



Putting a time scale on emerging climate change stressors: a Vulnerability Index for Atlantic Ocean marine ecosystem services

Alexandra Loveridge^{a,*}, Zoe Jacobs^a, Stephen Kelly^a, Andrew Yool^a, Stefanie Rynders^a, Svetlana Jevrejeva^b, Joanne Williams^b, Ludivine Conte^c, Jason Holt^b, Adrian Martin^a, Yuri Artioli^c, Ekaterina Popova^a

^a National Oceanography Centre, European Way, Southampton, SO14 3ZH, United Kingdom

^b National Oceanography Centre, Joseph Proudman Building, Brownlow St, Liverpool, L3 5DA, United Kingdom

^c Plymouth Marine Laboratory, Plymouth, PL1 3DH, United Kingdom

ARTICLE INFO

Keywords:

Climate change
Marine ecosystem services
Vulnerability
Adaptation
Time of emergence
Socio-economic indicators

ABSTRACT

Marine ecosystem services underpin human wellbeing and support resilient socio-ecological systems, yet existing vulnerability assessments remain fragmented, often focusing on isolated industries and overlooking the whole-system socio-ecological context. To bridge this gap, we develop a comprehensive Vulnerability Index to assess marine ecosystem service vulnerability to emerging climate stressors in the Atlantic. Using high-resolution ocean simulations and moving beyond traditional long-term projections, we employ the Time of Emergence metric to address actionable decision-making timescales (2–3 decades). We found that all Atlantic marine ecosystem services are projected to be exposed to multiple emerging stressors before 2100, though the sequence and the timing of emergence are highly heterogeneous. Overall vulnerability is highest in tropical West Africa due to the early emergence of hypoxia and sea level rise extremes compound by low adaptive capacity. Additional hotspots are found in subpolar and polar regions driven by rapid sea ice retreat and the sensitivities of region-specific habitats alongside a high dependence on marine ecosystems. Coupled with socio-ecological data, we determined which services (provisioning, regulatory and cultural) are most sensitive to potential impacts in each EEZ. We anticipate this index to be a starting point to develop targeted vulnerability indices for specific ecosystem services and regions. Mitigative and adaptive efforts must be multi-scale and tailored to national and local contexts, addressing not only socio-economic differences but also variable climate stressors and their impacts. Uncertainties associated with time series data gaps and indicator aggregation, particularly for island and remote territories, highlight the need for targeted national adaptation.

1. Introduction

Healthy marine ecosystems underpin human wellbeing and are key to mitigating and adapting to climate change impacts (Refulio-Coronado et al., 2021; Visbeck, 2018; Ryabinin et al., 2019). Providing nutritious food and essential livelihoods, they supply valuable biotic and abiotic resources that play a central role in the global economy. In a changing world these ecosystems provide space for heritage preservation alongside sustainable marine ecotourism (Filho et al., 2022) and are integral to regulating the Earth system, particularly as nations increase their efforts to address climate change (Stocker, 2015; Reid et al., 2009). However, the capacity of ecosystems to deliver these essential services is threatened by sustained climatic trends intermittently disrupted by

acute, high impact extreme events (Mooney et al., 2009). Key climate stressors include ocean warming and deoxygenation, sea level rise and declines in sea ice, among others (Feng et al., 2021; Reyes–Mendoza et al., 2022; Schlegel et al., 2017; Henson et al., 2010; Popova et al., 2016; Doney et al., 2009; Cazenave and Cozannet, 2014). These have significant cascading and compounding effects on interconnected social and ecological environments (socio-ecological systems, Berkes and Folke, 1998), particularly when stressors emerge simultaneously. For example, long-term rising temperatures are shifting marine species' distributions, altering ecosystem structure and functioning (Bates et al., 2014; Pinsky et al., 2020; Pecl et al., 2017). This can result in commercial species shifting across jurisdictional boundaries, changing fishery resource availability, and threatening food security in countries

* Corresponding author.

E-mail address: alelov@noc.ac.uk (A. Loveridge).

<https://doi.org/10.1016/j.gloenvcha.2026.103251>

Received 4 December 2025; Received in revised form 15 October 2026; Accepted 17 October 2026

Available online 23 October 2026

0959-3780/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

where declines could exacerbate overexploitation of fish stocks and increase poverty as well as forced migration (Townhill et al., 2023; Jönsson and Kamali, 2012). Alongside these long-term changes, extreme events such as marine heatwaves have doubled in frequency since 1982, with these projected to increase both in scale and impact (Hobday et al., 2016; Laufkötter et al., 2020; Frölicher et al., 2018). Impacts of oceanic climate stressors on the ocean are not only limited to marine and near-shore areas: in 2024, the USA experienced the local extinction of the Key Largo tree cactus (*Pilosocereus millspaughii*), the first to be directly attributed to salt water intrusion from sea level rise (Possley et al., 2024). Without efforts to mitigate the negative effects of climate change and adapt to a changing environment, declining ecosystem services are likely to lead to further biodiversity loss, increase geopolitical and internal conflict (Townhill et al., 2023), and drive poverty within countries (Boyce et al., 2020), ultimately slowing down progress toward the Sustainable Development Goals (Lam et al., 2020).

Although many climate change effects will be felt on the individual to local level (e.g. displacement of people (Mester et al., 2023), reduced food security (Warner and van der Geest, 2013), changing/loss of livelihoods (Hamilton et al., 2003)), due to the underlying global processes driving these changes and the high connectivity between many systems, a coordinated response at a higher level is required (Kleisner et al., 2021; Vallury et al., 2022). As such, there is a pressing need to align national and international efforts to increase the resilience of systems to both long term climate stressors and extreme events (von Schuckmann et al., 2025). To this end, vulnerability analyses identify areas most at risk from climate change impacts, supporting a better understanding of commonalities and differences in impacts and improved decision-maker prioritisation. Using frameworks such as those developed by the IPCC (IPCC, 2013), the vulnerability of marine fisheries and aquaculture, coastal communities (Xu et al., 2025) and marine species faced with climate change impacts have been examined (Giddens et al., 2022). This methodology enables the harmonisation of various data types and cross-comparison across multiple scales. However, predicting the impacts of multi-stressors on increasingly complex socio-ecological systems is a challenge, particularly as the political, social and economic conditions vary among countries, with large disparities between developed economies and those still battling significant malnutrition, disease and poverty. Past studies have explored vulnerability at a national (Allison et al., 2009), regional, and global (Stewart-Sinclair et al., 2020) scale, resulting in a fragmented body of analyses that focus on individual industries and specific ecosystem services. This risks overlooking other dimensions of marine ecosystem services, as multiple benefits can be derived from a single service (Poe et al., 2014). A wider focus on marine ecosystem services is currently lacking at a national level, which would embed past focus areas into their broader socio-ecological contexts, enabling a whole systems approach to adaptive and mitigative policies in sensitive areas.

Several past studies have used climate model projections to forecast multiple stressors (Giddens et al., 2022; Allison et al., 2009; Cinner et al., 2013; Debortoli et al., 2019; Bueno-Pardo et al., 2021). Many of these focus on temperature as the key ecosystem stressor centred around specific industries or research areas (e.g. fisheries, coral reefs, etc.), and few address all major climate-related drivers simultaneously. Giddens et al. (2022) is a notable exception, focusing on the vulnerability of marine species to biologically-relevant factors in the Pacific Islands Region (including temperature, ocean acidification, mixed layer depth, surface oxygen, and primary productivity among others) (Giddens et al., 2022). However, considering multiple ecosystem stressors can complicate management action. Stressors will not emerge simultaneously across all regions within timescales relevant to decision-makers (2–3 decades) and downstream impacts of multi-stressors on marine ecosystem services are in many cases understudied. In particular, large regions such as the Atlantic encompass a large variety of ecosystems that provide a range of services, as well as countries at different stages of development that rely on different ecosystem services (Magalhães Filho

et al., 2022).

Use of a Vulnerability Index enables the examination of a wide selection of climatic, ecological and socio-economic variables, identifying coastal states with low adaptive capacity and high sensitivity to climate stressors that will threaten marine ecosystem services. This combined assessment provides valuable guidance for strategic planning, prioritisation and adaptation planning. To enable such an analysis at the scale of national Exclusive Economic Zones (EEZs), we use high-resolution climate projections to identify in which decade climate stressors are most likely to emerge and pinpoint which coastal states are likely to experience these changes the soonest. Finally, we highlight which category of marine ecosystem services (Provisioning, Regulation & Maintenance, Cultural) are likely to be most vulnerable to emerging climate stressors in Atlantic coastal states.

2. Methods

We assessed the relative vulnerability of marine ecosystem services in Atlantic EEZ territories to climate stressors following the Vulnerability framework outlined in the fifth assessment report of the Intergovernmental Panel on Climate Change and used in previous vulnerability assessments (Allison et al., 2009; Debortoli et al., 2019; Blasiak et al., 2017). Alongside the index calculation, details of the study area, marine ecosystem services framework, time of emergence metric, and component indicators (climatic, ecological and socio-economic variables) are provided below.

2.1. Vulnerability index

Vulnerability is calculated as a normalised, unitless score between 0 and 1:

$$\text{Vulnerability} = (\text{Exposure} + \text{Sensitivity}) - \text{Adaptive Capacity}$$

where Exposure is the magnitude and duration of climate stressors to which a system is exposed, represented in this analysis by the time of emergence of a climate stressor. Sensitivity is the degree to which a marine ecosystem service is affected by climate stressors and Adaptive Capacity is the extent to which governance systems within a territory can adjust to, or mitigate, climate stressor impacts on an ecosystem service (IPCC, 2013). The higher the final Vulnerability Index score, the more vulnerable an EEZ territory is to climate stressors. Indicators were selected based on relevance to marine ecosystem services and are sourced from established national and international databases (UNCTAD, World Bank, FAO, etc.) to ensure reliability and replicability.

2.2. Study area

The study includes countries bordering the Atlantic Ocean and their Exclusive Economic Zones (EEZs) extending up to 200 nautical miles beyond a state's territorial sea. Countries with overseas territories, or with disconnected EEZs (e.g. France-Guadeloupe) were separated into distinct territories as they are likely to experience different climate change impacts. The term “territory” (terrestrial areas) and “EEZ territory” (marine areas) used in this analysis includes non-sovereign territories, and this analysis does not imply an opinion on the legal or development status of any country or of its authorities or concern the delimitation of its frontiers or boundaries. In addition, due to their size and span across large latitudes, the Brazilian, USA, and Canadian EEZs were sub-divided according to the Large Marine Ecosystems of the World (LMEs). This resulted in 87 countries encompassing 110 EEZ territories. Where included in national-level statistical reporting, identical data was given to EEZ territories of the same country (e.g. mainland France and Guadeloupe). Joint regime and uninhabited islands were excluded from the analysis and of the overlapping claim areas, only South Georgia, the Falkland Islands and Western Sahara were included

due to their large size and inhabited nature.

EEZ territory shapefiles (World EEZ v12) were downloaded from Marine Regions (Flanders Marine Institute, 2025). Large Marine Ecosystems were downloaded from DataHub (Data, 2025), with the data originally sourced by National Oceanic and Atmospheric Administration (NOAA).

2.3. Marine ecosystem services framework

Marine ecosystem services are the contributions that marine ecosystems make to human well-being, specifically to the final outputs or products derived from ecological systems (Haines-Young and Potschin, 2012), following the European Environment Agency's Common International Classification of Ecosystem Services (CICES V5.1, European Environment Agency, 2018). To avoid double accounting, CICES integrates the 'Supporting' services often categorised separately in other classifications.

Provisioning services encompass the fulfilment of material and energy needs, such as the harvestable share of biotic and abiotic materials (e.g. fish, water, seaweed) used for products or building. Regulation and Maintenance services encompass services such as the dilution of pollutants in the environment and coastal protection, and cultural services encompass the non-material characteristics of ecosystems, such as enabling education, aesthetic and spiritual experiences. Broad categories are used as a necessary simplification to enable a large, Atlantic scale analysis. In particular, capturing the breadth of cultural ecosystem services through proxy indicators is challenging, as such, indicators may not fully capture cultural values, identities, meanings, spiritual connections and local knowledge systems when examined at the Atlantic scale.

2.4. Exposure (E)

2.4.1. Ocean model projections

The ocean is represented physically by the Nucleus for European Modelling of the Ocean framework (NEMO v4.0) (Madec et al., 2013), and biogeochemically by the Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification (MEDUSA) (Yool et al., 2013). NEMO is composed of an ocean general circulation model, Océan PARallélisé version 9 (OPA9; Madec & Team, 2008), coupled to a sea ice model, Sea Ice modelling Integrated Initiative (SI3) (Vancoppenolle et al., 2023). The NEMO domain has a tripolar grid with a horizontal resolution of 1/12-degree, and 75 vertical z-levels ranging in thickness from ~1 m at the surface to ~200 m at depth. MEDUSA is a nutrient, phytoplankton, zooplankton, detritus (NPZD) model that represents the biogeochemical cycles of nitrogen, silicon, iron, carbon, oxygen and alkalinity. MEDUSA's dual size structure resolves small (nanophytoplankton and microzooplankton) and large (microphytoplankton and mesozooplankton) components. Similar to its living components, MEDUSA's detritus is also split into two size classes, with small, slow-sinking particles and large, fast-sinking particles. Full description and evaluation of MEDUSA can be found in (Yool et al., 2013; Yool et al., 2021).

The coupled NEMO-MEDUSA model is then used in a simulation over the period 1980 to 2100. This is forced at its surface boundary with atmospheric output from a simulation of the UK's Earth system model, UKESM1.1 (Mulcahy et al., 2023). The high model spatial resolution used here imposes significant computational demands limiting this work to a single future climate scenario. This scenario, SSP3-7.0 ("Regional Rivalry") (O'Neill et al., 2016), reflects revised expectations for a plausible high-emissions trajectory reaching radiative forcing of 7.0 W m⁻² by 2100 (Ritchie and Dowlatabadi, 2017). UKESM is an ESM with high equilibrium climate sensitivity and so has a comparatively high response to this radiative forcing than other CMIP6 models. To assess the sensitivity of our results to the choice of coupled physical and biogeochemical model, the same exposure indicators were also calculated using the 1/4

degree NEMO-ERSEM ensemble (details in Supplementary Information) (Artioli et al., 2024).

The NEMO-MEDUSA model does not include tides or extreme sea level events from storm surges; however coastal flooding poses a major risk for coastal communities and needs to be accounted for. To quantify extreme sea level events, probabilistic sea level projections for RCP4.5 are used, which are closest to SSP3-7.0 projections of sea level rise in AR6 IPCC (Jackson and Jevrejeva, 2016; Jevrejeva et al., 2023). Probability density functions for future waves and storm surges with the RCP4.5 scenario are from (Vousdoukas et al., 2018). These are produced from simulations using atmospheric forcing from ERA-INTERIM for the baseline (1980–2014) and a 6-member CMIP5 Global Climate Model (GCM) ensemble for the future (Jevrejeva et al., 2023). Wind wave generation is simulated using the WW3 model (Mentaschi et al., 2017) and storm surges using DFLOW FM (Vousdoukas et al., 2018). Extreme sea levels are calculated along the Atlantic coast (100 km resolution along the coast), excluding some of Canada, Greenland and Svalbard due to limitations of the wave model.

2.4.2. Time of emergence calculation

Time of emergence is defined as the decade where the annual minimum (or maximum) of monthly means crosses a given threshold in at least 5 out of 10 years (Popova et al., 2016), calculated using either a baseline mean $\pm$ 2 standard deviations or the crossing of a critical threshold. It has the advantage over other climate change indicators as it provides a consistent and objective measure across multiple climate stressors. For each of the 9 indicators (Table 1), the time of emergence for each model grid cell is identified and recorded as a decade. Time of emergence for each EEZ territory was then calculated as the first decade in which $\geq 20\%$ of the EEZ (by area) had emerged.

For sea surface temperature, benthic temperature, primary production and sea ice concentrations, local means and standard deviations (σ)

Table 1
Details of the Exposure indicators.

Stressor (Weighting)	Indicator	Method
Warming (0.33)	Sea Surface Temperature (SST)	Time of emergence based on annual means crossing baseline mean + 2 standard deviations.
Warming (0.33)	Benthic Temperature	Time of emergence based on annual means crossing baseline mean + 2 standard deviations, for on-shelf part of EEZ (areas where local bathymetry <200 m).
Warming (0.33)	Marine Heatwaves	Time of emergence for marine heatwave conditions occurring 180 days/year.
Deoxygenation (1)	Hypoxia	Time of emergence based on annual minimum (calculated from monthly means) of water column oxygen minimum crossing below 100 mmol/m ³ threshold.
Acidification (0.5)	Benthic aragonite and calcite saturation state (Ω)	Time of emergence based on annual minimum (calculated from monthly means) crossing below 1.0 threshold.
Acidification (0.5)	Surface pH	Time of emergence based on annual means crossing below baseline mean - 0.3 threshold.
Declining Productivity (1)	Declining Primary Productivity	Time of emergence based on annual means crossing baseline mean - 2 standard deviations.
Sea Level Rise (1)	Extreme sea levels (with tides)	Time of emergence for extreme sea level events where there is a 50% chance of once per-century sea level extremes becoming an annual event
Sea Ice Decline (1)	Declining sea ice concentrations	Time of emergence based on annual means crossing baseline mean - 2 standard deviations.

are calculated for a baseline period (1990–2019), and a threshold of 2 standard deviations from these means is used.

For hypoxia, benthic aragonite and calcite saturation state (benthic Ω) and surface pH, pre-defined thresholds from the literature are used (Tyson and Pearson, 1991; Gruber, 2011; Gutiérrez-Bravo et al., 2024). For oxygen, the hypoxic threshold is set at 100 mmol m⁻³, approximating literature values (e.g. Tyson and Pearson, 1991; Gruber, 2011; Gutiérrez-Bravo et al., 2024). For the carbonate chemistry property, we used two indicators, each with a specific threshold: the aragonite and calcite saturation state (Ω), with a threshold of 1.0 (Cala et al., 2024), and pH, for which an acidification of -0.3 units is used to represent an approximate doubling of H⁺ ions (Kroecker et al., 2013).

Marine heatwaves are calculated using the widely accepted Hobday et al. (2016) method (Hobday et al., 2016): detected when the SST exceeds the 90th percentile, based on a daily climatology from 1990 to 2019, for at least 5 days. The time of emergence indicator is defined as the decade where >5 years are experiencing MHW conditions for at least half of the year (>180 days).

For extreme sea levels, the time of emergence is specified as the decade at which previously rare (100 yr return period) sea-level extreme events start to occur regularly (1 yr return period) in at least 50% of simulations. For each individual location along the coastline, probability density functions of all extreme sea level components are combined in Monte Carlo simulations with 1000 ensembles, then 50th percentiles are compared by decade. Further details on critical thresholds are provided in the Supplementary Information.

In addition, a limited assessment of model uncertainty was undertaken by making opportunistic use of comparable pre-existing simulations. To assess the impact of model uncertainty on the analysis presented in this paper, we have repeated the assessment of the exposure indicators using the NEMO-ERSEM simulation based on the time of emergence and compared to those used in this paper for SST, primary productivity, pH and hypoxia. The result of this can be found in the Supplementary Information.

2.4.3. Exposure indicators

Exposure of marine ecosystem services to climate stressors is represented by the time of emergence of 9 indicators within EEZ territories outlined in Table 1. We classified the indicators into 7 stressor groups: warming (SST, benthic temperature, marine heatwaves), deoxygenation (hypoxia), acidification (benthic Ω and pH), declining productivity (declining primary productivity), sea level rise (extreme sea levels) and declining sea ice (declining sea ice concentrations). Indicators were weighted within each of the 7 stressor groups so that stressor groups were weighted equally in the final Exposure component.

2.5. Sensitivity (S)

We estimated Sensitivity of marine ecosystem services to climate stressors using 14 indicators. These were each aligned with the following categories: 'Provisioning', 'Maintenance and Regulation', and 'Cultural' services (Table 2). Further details on each indicator and alignments can be found in the Supplementary Information.

Indicators at a higher resolution than national required additional processing to calculate an EEZ territory-level indicator. The percentage of an EEZ covered by Marine Protected Areas (MPAs), blue carbon ecosystems (seagrass, saltmarsh, mangroves), and coral reefs was calculated using the area of each EEZ territory. The percentage of the population living in the Low Elevation Coastal Zone (under 10 m) and the percentage of the population living within 10 km of the coast was calculated from population density data, converted into population totals per grid cell and masked by elevation. For sub-national data (e.g. Canada Scotian Shelf), only data from the Atlantic coast was used, whereas for total country averages, all data was used. The percentage of artisanal fishing as a proportion of total fishing in an EEZ was derived from the Sea Around Us global fisheries catch data. Where reported at sub-national, data was aggregated to the relevant EEZ territory. Mega-fauna species were defined as per Estes et al. (2016) (Estes et al., 2016) and where available, native range maps were extracted from AquaMaps for each species (292 total, Supplementary Table 2). Using these, we

Table 2

Details of the Sensitivity indicators. Indicators marked with an asterisk (*) required additional processing beyond downloading the data from the source. Details of this can be found below and in the Supplementary Methods.

Ecosystem service category	Indicator	Unit	Source	Resolution
Provisioning	<i>Ocean Goods Trade</i>	USD	UNCTAD Data Hub (UNCTAD, 2021)	national
Provisioning	<i>Natural capital per capita – Fisheries</i>	Constant 2018 USD	The World Bank (World Bank, 2024a)	national
Provisioning	<i>Nutritional dependence on fish protein</i>	% of total protein in diet	FAOSTAT (FAO, 2025)	national
Regulation and Maintenance	<i>Atlantic EEZ territory area</i>	km ²	Marine Regions (Flanders Marine Institute, 2025)	national
Regulation and Maintenance	<i>Marine Protected Areas*</i>	% EEZ area	Protected Planet (UNEP-WCMC and IUCN, 2025)	sub-national
Regulation and Maintenance	<i>Coast-to-territory area ratio</i>	unitless	The World Factbook (Central Intelligence Agency, 2025)	national
Regulation and Maintenance	<i>Blue carbon ecosystems*</i>	% EEZ area	UNEP-WCMC (UNEP-WCMC, 2025)	sub-national
Regulation and Maintenance	<i>Population living in the Low Elevation Coastal Zone (under 10 m)*</i>	% total population	NASA SEDAC (Center For International Earth Science Information Network-CIESIN-Columbia University, 2017)	0.1 × 0.1°
Cultural	<i>Population living within 10 km of the coast</i>	% total population	NASA SEDAC (Center For International Earth Science Information Network-CIESIN-Columbia University, 2017)	0.1 × 0.1°
Cultural	<i>Value generated by artisanal fisheries*</i>	% of total landed value	Sea Around Us (Pauly et al., 2020)	national
Cultural	<i>Biodiversity*</i>	Number of megafauna species occurring in EEZ territory	AquaMaps (Kaschner et al., 2011; Kesner-Reyes et al., 2016)	0.5 × 0.5°
Cultural	<i>Coral reefs*</i>	% EEZ area	UNEP-WCMC (UNEP-WCMC et al., 2021)	sub-national
Cultural	<i>Fisheries employment*</i>	Number of people employed in capture fisheries as a percentage of the total population	Multiple sources (Supplementary Table 3)	national
Cultural	<i>Marine and Coastal Tourism</i>	Million USD	UNCTAD Data Hub (UNCTAD, 2021)	national

estimated the occurrence of species in EEZ territories following a > 0.5 probability of occurrence (default AquaMaps default). Fisheries employment data was calculated using the number of people employed in capture fisheries and the total population. Availability of representative indicators for the wide variety of existing Cultural ecosystem services at the Atlantic scale was low, so a focus on certain dimensions, such as livelihoods and wellbeing within a healthy environment was selected.

2.6. Adaptive capacity (AC)

Adaptive Capacity reflects the capacity of a governance system in a territory to adapt to, recover from, and minimise the harm resulting from climate stressors (Vallury et al., 2022). We selected 5 indicators to represent Adaptive Capacity in Atlantic coastal states Table 3. EEZ territories with high Adaptive Capacity scores have a high capacity to adapt or mitigate the impacts of climate change on their ecosystem services.

2.6.1. Vulnerability index calculation: from indicators to index

Individual indicators processed to EEZ territory level were normalised between 0 and 1 using a min-max normalisation to create dimensionless, comparable scales (Fig. 1). Indicators were then aggregated using a geometric mean within each component of the Vulnerability Index (across weighted indicators in E, and non-weighted indicators for S and AC), to obtain one score per EEZ territory (Böhringer and Jochem, 2007). To make no a priori assumptions about the importance of each indicator, indicators were weighted equally within the Sensitivity and Adaptive Capacity components (Blasiak et al., 2017; Hughes et al., 2012; Wabnitz et al., 2018).

All three Vulnerability Index components (E, S, AC) were then standardised again between 0 and 1 (across all EEZs) before calculating the final overall vulnerability score for each EEZ territory. Vulnerability within each category of marine ecosystem service (Provisioning, Regulation & Maintenance, Cultural) was also calculated by including only aligned Sensitivity indicators for each service category as outlined in Table 2.

Indicator availability was variable: 10 EEZ territories had 27/28 indicators available, and 18 EEZ territories had fewer than 20 indicators (16% of total EEZ territories, Fig. 3B), of which, Western Sahara excepting, were all island states such as Saint Barthélemy, Saint Martin and the Isle of Man.

We explored the robustness of the Vulnerability Index by removing single indicators and recalculating each component (E, S, AC). Removing individual indicators had little effect on the Vulnerability rankings, with high levels of correlation between the overall and the recalculated components (Kendall's rank correlation tau > 0.71 , test results available in Supplementary Information).

Table 3
Details of the Adaptive capacity indicators.

Indicator	Area	Source	Resolution
Life expectancy at birth	Health	The World Bank (World Bank, 2024b)	national
Adult literacy rate	Education	Our World in Data (UNESCO, 2024)	national
Government Effectiveness Index (GEI)	Governance	The World Bank (World Bank, 2024c)	national
Gross National Income (GNI)	Economic development	The World Bank (World Bank, 2024d)	national
Liner Shipping Connectivity Index (LSCI)	Connectivity	UNCTAD (UNCTAD, 2024)	national

3. Results

3.1. Spatial variability of exposure

The analysis shown in Fig. 2 indicates that three stressors with strong spatial gradients drive the observed time of emergence pattern across the Atlantic: hypoxia (Fig. 2g), sea level rise (Fig. 2h), and sea ice (Fig. 2i, Fig. 4). Hypoxia manifests along the African coast between 30°S and 30°N, broadly overlapping with the eastern tropical Atlantic oxygen minimum zone. Hypoxic conditions already exist in these regions, extending in places toward the western Atlantic margins and are showing slight change along their margins in later decades. Accelerating Arctic sea ice retreat will expose all currently ice-covered areas to high ecosystem risk by the 2030s, creating an additional stressor for Canada, Greenland, and Svalbard (Fig. 2i). The main exception is the Labrador sector of the Canadian EEZ, where exposure is delayed until the 2050s because of the high natural variability of sea-ice cover (Fig. 3a).

The pattern for extreme sea level stress is more complex (Fig. 2h). In our study extreme sea levels are represented as the sea surface height variations driven by storm surges, waves, tides, and sea-level rise (Jevrejeva et al., 2023). The areas most affected by sea-level rise are those with little present-day variability in extreme events. In tropical regions, even a small increase in mean sea level can make previously rare events occur more frequently (Jevrejeva et al., 2023; Voudoukas et al., 2018; Fox-Kemper, n.d.). Conversely, in regions (e.g. European coast) with high natural variability, rare events remain infrequent for longer despite sea-level rise (Voudoukas et al., 2018; Fox-Kemper, n.d.). These dynamics explain why the highest impacts are seen in the low latitudes and tropics of the Southern Hemisphere (Fig. 2h). In contrast, the tropics of the Northern Hemisphere are strongly affected by hurricanes, which already produce large temporal variability in extreme events, leading to a later time of emergence of the sea-level signal. In the equatorial zone (10°S–10°N), extreme sea levels already act as a stressor and are projected to expand across the tropics (20°S–20°N) between 2020 and 2040. Outside these regions, sea level does not emerge as a stressor until around 2080.

Of the other stressors, the patterns of emergence for SST and MHW (Fig. 2a, c) are relatively consistent across the Atlantic margins (2010–2040), excepting South Georgia and the South Sandwich Islands, where a large part of the EEZ emerges beyond 2060. Upwelling areas show a delay of 1–3 decades compared with surrounding regions, particularly evident in the West African upwelling system and in the upwelling associated with the Brazil–Malvinas Confluence Zone, which influences the Argentine shelf. Benthic temperature emerges as a stressor between 2030 and 2040 in areas with broad shallow shelves, notably over the north-west European and Argentinian shelves, and in Hudson Bay (Canada). The Argentinian shelf is also affected sooner by the aragonite and calcite saturation state (Fig. 2e), indicating that this broad, shallow shelf will be highly vulnerable to climate impacts.

Declining primary production emerges between 2020 and 2040 in three main areas: the polar North Atlantic (driven by the collapse of deep convection, Kelly et al., 2025), the western African margins and the Caribbean. Overall, the time of emergence is highly variable across the Atlantic, with the UK and the wider North West European Shelf likely impacted soonest. Caution is required when interpreting this stressor, however, as climate models consistently project a decline in primary production only in the northern North Atlantic, while projections for the other regions are highly uncertain (Tagliabue et al., 2021; Doléac et al., 2025).

In summary, high exposure in the tropics is primarily driven by hypoxic conditions and sea-level-related stressors, whereas in the high northern latitudes it is driven by sea-ice decline and acidification-related stressors with the addition of primary production decline in the subpolar North Atlantic. Emergence of temperature-related stressors, although spanning several decades, is relatively homogeneous across the Atlantic and does not significantly contribute to differences in country-level

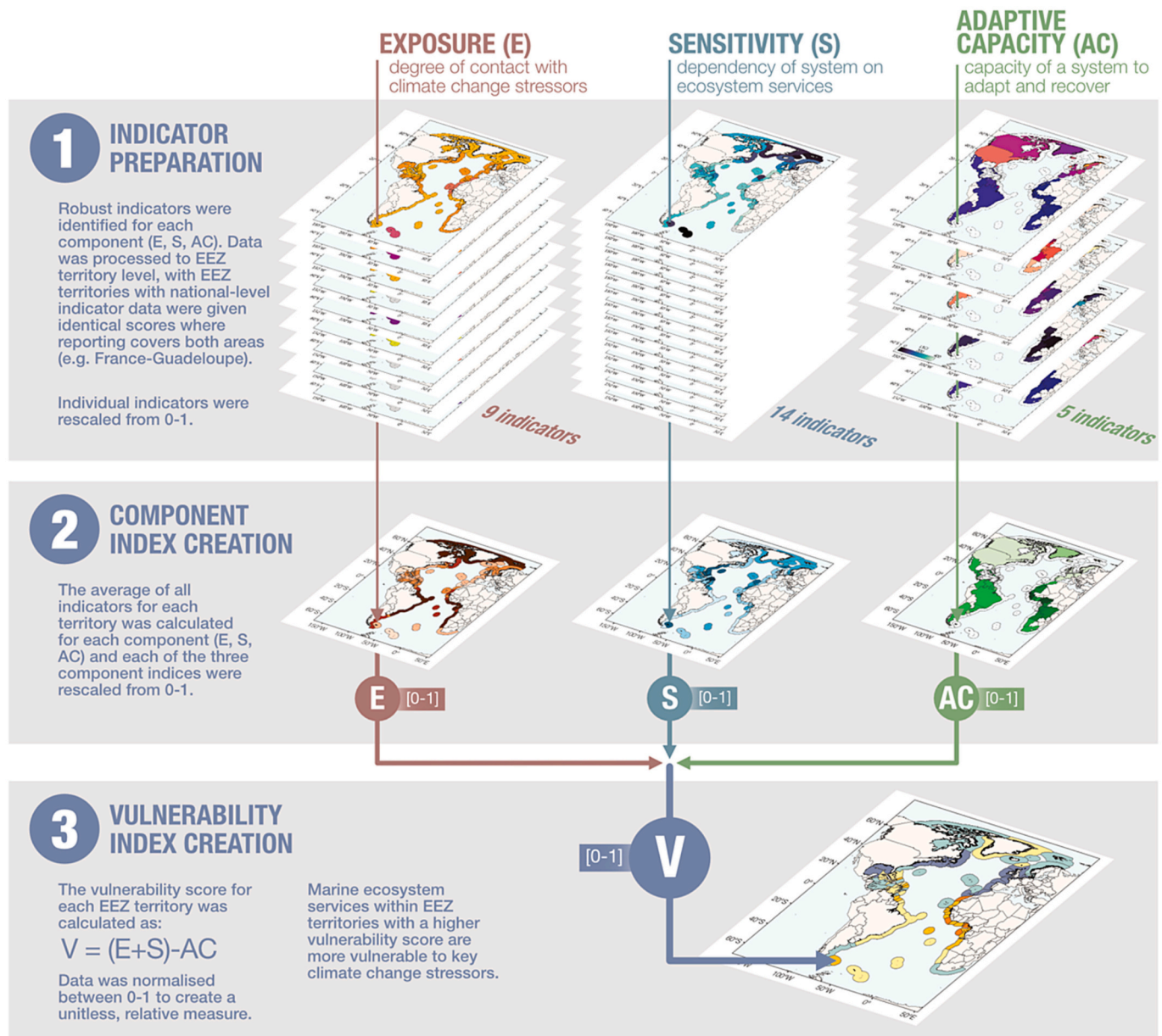


Fig. 1. Vulnerability analysis framework. Steps taken to create the Vulnerability Index.

exposure indicators.

How the heterogeneous spatiotemporal pattern of exposure to climate change stressors translates into exposure indices for each EEZ territory and their regional clusters is illustrated in Figure 3. Benthic calcite and aragonite undersaturation (Fig. 3b) is projected to have already emerged or being present in a natural (unrelated to anthropogenic climate change) state in many territories (2000–2010s, Fig. 3b). However, notable delays are evident, such as in some North American EEZ territories or their sub-regions (where emergence is delayed until 2020–2030) and in parts of Europe, where some EEZ territories are not affected until the 2040s or later. Hypoxia ($<100 \text{ mmol O}_2\text{m}^{-3}$) is projected to have already emerged (in the 2000s) or naturally present across many African and within some South American EEZ territories but Fig. 3a highlights outliers such as the Canadian Arctic, where emergence is delayed until the 2040s. This stressor does not emerge during the 21st century across most of Europe.

Progressing through the decades, temperature-related stressors emerge next, clustering around the 2020s and 2030s, but with earlier emergence in some Atlantic Small Island Developing States (SIDS) and

later emergence in several West African EEZ territories (Fig. 3a). All three thermal indicators (surface and benthic temperature, MHW) emerge as stressors in a large number of EEZ territories by 2040 (Fig. 3b). Sea-level extremes also begin to emerge in the 2020s, first in Western and Central Africa and then in the southern hemisphere tropics. Declines in primary production follow, first emerging in Europe in the 2030s, widespread by the 2040s–2060s, with emergence peaking in the 2060s. Surface ocean pH emerges last, again, with exceptions. For example, it emerges two to three decades earlier in the Canadian Arctic than in most other regions.

The geographical pattern of stressor emergence is complex, yet there is considerable spatiotemporal clustering and a clear sequence of stressors at the EEZ territory scale. This provides a strong basis for prioritising national efforts, as the order of emergence differs among EEZ territories, underscoring that no single adaptation strategy will suit all contexts.

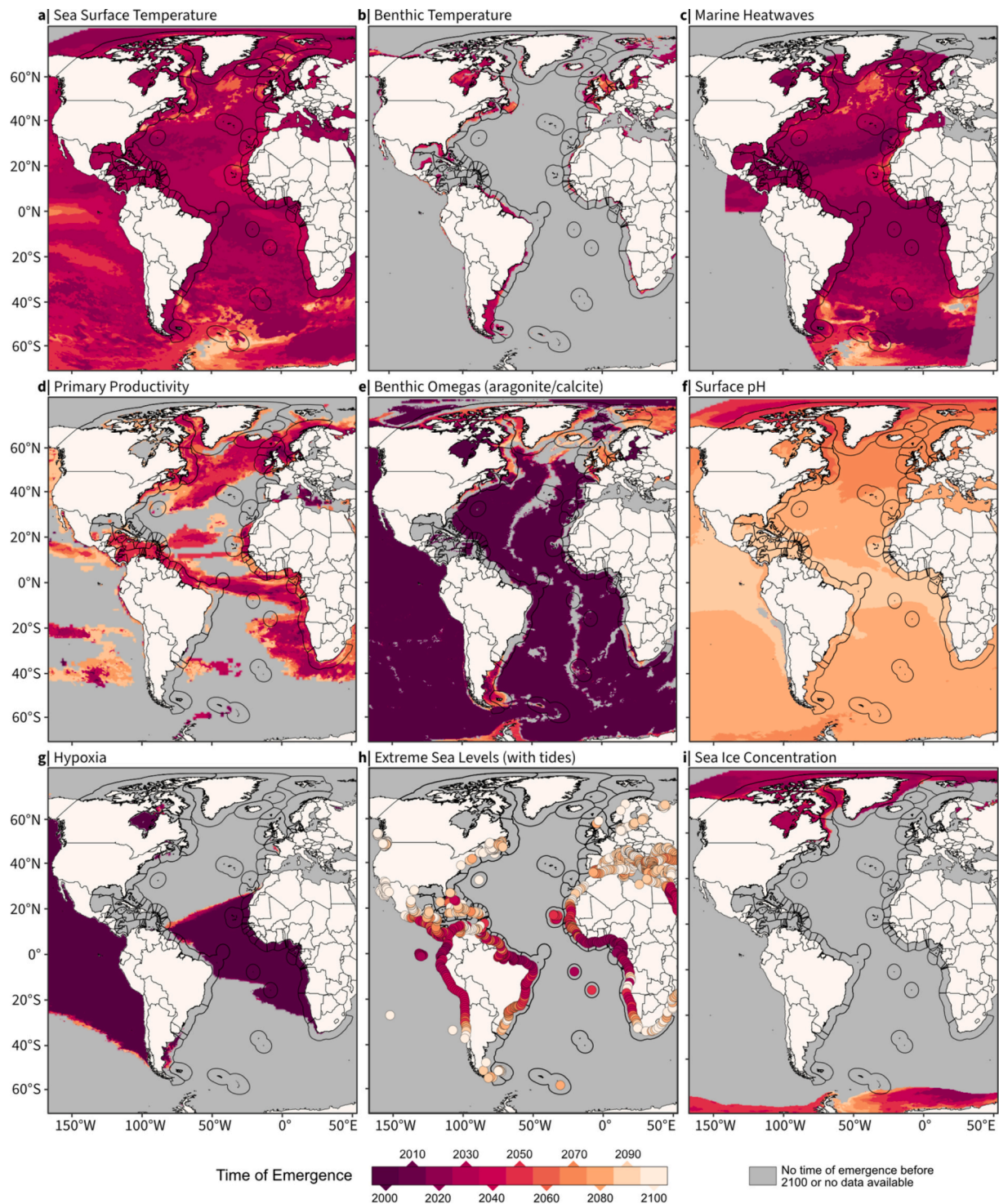


Fig. 2. Time of emergence (decade) for exposure indicators across the Atlantic. (a) Sea surface temperature; (b) Benthic temperature; (c) Marine heatwaves; (d) Primary productivity; (e) Benthic omegas; (f) Surface pH; (g) Hypoxia; (h) Extreme sea levels; (i) Sea ice concentration.

3.2. Vulnerability index

A breakdown of the Vulnerability Index components (Exposure, Sensitivity, Adaptive Capacity) and individual indicators is revealed in Fig. 4. Exposure patterns show strong spatial variability across the Atlantic margins, with EEZ territories in the polar areas of the North Atlantic and in the low- to mid-latitudes (0–40°S) of the Southern Hemisphere along both the African and South American coasts (Fig. 4a) most exposed to climate stressors. EEZ territories around subpolar

islands in the Southern Hemisphere (South Georgia and the Sandwich Islands), the Gulf of Mexico, parts of the Caribbean, and the north-west African coast ranked as least exposed to climate stressors. The pattern displays clear geographical clustering but does not follow the high–low latitude gradient, highlighting the need to examine time of emergence for individual stressors in more detail (Section 6.1, Fig. 2).

Marine ecosystem services in Caribbean EEZ territories rank as most sensitive to climate change stressors, particularly in Turks and Caicos, Antigua and Barbuda, Anguilla, and Saint Kitts and Nevis (Fig. 4b).

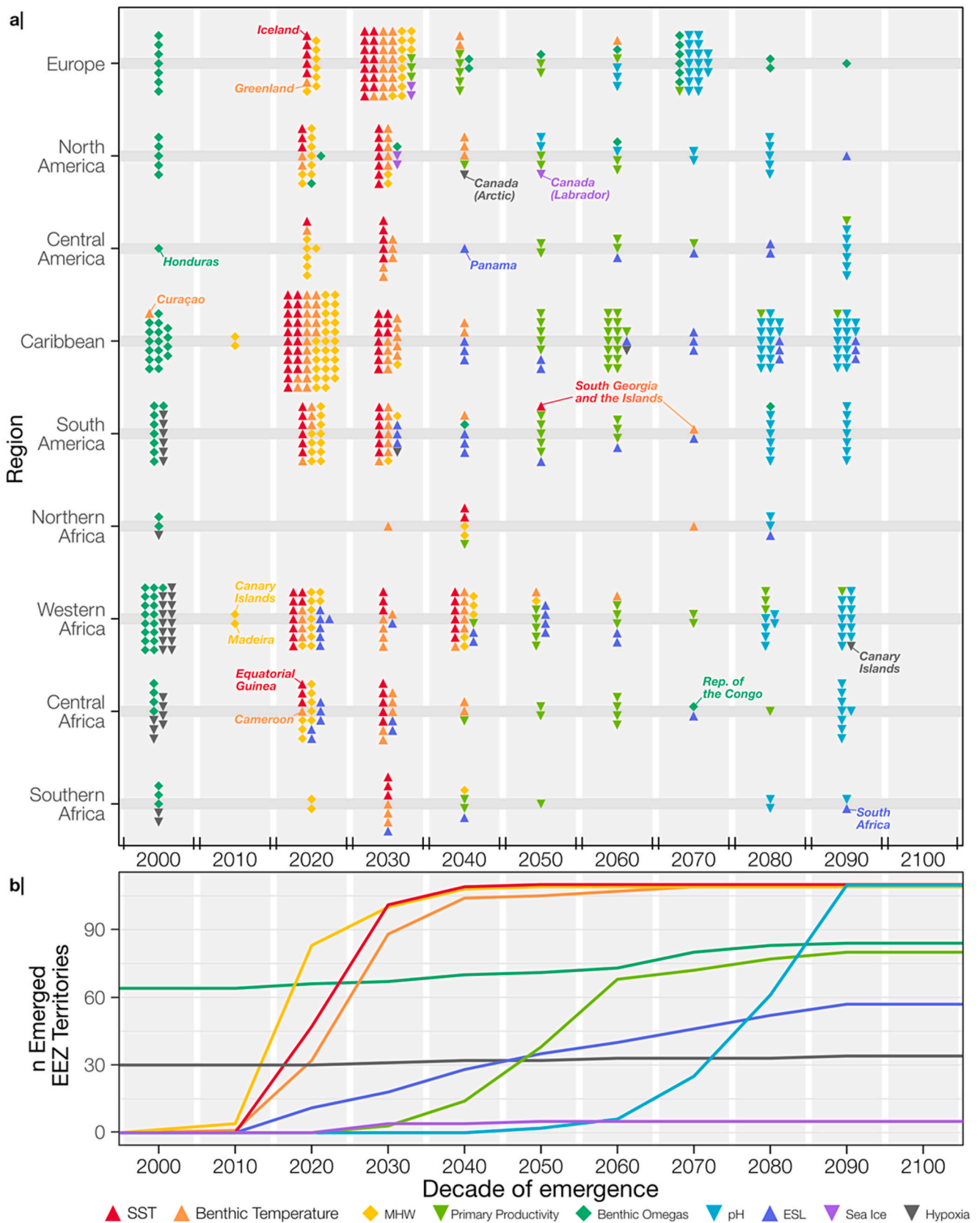


Fig. 3. Decade of emergence for climate change stressors. (a) Each point represents an EEZ territory across Atlantic geographical regions delineated by the UN geoscheme (Canaries and Madeira included in Western Africa for this visualisation). Example EEZ territories are labelled on the figure. (b) Number of EEZ territories in which a climate stressor has emerged per decade.

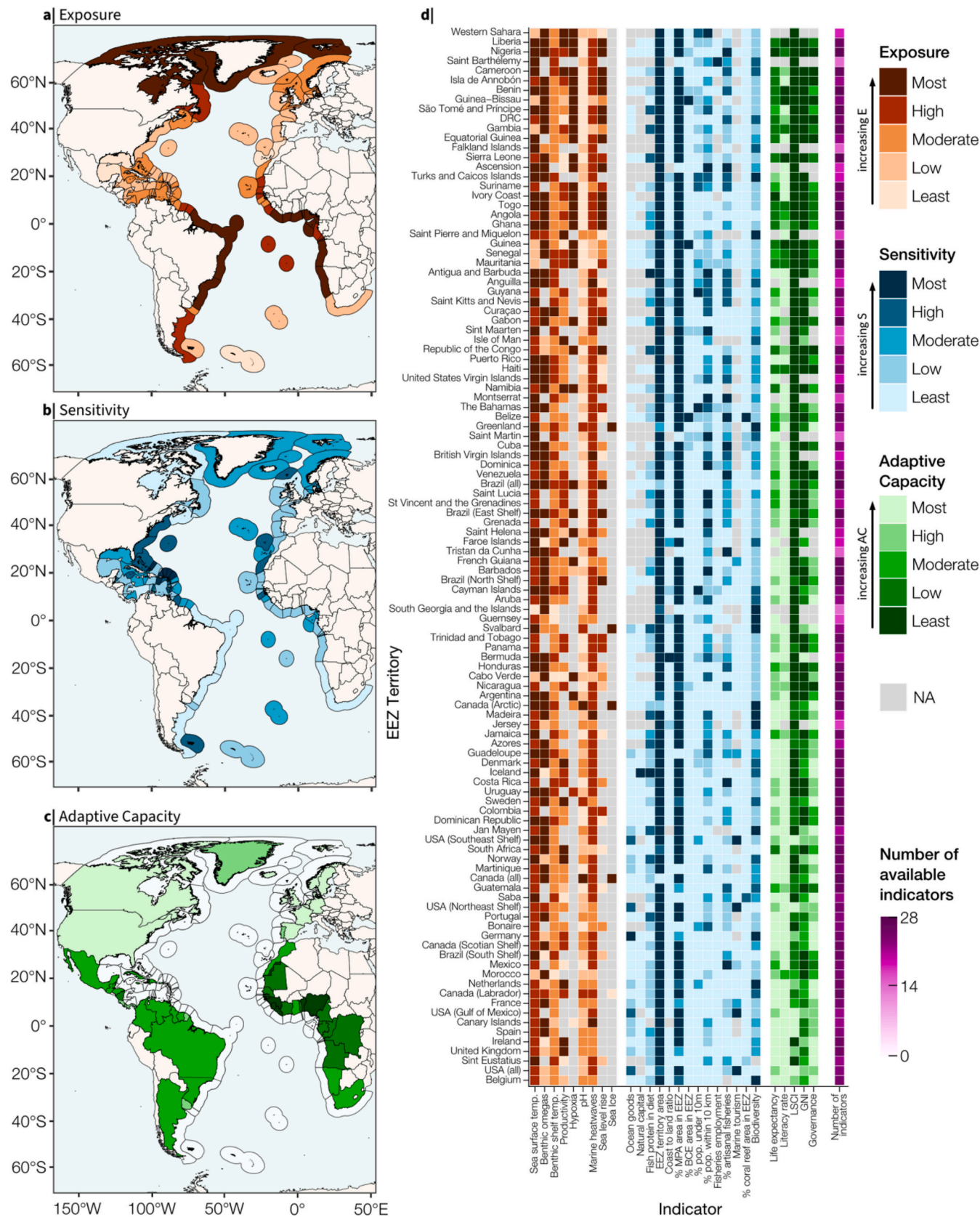


Fig. 4. Vulnerability Index breakdown by component and individual indicator. Component scores for (a) Exposure, (b) Sensitivity and (c) Adaptive Capacity. (d) Breakdown of all indicators and total number of indicators available per EEZ territory. EEZ territories are ranked by their overall Vulnerability score (unitless and normalised between [0–1]): Least vulnerable (0–0.2), Low vulnerability (0.2–0.4), Moderately vulnerable (0.4–0.6), Highly vulnerable (0.6–0.8), Most vulnerable (0.8–1).

These have comparatively small EEZs, with a low percentage of MPAs, and a large proportion of their population live within 10 km of the coast (Fig. 4d). In contrast, marine ecosystem services in North and South America rank as less sensitive to emerging climate change stressors, as they have larger EEZs, a higher diversity of marine megafauna, and a lower proportion of their population live on the coast or below 10 m below sea level. Sensitivity of services in European and African EEZ territories is heterogeneous, but are generally less sensitive to climate stressors than other Atlantic regions.

Developed economies in Europe and North America (e.g. the USA, Netherlands and Belgium) demonstrate the most capacity to adapt to the impacts of climate change (Fig. 4c). These are characterised by high human capital, strong governance systems and large economies. EEZ territories in developing economies in West Africa currently have the least capacity for adaptation, particularly Guinea, Guinea-Bissau and Liberia, with comparatively low literacy rates and life expectancies, weaker economies that are less integrated into global shipping networks, and weaker governance, which could result from fewer controls on corruption, political instability and poor regulatory quality. Countries in Central and South America have a moderate capacity to mitigate and adapt to the impacts of climate change through governance measures.

Overall, marine ecosystem services in West and Central African EEZ territories are the most vulnerable to climate stressors, in Liberia, Benin, Nigeria and Cameroon, as well as in Western Sahara (Fig. 5). Services in the Caribbean and South America are also more vulnerable than in Europe and North America, where overall vulnerability is low. However, notable exceptions exist at high latitudes with services in Greenland and South Georgia and the Sandwich Islands ranking as vulnerable to climate change stressors (Fig. 5a). In addition, seven of the top fifteen positions on the index are held by Least Developed Countries (LDCs, 12 of the 44 LDCs border the Atlantic) and/or SIDS (31 of the 57 SIDS border the Atlantic, Fig. 5b). Despite these regional-scale patterns, overall vulnerability of marine ecosystem services reflects each EEZ territory's specific context (Fig. 5b). For example, Liberian marine ecosystem services are predicted to be highly exposed to multiple climate change stressors including imminent increases in sea surface temperatures and acidification, as well as hypoxia and sea level rise, and were highly sensitive to potential impacts. Combined with a lower capacity to adapt, services in this EEZ were overall highly vulnerable to climate change stressors. Conversely, despite early reductions in primary productivity, Belgium was less exposed to other climate change stressors, was less sensitive to the impacts of climate change stressors than other EEZ territories, and had a high capacity to adapt to a changing environment, resulting in Belgian marine ecosystem services ranking as least vulnerable to climate change stressors. As this is a relative index, this does not indicate that marine ecosystem services in Belgium are not vulnerable to climate stressors; it indicated that they are less vulnerable than those in other Atlantic EEZ territories.

3.3. Marine ecosystem service categories

Each marine ecosystem service category was examined separately by selecting relevant Sensitivity indicators. Provisioning services are most vulnerable in Western and Central Africa and well as in South America (Fig. 6a). Provisioning services in Iceland, the Azores and Madeira also rank as highly vulnerable in contrast to regional patterns. Vulnerability of Regulatory marine ecosystem services largely follows patterns observed in the overall Index, with mid-latitude EEZ territories in West Africa such as Mauritania and Gambia most vulnerable, closely followed by EEZ territories in Central Africa and the Caribbean (Fig. 6b). Vulnerability of Cultural services is more heterogeneous, with Western and Central Africa, Brazil, the South Atlantic islands and Greenland more vulnerable (Fig. 6c) and European and North American EEZ territories less vulnerable across the three categories as compared to other Atlantic EEZ territories.

Moreover, we were able to identify which marine ecosystem services are likely to be most imminently at risk (Fig. 6d). Provisioning services are more vulnerable than other services in North America and Europe, in EEZ territories including the USA, Canada, Iceland, Norway, the UK, France, Spain and Portugal, as well as multiple states in West and Central Africa including the Republic of the Congo, Mauritania, Gambia, Sierra Leone, Senegal and Angola. These EEZ territories rely on a large trade of ocean goods, with a high natural capita concentrated in their fisheries and a high dependence on fish for protein. Regulatory services are most vulnerable in many West African states such as Guinea-Bissau, Benin, and Nigeria, as well as South American states including Uruguay, Guyana and Suriname. These EEZ territories may have a smaller than average EEZ, with few MPAs, a large coast-to-territory ratio, a large proportion of the EEZ territory covered by blue carbon ecosystems and a large proportion of the population living under 10 m above sea level. Finally, Cultural services are most at risk from climate change stressors in the Caribbean and Central America, as well as in the South Atlantic islands and Greenland, in EEZ territories such as Cuba, Belize, Panama, St Helena, and Ascension and Tristan da Cunha. These EEZ territories are likely to have a large population living within 10 km of the coast, a large value generated by artisanal fisheries and marine and coastal tourism, and with high employment in fisheries, low biodiversity, and a subset of these have a high presence of coral reefs.

4. Discussion

4.1. Overall vulnerability

Our analysis assesses the national-level vulnerability of marine ecosystem services to climate change across Atlantic coastal countries, based on their Exposure and Sensitivity to climate stressors, as well as the Adaptive Capacity of governance systems to mitigate negative impacts. We consider a broad suite of climatic stressors, using time of emergence as the Exposure metric. Consistent with previous global ecosystem vulnerability assessments (e.g. Allison et al., 2009; Blasiak et al., 2017), our results highlight elevated vulnerability in tropical regions. The highest vulnerability is concentrated in tropical West Africa, driven by high exposure to early-emerging stressors, including temperature-related stressors, sea-level extremes, hypoxia, and acidification, reflecting the influence of major upwelling systems and proximity to the oxygen minimum zone. It is further amplified by the high sensitivity of habitats and communities dependent on ecosystems and fisheries, particularly in upwelling regions, and the low adaptive capacity of Least Developed Countries in this region. Our study also identifies elevated vulnerability in subpolar and polar regions. For Greenland, this is linked to ice retreat, while for other such as the Falkland Islands, South Georgia, and the Faroe Islands, it arises from a combination of context-specific regional factors, such as early emergence of warming stressors and low coverage of the EEZ territory by MPAs in the case of the Falkland and Faroe Islands, amplified by a low connectivity to international shipping networks as is the case for all three EEZ territories.

Our results are consistent with other national-scale analyses of ecosystem service vulnerability that highlighted marine fisheries in developing economies as highly vulnerable to climate change impacts (Blasiak et al., 2017). In particular, seven of the top 15 positions in our index are held by Least Developed Countries (LDCs) and/or SIDS. Alongside a high vulnerability to external economic shocks, natural and man-made hazard-induced disasters and communicable diseases, these countries will have to manage the impacts of climate stressors on their marine ecosystem services, with direct and far-reaching impacts on socio-ecological systems. For example, sea level rise and increasing temperatures are likely to disrupt blue carbon storage in seagrass and mangrove ecosystems (Lovelock and Reef, 2020) and have knock on effects on food security and supply chain efficiency, widening existing socio-economic equity gaps (Boyce et al., 2020; Er Kara et al., 2021;

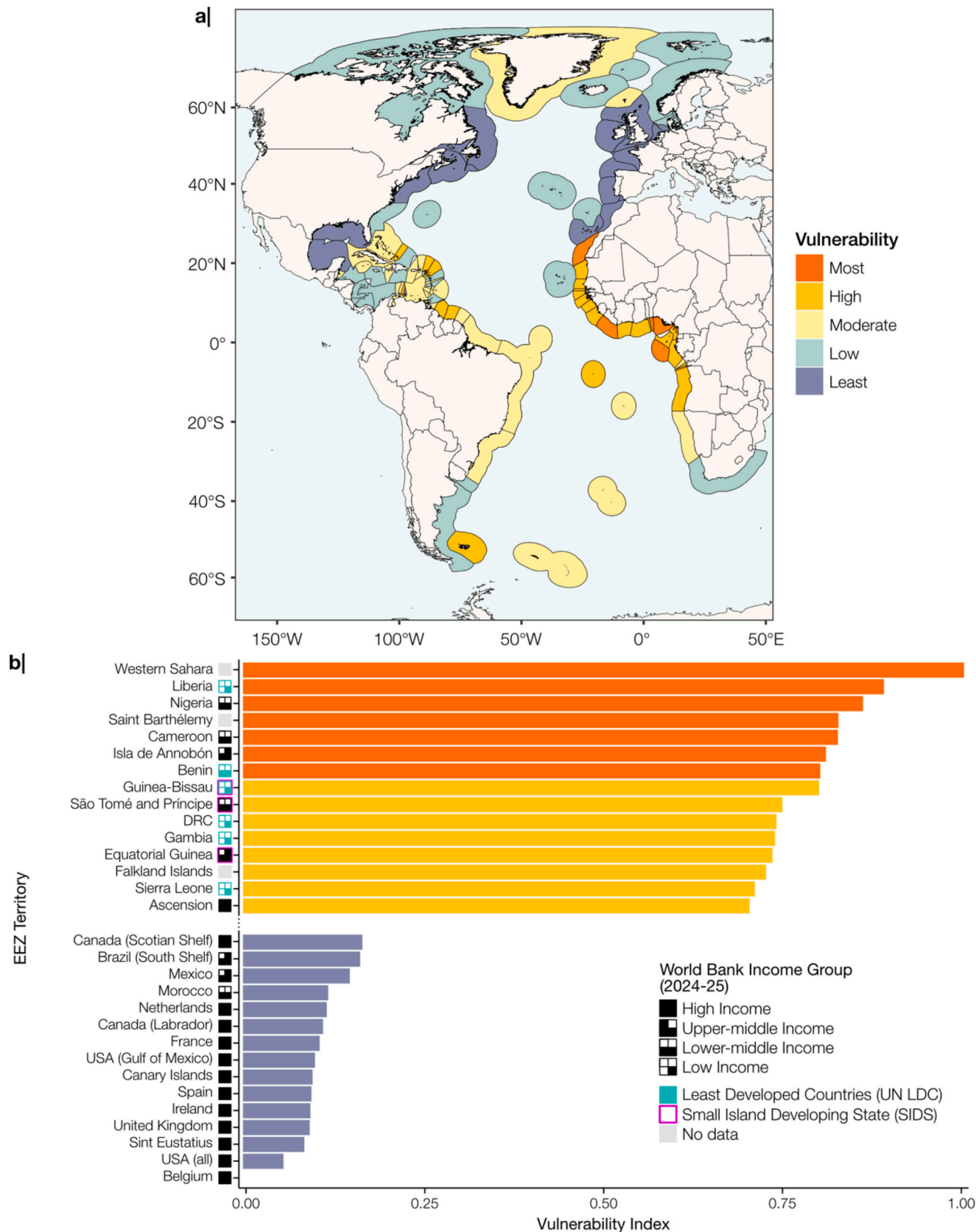


Fig. 5. Relative vulnerability of Atlantic coastal states to climate change stressors (unitless and normalised between [0–1]): Least vulnerable (0–0.2], Low vulnerability (0.2–0.4], Moderately vulnerable (0.4–0.6], Highly vulnerable (0.6–0.8], Most vulnerable (0.8–1). (a) Vulnerability scores across all Atlantic EEZ territories; (b) 15 top and bottom ranking EEZ territories.

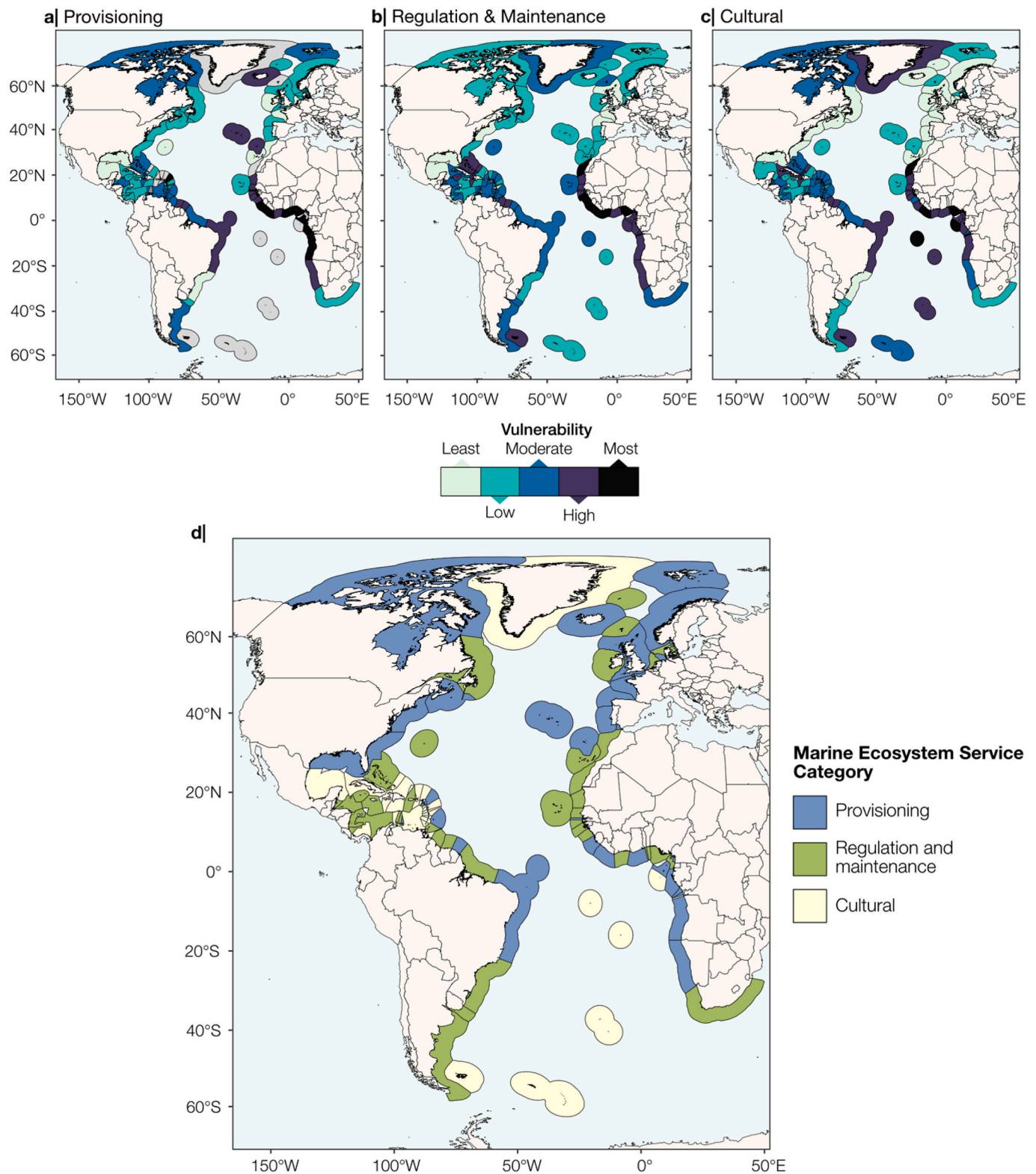


Fig. 6. Relative vulnerability of each marine ecosystem service category to climate stressors (unitless and normalised between [0–1]): Least vulnerable (0–0.2], Low vulnerability (0.2–0.4], Moderately vulnerable (0.4–0.6], Highly vulnerable (0.6–0.8], Most vulnerable (0.8–1): (a) Provisioning, (b) Regulation and maintenance, (c) Cultural, and (d) indicates the marine ecosystem service within each EEZ territory that is most at risk from climate change stressors.

Becker et al., 2018). For developing economies such as SIDS, who have, on average, EEZs 28 times larger than the country's land mass and rely on marine ecosystem services provided by the marine environment, this will act as a barrier to ongoing economic, social and environmental development.

Long-term climate change projections (2060, 2100 and beyond) (Allison et al., 2009; Blasiak et al., 2017) produce a highly uncertain picture due to potentially complex multi-stressor impacts, and result in a mismatch between the projection of future impacts and decision-making timescales (Chapman et al., 2014). This work highlights a serious need

for research to use metrics such as time of emergence in combination with cross-scale climate projections to communicate timescales of climate change and support ongoing prioritisation of policy interventions. As climate change progresses throughout the century, marine ecosystem services will be exposed (in many cases, are already exposed) to multiple stressors. However, these stressors do not emerge simultaneously or in the same combinations across regions. Our analysis reveals clear geographical patterns in emergence of climate stressors, with distinct hotspots of high and early risk. Within hotspots of high overall vulnerability such as western Africa, time of emergence also varies between countries and indicators. For example, extreme sea levels emerge over a span of 50 years, and declines in primary productivity emerge across 60 years in the region (Fig. 3). This is highly likely to result in different impacts in each area. Mitigative and adaptive behaviours will therefore need to differ depending on the emerging stressors in each area, as well as the cultural context and governance systems in place in each country. In Liberia and Nigeria for example, two areas with highly vulnerable marine ecosystem services, a combination increasing temperatures and sea level rise threaten ecosystem services, and low adaptive capacity of governance systems makes mitigative and/or adaptive policies more difficult to implement in this region. In the same region, vulnerability in Western Sahara is driven by exposure to decreases in primary productivity and hypoxia, and missing data from this region makes it more difficult to examine the adaptive capacity. Further research is needed to understand ongoing impacts, and these locations could serve as case studies for early learning and for sharing expertise with similar locations (Hobday and Pecl, 2014). The time of emergence metric puts a timescale on emerging climate change stressors in each EEZ territory, demonstrating the likely sequence of climate stressor emergence across the early, mid, or late 21st century.

Our results agree with and further emphasise past work on vulnerability that adaptation planning needs to consider country-dependent context. Climate change will have the largest impact in national waters where sensitive marine ecosystem services are exposed to stressors, coupled with a low capacity to implement effective policies to mitigate negative impacts. It is therefore critically important to consider the context of each EEZ territory as different policy and management approaches will be needed to address different facets of vulnerability (Ding et al., 2017). Interventions will be most effective when implemented on multiple levels depending on the scale of likely impacts, and must be responsive to national realities and cultural nuance (Ogier et al., 2025). By identifying which marine ecosystem services were most vulnerable to climate change stressors in each Atlantic EEZ territory, this study highlights areas where future research could support adaptive and mitigative action in the face of substantial environmental change.

4.2. Vulnerability of different marine ecosystem service categories

Multiple studies have focused on provisioning services due to the reliance of many coastal states on the ocean for food and energy security (Allison et al., 2009; Blasiak et al., 2017; Bell et al., 2011; Cao et al., 2023). For coastal states where provisioning services are most vulnerable to climate change stressors, clearly defined interventions promoting a sustainable blue economy by protecting and restoring natural capital in national waters, as well as emphasising transparent and detailed social and economic statistics on the fisheries sector, will enhance resilience of socio-ecological systems (Syddall et al., 2021). However, vulnerable regions vary significantly; from OECD nations that are reducing the proportion of value generated from fisheries to others that rely heavily on marine fisheries and aquaculture (Blasiak et al., 2017; Ding et al., 2017). Interventions will therefore vary depending on national context.

Regulation and maintenance services were most vulnerable in EEZ territories with a high occurrence of blue carbon ecosystems and a significant proportion of the population living in the Low Elevation Coastal Zone of <10 m. Blue carbon ecosystems such as seagrass and mangroves

mainly occupy the intertidal and shallow water environments and sea level rise is one of the main drivers impacting blue carbon stocks (Lovelock and Reef, 2020). In nearshore developed areas where blue carbon ecosystems degrade as they cannot move inland due to hardening shorelines and human-modified environments, extreme water levels could endanger both coastal populations and ecosystems (Macreadie et al., 2019). Adopting nature-based solutions in coastal areas, as well as restoring blue carbon ecosystems could form part of a strategy to achieve sustainable coastal flood defences whilst also conserving important coastal ecosystems (Luisetti et al., 2011).

Finally, Cultural services are highly context dependent depending on the locality and actors in question as values, meanings and identities are dynamic across time (Poe et al., 2014). Changing temperatures and sea level rise will directly impact the provision of cultural services: driving the loss of natural beauty due to accelerated habitat degradation, changing phenological rhythms and species distributions, and reducing access to seasonal harvesting sites (Moerlein and Carothers, 2012). In marine ecosystem service research, Cultural services are often overlooked in larger-scale analyses due to their inherently intangible nature, with significantly work needed to develop more representative indicators to better embody their importance to physical, mental and spiritual well-being, as well as their impact on cultural values, identities, meanings, spiritual connections and local knowledge systems (Erskine et al., 2021). The reliance on proxies (e.g. artisanal fisheries, coral reef extent) shapes our interpretation of vulnerability by highlighting risks to the more “utilitarian” aspects of culture. However, this approach may overlook ‘hidden’ vulnerabilities in regions where cultural identity is deeply tied to the sea but lacks a high economic or employment footprint which, if fully taken into account, may add additional complexity and nuances to the patterns of spatial variability of cultural ecosystem services (or ToE). For example, in the Bocas del Toro archipelago along the Caribbean coast of the northwestern region of Panama, mangroves enable social interactions such as fishing, snorkelling, and generational storytelling, define local cultural identity, and engender a sense of security (Scott et al., 2024). In the Arctic, plants and animals harvested from local environments hold high spiritual, cultural, traditional and social values for Indigenous Peoples (Steiner et al., 2021), and in Western Europe, species such as *Cerastoderma edule*, the common cockle, provide artistic inspiration and a strong maritime heritage, as well as being the focus of multiple folk stories (Jackson-Bu   et al., 2022). Development of more representative indicators to more effectively include Cultural services in large-scale analyses, as well as increasing ocean literacy in both coastal and inland populations, and enhancing biodiversity and ecosystem health through effective management of marine protected areas, could make supporting cultural services increasingly cost-effective with positive knock-on effects to other services (Erskine et al., 2021). In particular, investigating impacts to Cultural services requires an interdisciplinary, often-times smaller-scale interdisciplinary approach, integrating approaches such as ethnography, oral history and sociocultural investigation to support targeted, actionable adaptation (Poe et al., 2014). This will require improved representation and championing of different value and knowledge systems in decision-making processes and western scientific research (e.g. Bishop et al., 2022).

There is a strong interdependence between marine ecosystem services as they are not produced on a one-to-one, service-to-benefit basis (Klain et al., 2014). This is reflected in the largely similar pattern seen across the marine ecosystem service category indices (Fig. 6). Where linkages are strong, interventions to create resilience and reduce vulnerability in one marine ecosystem service will often benefit other services and reduce a system's overall vulnerability to climate change and other direct anthropogenic (e.g. land based pollution) impacts. For example, implementing an actively managed, strongly regulated and large-enough marine protected area has been demonstrated to have wide-ranging benefits beyond the initial goals of the area in question (Horta e Costa et al., 2025). As well as supporting increased biomass and

biodiversity within the area, given the “spillover effect”, MPAs also directly benefit local industries by providing enhanced marine ecosystem services comparative to other areas. MPAs covering nursery and spawning areas have been shown to increase nearby fishery productivity, supporting increased biodiversity which also enhances the quality of eco-tourism sightings. For certain ecosystems such as coral reefs, mangroves and seagrass, they also provide nature-based solutions to mitigate the impacts of flooding and other extreme events, and improve overall water quality (Lynham and Villaseñor-Derbez, 2024). Conversely, emerging stressors are likely to negatively impact marine ecosystem services. By examining vulnerability of a broader selection of marine ecosystem services to climate change stressors, our results highlight which services may require more immediate support than others to reduce vulnerability, and produce multiple co-benefits. This should be useful for adaptation planning, by enabling national policy-makers to prioritise efforts.

4.3. Multi-stressor emergence & spatial resolution

Almost all regions of the Atlantic are likely to experience multiple emerging stressors as early as the 2020s. However, impacts of these emerging stressors are difficult to predict as stressors may interact or even have compounding effects on marine ecosystems. In addition, stressors can drive changes at different scales, making predicting ongoing changes challenging (Glibert et al., 2022). This increases the uncertainty around modelling cascading and interacting effects. As such prioritising mitigative behaviours to reduce the impact of emerging stressors, or to target specific stressors that will impact critical ecosystem services is key to minimising compounding multi-stressor impacts and disruption. Future research should focus on characterising multi-stressor hotspots and identifying potential interactions between climate change stressors as these are likely to impact the provisioning of marine ecosystem services in vulnerable regions.

As demonstrated in Fig. 2, emergence of climate stressors often occurs on a different scale to human jurisdictions (e.g. moving fish stocks, change in basin circulation, erosion of landmark features). Similarly, provision of marine ecosystem services is not constrained to rigid EEZ boundaries. Management of impacts at multiple scales, particularly across different jurisdictions is therefore necessary to ensure sustainable management of marine ecosystem services. However, in Areas Beyond National Jurisdiction (ABNJ), national capacity to mitigate negative impacts of climate change is limited, despite national economies benefiting from marine ecosystem services provided in the ABNJ (Ottaviani and FAO, 2020). Recent progress such as the landmark Biodiversity Beyond National Jurisdictions (BBNJ) Agreement (entry into force on 17 January 2026 following 60 ratifications in September 2025) provides a framework for international coordination in these areas, however future research urgently needs to examine the vulnerability of ABNJ to emerging climate change stressors at the international level, to support increased conservation and sustainable management of marine ecosystem services not only within EEZs, but also around the globe.

4.4. Limitations

Several limitations and associated uncertainties should be considered when interpreting the results of this study. Firstly, although our analysis partially addresses structural model uncertainty by comparing results with another coupled physical–biogeochemical model forced by different ESMs (Supplementary Information), the ensemble remains small, as few high-resolution ocean projections are currently available. In the future, larger high-resolution ensemble approaches would provide a more robust estimate of future conditions. In addition, model performance in shelf and coastal regions is another important limitation. Even at 1/12-degree resolution the model will under-resolve fine-scale processes such as small-scale upwelling, and shelf-sea processes dynamics,

and nearshore extremes, which can be critical for some marine ecosystem services. Time of emergence estimates are also sensitive to model variability, scenario choice, and internal climate variability, which may shift emergence timing by several decades in some regions. Further, the study treats stressors as additive, whereas in reality, their interactions may be synergistic, antagonistic, or cascading, adding complexity and uncertainty to projected impacts.

Secondly, indicator and threshold choice inevitably introduces subjectivity, and alternative selections or weighting could shift vulnerability rankings. In addition, the use of normalisation could also underestimate high risk and over-estimate low risk areas. In addition, a broad-scale analysis necessarily does not engage with the nations and communities it describes. Socio-economic indicators were aggregated at national scales, masking sub-national heterogeneity and potentially underrepresenting highly exposed communities, particularly in SIDS and remote territories where data gaps are substantial. National and local actors will have widely different priorities and values, so the relative importance of each ecosystem service in each nation will vary between regions and across EEZs. As well as this, due to limited and uncertain forward projections for socio-economic indicators, adaptive capacity was assumed to be static, yet governance quality, economic capacity, and policy responses can change rapidly, potentially reducing or amplifying vulnerability over time. Future research should ‘ground-truth’ the outcomes of this work with climate-impact practitioners in selected case study regions, to explore if these results stand up to local scrutiny. The international science coordination actions may provide a vehicle for such activities. For example, The UN Decade Programme CoastPredict (www.coastpredict.org) has identified ~140 Pilot sites in 74 countries. Similarly, the All Atlantic Ocean Research and Innovation Alliance (<https://allatlanticocean.org>) is identifying Beacons sites of Coastal Resilience.

These limitations highlight the importance of interpreting the results as a comparative, rather than absolute, assessment and underscore the need for iterative refinement as new data, models, and socio-economic insights become available. Despite limitations, however, integrated vulnerability assessments are essential for guiding timely and targeted adaptation, providing a comparative framework to identify priority regions and services despite uncertainty.

4.5. Conclusions

In conclusion, we assessed the vulnerability of marine ecosystem services across Atlantic EEZ territories using a relative Vulnerability Index. Marine ecosystem services across the Atlantic are exposed to multiple climate stressors, and the timing of stressor emergence is highly heterogeneous. Future projections require high-resolution models able to resolve shelf and regional dynamics, especially given substantial within-region differences, with the tropics most impacted by hypoxia and sea level extremes, while high latitudes stressed by declining sea ice, acidification, and reduced primary production. Vulnerability of marine ecosystem services in West Africa is driven by high exposure to early-emerging stressors, amplified by a high sensitivity of habitats and communities, and a low adaptive capacity of Least Developed Countries in this area. Subpolar and polar regions also rank as highly vulnerable, although developed economies in these regions generally show lower vulnerability due to robust governance and larger infrastructure. Adaptive responses must therefore be tailored to national and local contexts, to address not only socio-economic differences, but also a variable exposure to climate stressors. Finally, data gaps and indicator aggregation introduce uncertainties, highlighting the need for local expert input into future studies.

Data statement

The following data were derived from the following resources available in the public domain: UNCTADstat (Ocean goods trade, Marine

and coastal tourism, Liner Shipping Connectivity Index (LSCI)), The World Bank (Fisheries natural capital per capita, Literacy rate, Government Effectiveness Index (GEI), Gross National Income per capita, Life expectancy at birth), FAO STAT (Nutritional dependence on fish and seafood protein), Marine Regions (Marine Boundaries (EEZ)), Protected Planet (Marine protected areas), The World Fact Book, US Gov (Coast to territory area ratio), UNEP-WCMC (Blue carbon ecosystems (salt marsh, mangroves, seagrass), Coral reef habitat areas), NASA SEDAC (Gridded Population of the World (GPW)), Sea Around Us (Percentage of total landed fisheries value), Aquamaps (Megafauna species occurrence), multiple sources (Number of fishers (source details in Supplementary Information)). Remaining data that support the findings of this study are included within this paper and its Supplementary Information.

CRediT authorship contribution statement

Alexandra Loveridge: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zoe Jacobs:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Stephen Kelly:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Andrew Yool:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Stefanie Rynders:** Writing – review & editing, Methodology, Investigation. **Svetlana Jevrejeva:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Joanne Williams:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Ludivine Conte:** Writing – review & editing, Validation, Methodology. **Jason Holt:** Writing – review & editing. **Adrian Martin:** Writing – review & editing. **Yuri Artioli:** Writing – review & editing, Writing – original draft, Validation, Methodology. **Ekaterina Popova:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloenvcha.2026.103251>.

Data availability

Data will be made available on request.

References

- Allison, E.H., et al., 2009. Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fish.* 10, 173–196. <https://doi.org/10.1111/j.1467-2979.2008.00310.x>.
- Artioli, Y., et al., 2024. 2020–2070 Future projections report (NEMO-ERSEM & SEAPODYM). Mission Atlantic.
- Bates, A.E., et al., 2014. Defining and observing stages of climate-mediated range shifts in marine systems. *Glob. Environ. Chang.* 26, 27–38. <https://doi.org/10.1016/j.gloenvcha.2014.03.009>.
- Becker, A., Ng, A.K.Y., McEvoy, D., Mullett, J., 2018. Implications of climate change for shipping: ports and supply chains. *WIREs Clim. Change* 9, e508. <https://doi.org/10.1002/wcc.508>.
- Bell, J.D., Johnson, J.E., Hobday, A.J., 2011. In: *Pacific Community (Ed.), Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*.
- Berkes, F., Folke, C., 1998. Linking social and ecological systems for resilience and sustainability. In: *Linking social and ecological systems: management practices and social mechanisms for building resilience*, 1, p. 4.
- Bishop, B., Oliver, E.C.J., Aporta, C., 2022. Co-producing maps as boundary objects: bridging Labrador Inuit knowledge and oceanographic research. *J. Cult. Geogr.* 39, 55–89. <https://doi.org/10.1080/08873631.2021.1998992>.
- Blasiak, R., et al., 2017. Climate change and marine fisheries: least developed countries top global index of vulnerability. *PLoS One* 12, e0179632. <https://doi.org/10.1371/journal.pone.0179632>.
- Böhlinger, C., Jochem, P.E.P., 2007. Measuring the immeasurable — a survey of sustainability indices. *Ecol. Econ.* 63, 1–8. <https://doi.org/10.1016/j.ecolecon.2007.03.008>.
- Boyce, D.G., Lotze, H.K., Tittensor, D.P., Carozza, D.A., Worm, B., 2020. Future Ocean biomass losses may widen socioeconomic equity gaps. *Nat. Commun.* 11, 2235. <https://doi.org/10.1038/s41467-020-15708-9>.
- Bueno-Pardo, J., et al., 2021. Climate change vulnerability assessment of the main marine commercial fish and invertebrates of Portugal. *Sci. Rep.* 11, 2958. <https://doi.org/10.1038/s41598-021-82595-5>.
- Cala, B.A., Sulpis, O., Wolthers, M., Humphreys, M.P., 2024. Synthesis of in situ marine calcium carbonate dissolution kinetic measurements in the water column. *Glob. Biogeochem. Cycles* 38, e2023GB008009.
- Cao, L., et al., 2023. Vulnerability of blue foods to human-induced environmental change. *Nat. Sustainability* 6, 1186–1198. <https://doi.org/10.1038/s41893-023-01156-y>.
- Cazenave, A., Cozannet, G.L., 2014. Sea level rise and its coastal impacts. *Earth's Future* 2, 15–34. <https://doi.org/10.1002/2013EF000188>.
- Center For International Earth Science Information Network-CIESIN-Columbia University, 2017. Gridded population of the world, version 4 (GPWv4) (ed NASA socioeconomic Data and applications Center (SEDAC)), palisades, NY. <https://doi.org/10.7927/H49C6VHW>.
- Central Intelligence Agency, 2025. *The World Factbook 2025*. Washington, DC.
- Chapman, S., et al., 2014. Publishing trends on climate change vulnerability in the conservation literature reveal a predominant focus on direct impacts and long time-scales. *Divers. Distrib.* 20, 1221–1228. <https://doi.org/10.1111/ddi.12234>.
- Cinner, J., et al., 2013. Evaluating social and ecological vulnerability of coral reef fisheries to climate change. *PLoS One* 8, e74321. <https://doi.org/10.1371/journal.pone.0074321>.
- Core Data. Large Marine Ecosystems (Online Dataset) (2025). Accessed on 5 February 2025.
- DeBortoli, N.S., Clark, D.G., Ford, J.D., Sayles, J.S., Diaconescu, E.P., 2019. An integrative climate change vulnerability index for Arctic aviation and marine transportation. *Nat. Commun.* 10, 2596. <https://doi.org/10.1038/s41467-019-10347-1>.
- Ding, Q., Chen, X., Hilborn, R., Chen, Y., 2017. Vulnerability to impacts of climate change on marine fisheries and food security. *Mar. Policy* 83, 55–61. <https://doi.org/10.1016/j.marpol.2017.05.011>.
- Doléac, S., Lévy, M., El Hourany, R., Bopp, L., 2025. Toward more robust net primary production projections in the North Atlantic Ocean. *Biogeosciences* 22, 841–862. <https://doi.org/10.5194/bg-22-841-2025>.
- Doney, S.C., Fabry, V.J., Feely, R.A., Kleypas, J.A., 2009. Ocean acidification: the other CO2 problem. *Ann. Rev. Mar. Sci.* 1, 169–192. <https://doi.org/10.1146/annurev.marine.010908.163834>.
- Er Kara, M., Ghadge, A., Bititci, U.S., 2021. Modelling the impact of climate change risk on supply chain performance. *Int. J. Prod. Res.* 59, 7317–7335. <https://doi.org/10.1080/00207543.2020.1849844>.
- Erskine, E., Baillie, R., Lusseau, D., 2021. Marine protected areas provide more cultural ecosystem services than other adjacent coastal areas. *One Earth* 4, 1175–1185. <https://doi.org/10.1016/j.oneear.2021.07.014>.
- Estes, J.A., Heithaus, M., McCauley, D.J., Rasher, D.B., Worm, B., 2016. Megafaunal impacts on structure and function of ocean ecosystems. *Annu. Rev. Environ. Resour.* 41, 83–116. <https://doi.org/10.1146/annurev-environ-110615-085622>.
- European Environment Agency, 2018. Common International Classification of Ecosystem Services (CICES) V5.1.
- FAO. Food balance sheets and supply utilization accounts resource handbook 2025. FAO statistical development series 148 (FAO, 2025). Doi: <https://doi.org/10.4060/cd4472en>.
- Feng, M., et al., 2021. Multi-year marine cold-spells off the west coast of Australia and effects on fisheries. *J. Mar. Syst.* 214, 103473. <https://doi.org/10.1016/j.jmarsys.2020.103473>.
- Filho, L.M., Roebeling, P., Villasante, S., Bastos, M.I., 2022. Ecosystem services values and changes across the Atlantic coastal zone: considerations and implications. *Mar. Policy* 145, 105265. <https://doi.org/10.1016/j.marpol.2022.105265>.
- Flanders Marine Institute, 2025. Maritime Boundaries Geodatabase, version 12. <https://doi.org/10.14284/628>. Accessed on 10th July 2025.
- Fox-Kemper, B. in AGU fall meeting abstracts. U13B-09.
- Frölicher, T.L., Fischer, E.M., Gruber, N., 2018. Marine heatwaves under global warming. *Nature* 560, 360–364. <https://doi.org/10.1038/s41586-018-0383-9>.
- Giddens, J., et al., 2022. Assessing the vulnerability of marine life to climate change in the Pacific Islands region. *PLoS One* 17, e0270930. <https://doi.org/10.1371/journal.pone.0270930>.
- Glibert, P.M., et al., 2022. Stressing over the complexities of multiple stressors in marine and estuarine systems. *Ocean-Land-Atmos. Res.* 2022. <https://doi.org/10.34133/2022/9787258>.
- Gruber, N., 2011. Warming up, turning sour, losing breath: ocean biogeochemistry under global change. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* 369, 1980–1996.

- Gutiérrez-Bravo, J.G., et al., 2024. Anoxic waters constrain the vertical distribution of fish developmental stages in an oxygen minimum zone. *Limnol. Oceanogr.* 69, 1521–1534.
- Haines-Young, R., Potschin, M., 2012. Common international classification of ecosystem services (CICES, version 4.1). European Environment Agency, p. 107, 33.
- Hamilton, L.C., Brown, B.C., Rasmussen, R.O., 2003. West Greenland's cod-to-shrimp transition: local dimensions of climatic change. *Arctic* 56, 271–282.
- Henson, S.A., et al., 2010. Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. *Biogeosciences* 7, 621–640. <https://doi.org/10.5194/bg-7-621-2010>.
- Hobday, A.J., et al., 2016. A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr.* 141, 227–238. <https://doi.org/10.1016/j.pocean.2015.12.014>.
- Hobday, A.J., Pecl, G.T., 2014. Identification of global marine hotspots: sentinels for change and vanguards for adaptation action. *Rev. Fish Biol. Fish.* 24, 415–425. <https://doi.org/10.1007/s11160-013-9326-6>.
- Horta e Costa, B., et al., 2025. Marine protected areas stage of establishment and level of protection are good predictors of their conservation outcomes. *Cell Rep. Sustain.* 2, 100345. <https://doi.org/10.1016/j.crsus.2025.100345>.
- Hughes, S., et al., 2012. A framework to assess national level vulnerability from the perspective of food security: the case of coral reef fisheries. *Environ. Sci. Policy* 23, 95–108. <https://doi.org/10.1016/j.envsci.2012.07.012>.
- IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1535.
- Jackson, L.P., Jevrejeva, S., 2016. A probabilistic approach to 21st century regional sea-level projections using RCP and high-end scenarios. *Glob. Planet. Change* 146, 179–189.
- Jackson-Buée, M., et al., 2022. Inter-country differences in the cultural ecosystem services provided by cockles. *People Nat.* 4, 71–87. <https://doi.org/10.1002/pan3.10252>.
- Jevrejeva, S., Williams, J., Voudoukas, M.I., Jackson, L.P., 2023. Future Sea level rise dominates changes in worst case extreme sea levels along the global coastline by 2100. *Environ. Res. Lett.* 18, 024037.
- Jönsson, J.H., Kamali, M., 2012. Fishing for development: a question for social work. *Int. Soc. Work.* 55, 504–521. <https://doi.org/10.1177/0020872812436625>.
- Kaschner, K., Tittensor, D.P., Ready, J., Gerrodette, T., Worm, B., 2011. Current and future patterns of global marine mammal biodiversity. *PLoS One* 6, e19653. <https://doi.org/10.1371/journal.pone.0019653>.
- Kelly, S., et al., 2025. Abrupt changes in the timing and magnitude of the North Atlantic bloom over the 21st century. *J. Geophys. Res. Oceans* 130, e2024JC022284. <https://doi.org/10.1029/2024JC022284>.
- Kesner-Reyes, K., Garilao, C., Kaschner, K., Barile, J., Froese, R., 2016. AquaMaps: algorithm and data sources for marine organisms (eds Rainer Froese & Daniel Pauly).
- Klain, S.C., Satterfield, T.A., Chan, K.M.A., 2014. What matters and why? Ecosystem services and their bundled qualities. *Ecol. Econ.* 107, 310–320. <https://doi.org/10.1016/j.ecolecon.2014.09.003>.
- Kleisner, K.M., et al., 2021. Identifying policy approaches to build social–ecological resilience in marine fisheries with differing capacities and contexts. *ICES J. Mar. Sci.* 79, 552–572. <https://doi.org/10.1093/icesjms/fsab080>.
- Kroecker, K.J., et al., 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Glob. Chang. Biol.* 19, 1884–1896.
- Lam, V.W.Y., et al., 2020. Climate change, tropical fisheries and prospects for sustainable development. *Nat. Rev. Earth Environ.* 1, 440–454. <https://doi.org/10.1038/s43017-020-0071-9>.
- Laufkötter, C., Zscheischler, J., Frölicher, T.L., 2020. High-impact marine heatwaves attributable to human-induced global warming. *Science* 369, 1621–1625. <https://doi.org/10.1126/science.aba0690>.
- Lovelock, C.E., Reef, R., 2020. Variable impacts of climate change on blue carbon. *One Earth* 3, 195–211. <https://doi.org/10.1016/j.oneear.2020.07.010>.
- Luisetti, T., et al., 2011. Coastal and marine ecosystem services valuation for policy and management: managed realignment case studies in England. *Ocean Coastal Manag.* 54, 212–224. <https://doi.org/10.1016/j.ocecoaman.2010.11.003>.
- Lynham, J., Villaseñor-Derbez, J.C., 2024. Evidence of spillover benefits from large-scale marine protected areas to purse seine fisheries. *Science* 386, 1276–1281. <https://doi.org/10.1126/science.adn1146>.
- Macreadie, P.I., et al., 2019. The future of blue carbon science. *Nat. Commun.* 10, 3998. <https://doi.org/10.1038/s41467-019-11693-w>.
- Madec, G., et al., 2013. NEMO ocean engine. Notes du Pôle de modélisation de l'Institut Pierre-Simon Laplace (IPSL) (v4.0, Number 27). <https://doi.org/10.5281/zenodo.3878122>.
- Magalhães Filho, L.N.L., Roebeling, P.C., Costa, L.F.C., de Lima, L.T., 2022. Ecosystem services values at risk in the Atlantic coastal zone due to sea-level rise and socioeconomic development. *Ecosyst. Serv.* 58, 101492. <https://doi.org/10.1016/j.ecoser.2022.101492>.
- Mentaschi, L., Voudoukas, M.I., Voukouvalas, E., Dosio, A., Feyen, L., 2017. Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns. *Geophys. Res. Lett.* 44, 2416–2426. <https://doi.org/10.1002/2016GL072488>.
- Mester, B., et al., 2023. Human displacements from tropical cyclone Idai attributable to climate change. *Nat. Hazards Earth Syst. Sci.* 23, 3467–3485. <https://doi.org/10.5194/nhess-23-3467-2023>.
- Moerlein, K.J., Carothers, C., 2012. Total environment of change: impacts of climate change and social transitions on subsistence fisheries in Northwest Alaska. *Ecol. Soc.* 17.
- Mooney, H., et al., 2009. Biodiversity, climate change, and ecosystem services. *Curr. Opin. Environ. Sustain.* 1, 46–54. <https://doi.org/10.1016/j.cosust.2009.07.006>.
- Mulcahy, J.P., et al., 2023. UKESM1.1: development and evaluation of an updated configuration of the UK earth system model. *Geosci. Model Dev.* 16, 1569–1600. <https://doi.org/10.5194/gmd-16-1569-2023>.
- O'Neill, B.C., et al., 2016. The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.* 9, 3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>.
- Ogier, E.M., et al., 2025. Novel marine-climate interventions hampered by low consensus and governance preparedness. *Nature Climate Change* 15, 375–384. <https://doi.org/10.1038/s41558-025-02291-4>.
- Ottaviani, D., 2020. In: FAO (Ed.), *Economic Value of Ecosystem Services from the Deep Seas and the Areas beyond National Jurisdiction*.
- Pauly, D., Zeller, D., Palomares, M.L.D., 2020. Sea Around Us Concepts, Design and Data. searounds.us.
- Pecl, G.T., et al., 2017. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* 355, eaai9214. <https://doi.org/10.1126/science.aai9214>.
- Pinsky, M.L., Selden, R.L., Kitchel, Z.J., 2020. Climate-driven shifts in marine species ranges: scaling from organisms to communities. *Ann. Rev. Mar. Sci.* 12, 153–179. <https://doi.org/10.1146/annurev-marine-010419-010916>.
- Poe, M.R., Norman, K.C., Levin, P.S., 2014. Cultural dimensions of socioecological systems: key connections and guiding principles for conservation in coastal environments. *Conserv. Lett.* 7, 166–175. <https://doi.org/10.1111/conl.12068>.
- Popova, E., et al., 2016. From global to regional and back again: common climate stressors of marine ecosystems relevant for adaptation across five ocean warming hotspots. *Glob. Chang. Biol.* 22, 2038–2053. <https://doi.org/10.1111/gcb.13247>.
- Possley, J., et al., 2024. First US vascular plant extirpation linked to sea level rise? *Pilosocereus millsapughii* (Cactaceae) in the Florida keys, USA. *J. Botanical Res. Inst. Texas* 18, 211–223.
- Refugio-Coronado, S., et al., 2021. Coastal and marine socio-ecological systems: a systematic review of the literature. *Front. Mar. Sci.* 8. <https://doi.org/10.3389/fmars.2021.648006>.
- Reid, P.C., et al., 2009. Chapter 1 Impacts of the Oceans on Climate Change. In: *Advances in Marine Biology*, 56. Academic Press, pp. 1–150. [https://doi.org/10.1016/S0065-2881\(09\)56001-4](https://doi.org/10.1016/S0065-2881(09)56001-4).
- Reyes-Mendoza, O., Manta, G., Carrillo, L., 2022. Marine heatwaves and marine cold-spells on the Yucatan shelf-break upwelling region. *Cont. Shelf Res.* 239, 104707. <https://doi.org/10.1016/j.csr.2022.104707>.
- Ritchie, J., Dowlatabadi, H., 2017. Why do climate change scenarios return to coal? *Energy* 140, 1276–1291. <https://doi.org/10.1016/j.energy.2017.08.083>.
- Ryabinin, V., et al., 2019. The UN decade of ocean science for sustainable development. *Front. Mar. Sci.* 6. <https://doi.org/10.3389/fmars.2019.00470>.
- Schlegel, R.W., Oliver, E.C.J., Wernberg, T., Smit, A.J., 2017. Nearshore and offshore co-occurrence of marine heatwaves and cold-spells. *Prog. Oceanogr.* 151, 189–205. <https://doi.org/10.1016/j.pocean.2017.01.004>.
- Scott, C.P., Mach, L., Lucas, K.M., Myers, A.E., 2024. Whose cultural ecosystem service values matter? Exploring power inequities in diverse mangrove communities. *Hum. Ecol.* 52, 81–97. <https://doi.org/10.1007/s10745-023-00462-5>.
- Steiner, N.S., et al., 2021. Climate change impacts on sea-ice ecosystems and associated ecosystem services. *Elementa: Sci. Anthropocene* 9. <https://doi.org/10.1525/elementa.2021.00007>.
- Stewart-Sinclair, P.J., Last, K.S., Payne, B.L., Wilding, T.A., 2020. A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. *Ecol. Evol.* 10, 3518–3534. <https://doi.org/10.1002/ece3.6149>.
- Stocker, T.F., 2015. The silent services of the world ocean. *Science* 350, 764–765. <https://doi.org/10.1126/science.aac8720>.
- Syddall, V., Thrush, S., Fisher, K., 2021. Transdisciplinary analysis of Pacific tuna fisheries: a research framework for understanding and governing oceans as social-ecological systems. *Mar. Policy* 134, 104783. <https://doi.org/10.1016/j.marpol.2021.104783>.
- Tagliabue, A., et al., 2021. Persistent uncertainties in ocean net primary production climate change projections at regional scales raise challenges for assessing impacts on ecosystem services. *Front. Clim.* 3. <https://doi.org/10.3389/fclim.2021.738224>.
- Townhill, B.L., Couce, E., Tinker, J., Kay, S., Pinnegar, J.K., 2023. Climate change projections of commercial fish distribution and suitable habitat around north western Europe. *Fish Fish.* 24, 848–862. <https://doi.org/10.1111/faf.12773>.
- Tyson, R.V., Pearson, T.H., 1991. Modern and ancient continental shelf anoxia: an overview. *Geol. Soc. Lond. Spec. Publ.* 58, 1–24.
- UNCTAD, 2021. Towards a Harmonized International Trade Classification for the Development of Sustainable Oceans-based Economies. United Nations.
- UNCTAD, 2024. Port liner shipping connectivity index, quarterly. <https://unctadstat.unctad.org/datacentre/dataviewer/US.PLSCI>.
- UNEP-WCMC, 2025. Ocean+ Habitats. UNEP-WCMC, Cambridge, UK. <https://doi.org/10.34892/fpe3-ar97>.
- UNEP-WCMC, IUCN, 2025. In: UNEP-WCMC (Ed.), *Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-Based Conservation Measures (WD-OECM)*. IUCN, Cambridge, UK.
- UNEP-WCMC, WorldFish Centre, WRI, TNC, 2021. Global distribution of warm-water coral reefs, compiled from multiple sources including the Millennium Coral Reef Mapping Project. <https://doi.org/10.34892/i2wv-5t34>.
- UNESCO, 2024. Institute for Statistics (UIS), via World Bank (2025) – processed by our world in Data. Adult Literacy Rate.
- Vallury, S., et al., 2022. Adaptive capacity beyond the household: a systematic review of empirical social-ecological research. *Environ. Res. Lett.* 17, 063001.

- Vancoppenolle, M., et al., 2023. SI3, the NEMO Sea ice engine (V4.2release_doc1.0). Zenodo. <https://doi.org/10.5281/zenodo.7534900>.
- Visbeck, M., 2018. Ocean science research is key for a sustainable future. *Nat. Commun.* 9, 690. <https://doi.org/10.1038/s41467-018-03158-3>.
- von Schuckmann, K., Gues, F., Moreira, L., Liné, A., de Pascual Collar, Á., 2025. Ocean change in the northeastern Atlantic and adjacent seas: a multi-dimensional challenge for the environment, society, and economy, 9th edition of the Copernicus Ocean State Report (OSR9) 6-osr9, 3 (. <https://doi.org/10.5194/sp-6-osr9-3-2025>.
- Vousdoukas, M.I., et al., 2018. Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nat. Commun.* 9, 2360. <https://doi.org/10.1038/s41467-018-04692-w>.
- Wabnitz, C.C.C., et al., 2018. Climate change impacts on marine biodiversity, fisheries and society in the Arabian gulf. *PLoS One* 13, e0194537. <https://doi.org/10.1371/journal.pone.0194537>.
- Warner, K., van der Geest, K., 2013. Loss and damage from climate change: local-level evidence from nine vulnerable countries. *Int. J. Glob. Warm.* 5, 367–386. <https://doi.org/10.1504/ijgw.2013.057289>.
- World Bank, 2024a. *The Changing Wealth of Nations 2024: Revisiting the Measurement of Comprehensive Wealth*. World Bank, Washington DC.
- World Bank (Ed.), 2024b. *Health, Nutrition and Population Statistics: Life Expectancy at Birth, Total (Years)* (Ed World Bank). HealthStats, World Bank Group. <https://data.worldbank.org/indicator/SP.DYN.LE00.IN>.
- World Bank, 2024c. *Worldwide Governance Indicators, 2024 Update*. www.govindicators.org.
- World Bank, 2024d. *World Development Indicators: GNI Per Capita, Atlas Method (Current US\$)*. <https://data.worldbank.org/indicator/NY.GNP.PCAP.CD>.
- Xu, L., et al., 2025. Global coastal human settlement retreat driven by vulnerability to coastal climate hazards. *Nat. Clim. Chang.* <https://doi.org/10.1038/s41558-025-02435-6>.
- Yool, A., et al., 2021. Evaluating the physical and biogeochemical state of the global ocean component of UKESM1 in CMIP6 historical simulations. *Geosci. Model Dev.* 14, 3437–3472.
- Yool, A., Popova, E., Anderson, T.R., 2013. MEDUSA-2.0: an intermediate complexity biogeochemical model of the marine carbon cycle for climate change and ocean acidification studies. *Geosci. Model Dev.* 6, 1767–1811. <https://doi.org/10.5194/gmd-6-1767-2013>.