	8,29	4,02	8,29	0,76	8057,61	0
Greek Exclusive Economic Zone	1,9	5,06	1,9	5	0,03	1638,17	0,79	3,77	8,29	5,49	8,29	0,36	9996,29	0
Greenlandic Exclusive Economic Zone	2,03	8,29	2,29	8,29	0,12	2091,77	0,08	4,89	8,29	4,9	8,29	0,54	6410,46	0
Grenadian Exclusive Economic Zone	0,59	1,09	0,59	1,09	0	0	1	4,57	8,04	4,76	8,21	0,62	9242,6	0
Guadeloupean Exclusive Economic Zone	1,18	2,5	1,17	2,54	0	283,02	0,75	5,39	8,29	5,16	8,29	0,7	3692,57	0
Guam Exclusive Economic Zone	0,33	0,46	0,32	0,46	0	7,86	0,83	5,72	8,29	5,1	8,29	0,76	2084,23	0
Guatemalan Exclusive Economic Zone	2,03	6,76	1,96	6,45	0,12	609,28	0,91	5,95	8,29	4,36	8,29	0,76	7088,52	0
Guernsey Exclusive Economic Zone	2,19	3,26	2,43	3,46	0	2830,16	0,31	2,26	4,67	2,67	4,04	0,15	5217,31	0
Guinea Bissau Exclusive Economic Zone	2,75	6,11	2,76	6,11	0,06	5,77	0,96	8,02	8,29	7,24	8,29	0,99	1362,14	0
Guinean Exclusive Economic Zone	3,09	5,17	3,08	5,32	0,1	1,28	0,97	7,88	8,29	7,71	8,29	0,97	769,59	0,01
Guyanese Exclusive Economic Zone	1,05	3,34	1,06	3,34	0	65,47	0,98	6,35	8,29	6,33	8,29	0,83	6869,78	0
Haitian Exclusive Economic Zone	0,65	1,92	0,66	2	0	12,29	0,92	5,64	8,29	4,38	8,29	0,68	1630,39	0
Heard and McDonald Islands Exclusive Economic Zone	1,64	5,27	1,64	5,68	0,01	303,69	0,89	5,44	8,29	5,53	8,29	0,69	4170,42	0
Honduran Exclusive Economic Zone	1,46	5,68	1,45	5,68	0,05	100,8	0,82	7,62	8,29	6,07	8,29	0,94	1281,78	0,02
Howland and Baker Islands Exclusive Economic Zone	1,88	4,69	1,9	4,76	0,03	1925,26	0,08	4,27	8,29	3,46	8,29	0,55	8786,19	0
Icelandic Exclusive Economic Zone	1,43	5,21	1,46	5,21	0,01	3067,24	0,17	2,19	8,29	2,22	8,29	0,11	4684,52	0
Ile Europa Exclusive Economic Zone	0,4	0,69	0,41	0,69	0	77,8	0,98	3,61	8,29	5,46	8,29	0,36	6984,77	0
Indian Exclusive Economic Zone	1,6	6,31	1,61	5,95	0,04	845,99	0,87	5,06	8,29	4,43	8,29	0,62	7942,06	0
Indian Exclusive Economic Zone (Andaman and Nicobar Islands)	0,89	6,36	0,9	8,29	0,01	27,77	0,93	6,48	8,29	7,07	8,29	0,82	2530,42	0
Indonesian Exclusive Economic Zone	1,72	8,29	1,75	8,29	0,06	523,39	0,82	6,22	8,29	5,6	8,29	0,79	5909,9	0
Iranian Exclusive Economic Zone	1,51	5,24	1,51	5,24	0,04	67,74	0,99	6,55	8,29	7,12	8,29	0,8	7339,55	0,01
Iraqi Exclusive Economic Zone	0,37	0,37	0,37	0,37	0	0	1	8,29	8,29	8,29	8,29	1	46,26	0

Irish Exclusive Economic Zone	1,2	4,24	1,24	4,39	0,01	4374,35	0,51	2,14	6,71	2,59	8,29	0,08	10629,76	0
Israeli Exclusive Economic Zone	1,36	2,42	1,32	2,42	0	328,01	0,94	5,57	8,29	5,63	8,29	0,81	8261,88	0
Italian Exclusive Economic Zone	2,03	8,29	2,01	8,29	0,09	458,68	0,88	5,27	8,29	5,82	8,29	0,63	6674,83	0
Ivory Coast Exclusive Economic Zone	1,31	4,6	1,29	4,04	0	354,39	0,92	5,87	8,29	5,47	8,29	0,81	9044,59	0
Jamaican Exclusive Economic Zone	1,84	4,33	1,8	4,33	0	59,85	0,7	5,88	8,29	5,39	8,29	0,76	2171,31	0,01
Jan Mayen Exclusive Economic Zone	1,19	4,59	0,9	2,83	0	1827,12	0,33	3,14	8,29	1,42	4,13	0,29	5710,78	0
Japanese Exclusive Economic Zone	0,82	3,11	0,83	3,72	0	976,57	0,83	3,31	8,29	2,6	8,29	0,31	8166,8	0
Jarvis Island Exclusive Economic Zone	4,87	7,96	5,01	7,97	0,77	1158,28	0,58	5,73	8,29	7,65	8,29	0,71	5982,54	0
Jersey Exclusive Economic Zone	1,94	2,96	1,87	2,08	0	4493,13	0,75	2,65	4,83	2,28	3,12	0,25	4057,66	0
Johnston Atoll Exclusive Economic Zone	0,86	2,42	0,86	2,59	0	861,51	0,7	3,04	6,99	3,67	8,29	0,22	9677,27	0
Joint regime area Argentina / Uruguay	0,27	0,83	0,28	0,83	0	812,22	0,94	3,49	8,29	2,27	8,29	0,35	8816,04	0
Joint regime area Australia / Papua New Guinea	0,71	0,98	0,71	0,98	0	0	1	5,54	7,99	7,3	8,29	0,8	4367,53	0
Joint regime area Colombia / Dominican Republic	0,96	1,09	0,99	1,09	0	2,24	0,92	5,96	7,65	8,22	8,29	1	902,57	0
Joint regime area Colombia / Jamaica	1,84	3,42	1,64	3,29	0	24,22	0,28	6,23	8,29	6,99	8,29	0,94	1653,24	0
Joint regime area Costa Rica / Ecuador (Galapagos)	3,54	5,69	3,75	5,31	0,36	2427,54	0,36	5,04	7,64	6,84	8,29	0,73	7723,64	0
Joint regime area Croatia / Slovenia	0,16	0,16	0,16	0,16	0	0	1	8,29	8,29	7,76	8,29	1	19,54	0
Joint regime area Ecuador / Colombia	2,83	3,89	2,77	3,89	0	359,39	0,88	4,64	8,29	5,08	8,29	0,41	5099,99	0
Joint regime area Guyana / Barbados	0,8	0,8	0,8	0,8	0	0	1	8,29	8,29	8,29	8,29	1	87,34	0
Joint regime area Honduras / Cayman Islands	1,42	1,78	1,29	1,42	0	0	1	7,37	8,29	4,45	6,7	1	1115,43	0
Joint regime area Iceland / Denmark (Faeroe Islands)	1,18	1,62	1,69	1,89	0	2839,23	0,67	2,63	4,96	1,6	1,89	0,33	5516,51	0
Joint regime area Iceland / Norway (Jan Mayen)	1,13	4,07	1,05	4,23	0,01	1818,42	0,28	2,15	4,92	1,74	4,41	0,04	4434,9	0
Joint regime area Italy / France	2,43	2,45	2,34	2,45	0	0	1	7,03	8,29	5,32	5,59	1	281,36	0
Joint regime area Japan / Korea	0,79	2,34	0,81	2,34	0	1086,14	0,9	2,22	6,93	2,95	8,29	0,13	9294,55	0
Joint regime area Nigeria / Sao Tome and Principe	2,12	5,17	2,08	5,17	0,09	427,91	0,98	5,32	8,29	5,47	8,29	0,74	11492,6	0
Joint regime area Peru / Ecuador	2,26	3,01	2,17	3,01	0	237,4	0,94	3,55	6,09	5,66	8,29	0,25	5637,07	0
Joint regime area Senegal / Guinea Bissau	2,26	3,32	2,25	3,32	0	8,68	0,94	8	8,29	6,62	8,29	0,99	1801,1	0
Joint regime area Spain / France	0,89	1,07	0,94	1,07	0	78,62	0,83	2,35	3,37	3,7	4,8	0	8650,9	0
Joint regime area Sweden / Norway	0,15	0,15	0,15	0,15	0	0	1	2,72	2,72	7,68	7,68	0	7667,48	0

Joint regime area United Kingdom / Denmark (Faeroe Islands)	2,13	4,03	2,04	3,41	0,05	2979,72	0,32	1,51	3,8	6,72	8,29	0	10683,49	0
Joint regime area United States / Russia	0,29	0,42	0,27	0,37	0	555,66	0,76	1,97	4,08	2,86	4,92	0,05	4237,22	0
Jordanian Exclusive Economic Zone	1,26	1,29	1,4	1,57	0	13,85	0,5	3,45	3,85	3,48	4,47	0	12358,71	0
Juan de Nova Exclusive Economic Zone	0,77	1,87	0,77	1,87	0	0	1	7,67	8,29	7,68	8,29	0,96	7090,55	0
Kenyan Exclusive Economic Zone	0,64	1,92	0,64	1,92	0	0	1	5,35	8,29	6,2	8,29	0,68	6448,96	0
Kerguelen Exclusive Economic Zone	1,15	3,31	1,16	3,35	0	323,68	0,92	3,77	8,29	4,91	8,29	0,42	6530,46	0
Kiribati Exclusive Economic Zone (Gilbert Islands)	2,22	6,22	2,26	5,29	0,06	1285,95	0,34	5,24	8,29	4,79	8,29	0,68	6507,09	0
Kiribati Exclusive Economic Zone (Line Islands)	1,87	8,29	1,89	8,29	0,15	125,51	0,57	5,47	8,29	6,38	8,29	0,73	2589,36	0
Kiribati Exclusive Economic Zone (Phoenix Islands)	1,89	5,43	1,97	5,44	0,07	1964,05	0,4	4,27	8,29	5,1	8,29	0,5	7017,57	0
Kuwaiti Exclusive Economic Zone	0,3	0,44	0,3	0,44	0	0	1	5,54	8,29	5,59	8,29	0,65	13840,16	0
Latvian Exclusive Economic Zone	0,25	1,13	0,24	1,13	0	2,03	0,96	6,12	8,29	5,04	8,29	0,77	288,34	0,11
Lebanese Exclusive Economic Zone	0,9	1,24	0,9	1,24	0	301,78	0,97	3,91	8,29	4,62	8,21	0,48	8595,82	0
Liberian Exclusive Economic Zone	2,22	6,23	2,3	6,58	0,13	1265,98	0,77	5,82	8,29	6,27	8,29	0,75	9702,41	0
Libyan Exclusive Economic Zone	1,54	8,29	1,53	8,29	0,1	220,97	0,95	5,51	8,29	7,12	8,29	0,7	7855,18	0
Lithuanian Exclusive Economic Zone	0,09	0,19	0,09	0,19	0	0	1	6,67	8,29	2,5	6,69	0,85	182,01	0
Madagascan Exclusive Economic Zone	0,84	3,63	0,84	3,63	0	208,74	0,92	3,98	8,29	6,04	8,29	0,4	6768,41	0
Malaysian Exclusive Economic Zone	1,66	8,29	1,66	8,29	0,03	764,89	0,82	5,01	8,29	4,95	8,29	0,64	5361,96	0
Maldives Exclusive Economic Zone	0,73	2,58	0,73	2,58	0	106,13	0,93	5,2	8,29	6,04	8,29	0,66	5504,37	0
Maltese Exclusive Economic Zone	0,91	2,62	0,9	2,62	0	750,86	0,94	3,52	8,29	5,81	8,29	0,36	10227,05	0
Marshall Islands Exclusive Economic Zone	0,68	2,63	0,68	2,64	0	79,96	0,89	4,94	8,29	5,44	8,29	0,61	6529,23	0
Martinican Exclusive Economic Zone	1,13	2,28	1,15	2,28	0	17,5	0,86	5,72	8,29	5,53	8,29	0,75	1504,38	0
Mauritanian Exclusive Economic Zone	2,33	5,49	2,39	5,76	0,08	861,99	0,81	5,73	8,29	4,37	8,29	0,74	6830,24	0,01
Mauritian Exclusive Economic Zone	0,5	2,23	0,5	2,29	0	185,31	0,87	2,97	8,29	4,22	8,29	0,23	6846,74	0
Mexican Exclusive Economic Zone	0,93	7,18	0,92	8,21	0,02	305,61	0,92	5,5	8,29	4,51	8,29	0,67	5155,44	0
Micronesian Exclusive Economic Zone	0,62	3,91	0,62	3,91	0	23,11	0,94	6,33	8,29	5,33	8,29	0,84	3186,36	0
Monégasque Exclusive Economic Zone	6,43	7,01	6,74	7,42	1	11886,27	0	7,05	8,29	7,34	8,29	1	17318,51	0
Montenegrin Exclusive economic Zone	4,57	6,76	3,99	6,76	0,5	25,49	0,8	4,84	8,29	8,02	8,29	0,7	5261,05	0
Montserrat Exclusive Economic Zone	2,04	2,38	2,13	2,38	0	82,05	0,89	6,67	8,29	4,88	8,29	0,78	302,32	0

Moroccan Exclusive Economic Zone	1,37	5,07	1,4	5,07	0,02	949,81	0,84	4,8	8,29	3,69	8,29	0,58	7740,31	0
Mozambican Exclusive Economic Zone	0,83	8,29	0,84	8,29	0,03	239,54	0,92	5,51	8,29	7,19	8,29	0,68	6567,84	0
Myanmar Exclusive Economic Zone	1,3	8,29	1,37	8,29	0,06	620,94	0,88	5,86	8,29	5,07	8,29	0,73	8851,8	0
Namibian Exclusive Economic Zone	1,12	3,12	1,11	3,08	0	711,93	0,91	5,07	8,29	3,58	8,29	0,65	6299,78	0
Nauruan Exclusive Economic Zone	2,76	5,52	2,65	5,67	0,18	596,84	0,3	6,73	8,29	6,32	8,29	0,82	6839,19	0
New Caledonian Exclusive Economic Zone	0,13	0,83	0,13	0,83	0	34,38	0,98	3,45	8,29	3,27	8,29	0,34	8570,01	0
New Zealand Exclusive Economic Zone	0,54	3,75	0,54	3,75	0	309,14	0,94	3,14	8,29	3,39	8,29	0,26	7650,23	0
Nicaraguan Exclusive Economic Zone	1,96	5,69	1,97	5,69	0,13	162,14	0,7	6,59	8,29	6,6	8,29	0,83	1931,43	0
Nigerian Exclusive Economic Zone	1,43	4,31	1,44	4,86	0	234,86	0,97	6,44	8,29	5,72	8,29	0,84	9512,59	0
Niue Exclusive Economic Zone	0,83	3,65	0,82	3,29	0	1100,86	0,74	3,28	8,29	2,8	8,29	0,3	8521,55	0
Norfolk Island Exclusive Economic Zone	0,24	0,59	0,24	0,59	0	65,49	0,99	3,31	8,29	4,02	8,29	0,31	9244,78	0
North Korean Exclusive Economic Zone	0,91	2,29	0,9	2,29	0	1413,38	0,81	2,93	8,29	2,02	8,29	0,26	9085,99	0
Northern Mariana Exclusive Economic Zone	0,55	1,78	0,55	1,78	0	55,21	0,92	5,05	8,29	4,81	8,29	0,61	4559,31	0
Norwegian Exclusive Economic Zone	1,27	4,75	1,33	4,21	0	4233,57	0,28	2,02	7,98	2,84	8,29	0,07	8232,34	0
Oecussi Ambeno Exclusive Economic Zone	0,42	0,48	0,42	0,48	0	0	1	4,64	5,41	7,41	8,29	0,67	5200,88	0
Omani Exclusive Economic Zone	1,41	4,42	1,41	4,42	0	212,11	0,98	6,24	8,29	6,39	8,29	0,82	8394,55	0
Overlapping claim Alhucemas Islands: Spain / Morocco	1,12	1,12	1,03	1,03	0	0	1	2,19	2,19	2,63	2,63	0	12281,4	0
Overlapping claim Ceuta: Spain / Morocco	1,02	1,3	1,18	1,62	0	3430,42	0,6	2,19	3,21	1,21	1,74	0	11015,6	0
Overlapping claim Chafarinas Islands: Spain / Morocco	2,26	2,26	2,26	2,26	0	0	1	3,85	3,85	3,68	3,68	0	12113,19	0
Overlapping claim Doumeira Islands: Djibouti / Eritrea	0,98	1,01	0,98	1,01	0	0	1	6,62	8,04	8	8,29	1	6953,62	0
Overlapping claim Falkland / Malvinas Islands: UK / Argentina	0,31	1,32	0,31	1,32	0	190,61	0,9	2,03	8,29	2,48	8,29	0,06	5843,47	0
Overlapping claim Gibraltarian Exclusive Economic Zone	1,11	1,12	1,11	1,12	0	0	1	2,96	3,21	1,12	1,3	0	12504,89	0
Overlapping claim Glorioso Islands: France / Madagascar	0,4	0,54	0,42	0,54	0	2,88	0,93	3,68	8,29	5,04	8,29	0,4	5622,18	0
Overlapping claim Ile Tromelin: Reunion / Madagascar / Mauritus	0,4	1,15	0,4	1,12	0	252,33	0,8	2,67	6	5,22	8,29	0,14	5005,58	0
Overlapping claim Kuril Islands: Japan / Russia	0,89	2,72	0,9	2,72	0	968,72	0,79	2,69	8,04	2,96	8,29	0,23	8269,07	0
Overlapping claim Liancourt Rocks: Japan / South Korea	0,63	0,71	0,54	0,56	0	0	1	2,02	3,01	0,22	0,27	0	13954,38	0
Overlapping claim Matthew and Hunter Islands: New Caledonia / Vanuatu	0,07	0,21	0,07	0,21	0	86,82	0,99	2,95	8,29	2,07	7,84	0,21	9277,43	0
Overlapping claim Mayotte: France / Comoros	0,42	0,73	0,42	0,73	0	0,69	0,99	5,41	8,29	6,09	8,29	0,69	6818,39	0

Overlapping claim Melilla: Spain / Morocco	1,58	1,58	1,88	1,88	0	1396,57	0	2,7	2,7	3,26	3,26	0	19388,71	0
Overlapping claim Navassa Island: USA / Haiti / Jamaica	0,67	0,98	0,71	0,98	0	2,64	0,95	5,46	8,29	4,35	7,25	0,71	1863,77	0
Overlapping claim Peñón de Vélez de la Gomera: Spain / Morocco	0,92	0,99	0,92	0,99	0	0	1	4,53	4,83	1,36	2,13	1	4025,82	0
Overlapping claim Perejil Island: Spain / Morocco	1,16	1,3	1,27	1,62	0	276,4	0,67	2,4	3,14	1,59	1,74	0	9974,07	0
Overlapping claim Qatar / Saudi Arabia / United Arab Emirates	0,86	0,86	0,86	0,86	0	0	1	1,04	1,04	7,52	7,52	0	8684,44	0
Overlapping claim Senkaku Islands: Japan / China / Taiwan	1,32	2,82	1,34	2,98	0	1280,11	0,8	3,91	8,29	4,02	8,29	0,46	6732,47	0
Overlapping claim South China Sea	1,83	3,73	1,8	3,58	0	2492,24	0,44	2,85	8,29	4,38	8,29	0,22	7252,19	0
Overlapping claim South Georgia and South Sandwich Islands: UK / Argentina	0,45	4,56	0,43	4,31	0	238,61	0,92	2,66	8,29	3,59	8,29	0,17	7134,89	0
Overlapping claim Ukrainian Exclusive Economic Zone	1,57	3,93	1,62	4,29	0	2498,27	0,45	5	8,29	3,21	8,29	0,65	6354,35	0,02
Overlapping claim Western Saharan Exclusive Economic Zone	1,53	4,59	1,57	6,07	0,02	2076,08	0,75	4,04	8,29	3,05	8,29	0,48	7802,32	0
Overlapping claim: Canada / USA	1,2	3,5	1,23	5,24	0	1727,83	0	4,43	8,29	4,22	8,29	0,59	3918,31	0
Overlapping claim: Iran / United Arab Emirates	1,54	1,86	1,54	1,86	0	0	1	7,68	8,29	8,29	8,29	1	7936,42	0
Overlapping claim: Kenya / Somalia	0,82	1,23	0,82	1,23	0	0,46	0,98	4,22	8,01	6,85	8,29	0,6	4923,46	0
Overlapping claim: Puerto Rico / Dominican Republic	0,47	0,7	0,48	0,73	0	18,41	0,92	8,29	8,29	4,48	8,29	1	330,88	0
Overlapping claim: Sudan / Egypt	1,07	1,35	1,1	1,35	0	3,46	0,96	4,48	8,29	4,98	8,29	0,5	10683,55	0
Overlapping claim: Trinidad and Tobago / Venezuela / Guyana	0,51	0,68	0,51	0,68	0	0	1	4,47	6,36	8,26	8,29	0,67	5975,28	0
Overlapping claim: Venezuela / Aruba / Dominican Republic	1,33	1,33	0,16	0,16	0	38,55	0	8,29	8,29	4,32	4,32	1	1020,39	0
Overlapping claim: Venezuela / Colombia / Dominican Republic	1,67	1,67	2,2	2,2	0	38,55	0	8,29	8,29	8,29	8,29	1	85,18	0
Pakistani Exclusive Economic Zone	2,52	8,29	2,53	8,29	0,19	535,35	0,93	6,32	8,29	7,49	8,29	0,77	7914,77	0
Palau Exclusive Economic Zone	0,34	0,92	0,34	0,92	0	12,34	0,97	6,71	8,29	4,83	8,29	0,86	3125,82	0
Palestinian Exclusive Economic Zone	1,32	1,33	1,32	1,33	0	0	1	3,33	4,66	6,13	8,29	0,5	882,36	0
Palmyra Atoll Exclusive Economic Zone	1,48	4,45	1,48	4,38	0,01	468,85	0,73	4,49	8,29	4,38	8,29	0,55	8096,08	0
Panamanian Exclusive Economic Zone	2,14	5,74	2,14	5,74	0,09	250,14	0,9	6,04	8,29	5,82	8,29	0,78	5205,51	0,01
Papua New Guinean Exclusive Economic Zone	0,93	6,49	0,93	6,43	0,01	36,25	0,95	6,67	8,29	6,5	8,29	0,84	3391,32	0
Peruvian Exclusive Economic Zone	1,83	6,03	1,79	6,27	0,02	3376,85	0,56	3,81	8,29	2,51	8,29	0,41	7536,12	0
Philippines Exclusive Economic Zone	1,54	6,26	1,58	6,74	0,01	507,35	0,79	5,83	8,29	5,25	8,29	0,73	4031,39	0
Pitcairn Islands Exclusive Economic Zone	0,42	2,56	0,41	2,56	0	215,29	0,95	4,34	8,29	2,62	7,27	0,52	6360,44	0

Polish Exclusive Economic Zone	0,13	0,34	0,13	0,35	0	17,94	0,88	3,1	8,29	5,21	8,29	0,29	197,54	0,01
Portuguese Exclusive Economic Zone	1,55	5,04	1,55	4,75	0,03	1717,86	0,65	3,38	8,29	2,99	8,29	0,32	6676,34	0
Portuguese Exclusive Economic Zone (Azores)	1,47	5,33	1,38	5,75	0,01	3035,84	0,52	3,17	8,29	2,22	8,29	0,27	8640,86	0
Portuguese Exclusive Economic Zone (Madeira)	1,66	3,79	1,68	3,88	0	474,23	0,69	4,51	8,29	5,31	8,29	0,52	2555,2	0
Puerto Rican Exclusive Economic Zone	0,59	3,3	0,6	3,3	0	7,57	0,9	7,33	8,29	5,71	8,29	0,9	330,34	0
Qatari Exclusive Economic Zone	0,57	0,83	0,57	0,83	0	0	1	4,77	8,29	6,45	8,29	0,54	13098,64	0
Réunion Exclusive Economic Zone	0,74	1,79	0,74	1,78	0	254,63	0,88	3,2	8,29	5,18	8,29	0,25	8236,97	0
Romanian Exclusive economic Zone	1,9	3,81	1,81	3,49	0	1759,3	0,63	5,25	8,29	2,63	7,69	0,75	7323,99	0
Russian Exclusive economic Zone	0,81	7,67	0,89	8,29	0,01	884,47	0,48	3,68	8,29	3,79	8,29	0,38	4350,59	0
Saba Exclusive Economic Zone	1,38	1,61	1,38	1,61	0	0	1	5,53	8,29	5,98	8,29	0,6	439,15	0
Saint Kitts and Nevis Exclusive Economic Zone	1,9	2,13	1,9	2,13	0	0	1	6,39	8,29	5,83	8,29	0,83	442,72	0
Saint Lucia Exclusive Economic Zone	0,47	0,86	0,47	0,86	0	2,16	0,92	5,59	8,29	4,81	8,29	0,84	3873,34	0
Saint Vincent and the Grenadines Exclusive Economic Zone	0,39	0,69	0,39	0,69	0	336,28	0,96	4,98	8,29	6,43	8,29	0,61	2885,19	0
Saint-Barthélemy Exclusive Economic Zone	0,92	1,04	0,92	1,04	0	0	1	5,67	8,29	6,93	8,29	0,8	245,61	0
Saint-Martin Exclusive Economic Zone	0,77	0,84	0,77	0,84	0	0	1	7,81	8,29	5,95	8,29	1	178,84	0
Saint-Pierre and Miquelon Exclusive Economic Zone	0,28	0,41	0,28	0,41	0	187,75	0,91	3,15	5,14	0,94	2,29	0,26	6814,23	0
Samoan Exclusive Economic Zone	0,06	0,12	0,06	0,12	0	0	1	3,88	8,29	3,64	8,29	0,44	13521,97	0
Sao Tome and Principe Exclusive Economic Zone	1,79	5,37	1,79	5,37	0,02	676,39	0,78	6,34	8,29	5,51	8,29	0,86	8439,66	0
Saudi Arabian Exclusive Economic Zone	0,83	1,84	0,82	1,82	0	216,1	0,96	5,35	8,29	6,1	8,29	0,67	10329,49	0
Senegalese Exclusive Economic Zone	2,43	5,61	2,39	5,02	0,03	62,62	0,87	7,32	8,29	5,57	8,29	0,94	4085,27	0
Seychellois Exclusive Economic Zone	0,46	1,24	0,46	1,24	0	82,42	0,96	3,78	8,29	5,25	8,29	0,42	6411,93	0
Sierra Leonian Exclusive Economic Zone	2,27	4,15	2,25	4,15	0,01	288,8	0,93	7,04	8,29	6,61	8,29	0,92	7207,93	0
Singaporean Exclusive Economic Zone	1,44	1,44	1,44	1,44	0	0	1	5,27	5,27	3,29	3,29	1	15398,92	0
Sint-Eustatius Exclusive Economic Zone	1,49	1,69	1,49	1,69	0	0	1	6,57	8,29	8,25	8,29	1	394,5	0
Sint-Maarten Exclusive Economic Zone	0,94	0,94	0,94	0,94	0	0	1	8,29	8,29	8,21	8,21	1	348,71	0
Slovenian Exclusive Economic Zone	0,12	0,12	0,12	0,12	0	0	1	8,29	8,29	6,28	6,28	1	148,4	0
Solomon Islands Exclusive Economic Zone	0,49	2,38	0,49	2,45	0	10,86	0,99	6,86	8,29	7,25	8,29	0,86	2258,29	0
Somali Exclusive Economic Zone	0,52	1,77	0,52	1,77	0	88,1	0,97	4,14	8,29	5,64	8,29	0,48	7401,19	0

South African Exclusive Economic Zone	0,55	2,81	0,55	2,91	0	618,33	0,94	3,33	8,29	3,42	8,29	0,31	9690,77	0
South African Exclusive Economic Zone (Prince Edward Islands)	1,15	6,78	1,17	8,29	0,03	1177,25	0,73	4,57	8,29	4,01	8,29	0,54	5705,38	0
South Korean Exclusive Economic Zone	1,12	3,99	1,14	4,18	0	2485,38	0,66	2,24	8,29	2,3	8,29	0,11	8816,94	0
Spanish Exclusive Economic Zone	1,32	4,48	1,32	4,69	0	989,09	0,82	3,43	8,29	3,72	8,29	0,32	7413,19	0
Spanish Exclusive Economic Zone (Canary Islands)	1,79	6,53	1,72	4,82	0,02	4914	0,33	3,27	8,29	2,68	8,29	0,29	6598,72	0
Sri Lankan Exclusive Economic Zone	1,78	5,2	1,8	5,27	0,03	353,04	0,85	4,6	8,29	6,14	8,29	0,54	5274,99	0
St, Helena Exclusive Economic Zone	1,51	5,02	1,49	4,74	0,01	1059,36	0,63	3,79	8,29	3,8	8,29	0,44	7944,2	0
Sudanese Exclusive Economic Zone	0,61	1,14	0,6	1,14	0	82,5	0,99	4,98	8,29	4,56	8,29	0,66	10491	0
Surinamese Exclusive Economic Zone	2,08	5,28	2,09	5,28	0,05	372,67	0,91	6,54	8,29	7,36	8,29	0,84	6452,61	0
Svalbard Exclusive Economic Zone	1,28	8,29	1,46	8,29	0,04	1586,82	0,21	3,72	8,29	2,97	8,29	0,36	4695,65	0
Swedish Exclusive Economic Zone	0,2	1,04	0,2	1,01	0	4,76	0,86	4,91	8,29	5,12	8,29	0,65	662,67	0
Syrian Exclusive Economic Zone	0,68	0,88	0,74	0,88	0	1600,64	0,82	2,99	6,37	3,54	6,31	0,29	8823,8	0
Taiwanese Exclusive Economic Zone	1,32	3,27	1,36	3,27	0	950,04	0,82	4,52	8,29	3,21	8,29	0,55	8154,2	0
Tanzanian Exclusive Economic Zone	0,81	2,18	0,82	2,18	0	104,69	0,94	4,41	8,29	6,9	8,29	0,54	6676,58	0
Thailand Exclusive Economic Zone	2,27	8,29	2,61	8,29	0,13	2448,89	0,53	3,97	8,29	5,02	8,29	0,44	7400,49	0
Togolese Exclusive Economic Zone	0,89	1,23	0,89	1,23	0	0	1	6,06	8,29	4,83	8,29	0,95	13596,63	0
Tokelau Exclusive Economic Zone	0,25	0,79	0,26	0,79	0	62,22	0,94	5,86	8,29	5,67	8,29	0,79	5586,68	0
Tongan Exclusive Economic Zone	0,3	1,89	0,3	2,2	0	398,73	0,92	3,11	8,29	2,33	8,29	0,28	8442,43	0
Trinidad and Tobago Exclusive Economic Zone	0,48	1,2	0,48	1,2	0	0	1	5,83	8,29	5,87	8,29	0,77	8384,4	0
Tristan Da Cunha Exclusive Economic Zone	1,34	8,29	1,32	8,29	0,05	2868,47	0,55	2,1	8,29	2,7	8,29	0,09	7870,22	0
Tunisian Exclusive Economic Zone	1,01	1,58	1,02	1,54	0	1,16	0,98	5,74	8,29	6,98	8,29	0,74	7256,55	0
Turkish Exclusive Economic Zone	1,57	4,38	1,59	4,27	0,01	1781,66	0,38	4,7	8,29	2,9	8,29	0,58	6096,22	0
Turks and Caicos Exclusive Economic Zone	1,87	4,67	1,71	4,33	0,03	176,94	0,59	7,2	8,29	5,49	8,29	0,92	3498,28	0,01
Tuvaluan Exclusive Economic Zone	0,71	2,66	0,71	2,66	0	22,77	0,95	6,41	8,29	5,82	8,29	0,84	5981,18	0
United Arab Emirates Exclusive Economic Zone	0,81	2,07	0,82	2,07	0	130,65	0,99	5,43	8,29	6,01	8,29	0,74	11191	0
United Kingdom Exclusive Economic Zone	1,4	4,03	1,45	3,74	0	3981,86	0,44	2,29	8,29	2,44	8,29	0,11	9935,18	0
United States Exclusive Economic Zone	0,72	6,25	0,7	6,25	0,01	568,72	0,89	3,62	8,29	2,53	8,29	0,37	6518,44	0
United States Exclusive Economic Zone (Alaska)	0,58	6,26	0,54	6,3	0	730,01	0,72	2,34	8,29	2,59	8,29	0,13	6382,69	0

United States Exclusive Economic Zone (Hawaii)	0,43	2,62	0,44	2,76	0	259,1	0,9	3,52	8,29	4	8,29	0,36	7641,34	0
Uruguayan Exclusive Economic Zone	0,49	1,97	0,5	1,97	0	623,45	0,95	5,41	8,29	3,39	8,29	0,63	7949,42	0
Vanuatu Exclusive Economic Zone	0,31	1,16	0,31	1,16	0	19,97	0,98	5,42	8,29	3,89	8,29	0,66	6834,37	0
Venezuelan Exclusive Economic Zone	0,95	8,29	0,95	8,29	0,01	78,28	0,92	5,28	8,29	5,1	8,29	0,69	4391,68	0
Vietnamese Exclusive Economic Zone	1,35	8,29	1,38	8,29	0,04	1088,07	0,74	3,66	8,29	4,1	8,29	0,37	7877,38	0
Virgin Islander Exclusive Economic Zone	0,84	1,66	0,83	1,66	0	6,91	0,96	6,56	8,29	6,25	8,29	0,79	406,13	0,04
Wake Island Exclusive Economic Zone	0,32	0,73	0,32	0,68	0	34,13	0,89	5,67	8,29	2,95	7,37	0,71	9073,14	0
Wallis and Futuna Exclusive Economic Zone	0,14	0,43	0,14	0,43	0	0,31	0,99	5,56	8,29	4,16	8,29	0,82	10293,2	0
Yemeni Exclusive Economic Zone	0,55	1,47	0,55	1,47	0	85,57	0,99	4,67	8,29	5,26	8,29	0,57	8850,23	0

Supplementary Table 3.3: Values for all EEZs are presented considering novel climates (NC), disappearing climates (DC), extreme climates proportion (ECP), average distance (AD) and refugia proportion (RP) for both SSP scenarios.