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Ocean change in the northeastern Atlantic and adjacent seas: a multi-dimensional challenge for the environment, society, and economy

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Abstract. An ocean narrative is a powerful tool for making complex ocean changes better accessible while informing decision-making and inspiring collective action. This ocean narrative reports on ocean change in the northeastern Atlantic and adjacent seas and discusses its broader implications for Europe's environment, economy, and society. The region is experiencing warming and acidification at rates exceeding the global average, with rising sea levels and record severe marine heatwaves (MHWs). These changes threaten marine ecosystems, biodiversity, cultural heritage, and key economic sectors, such as aquaculture and coastal tourism, which rely heavily on the balance and the health of the ocean. This ocean narrative emphasizes the importance of regional ocean indicators for the northeastern Atlantic and adjacent seas and underscores the importance of localized responses, as ocean changes affect regions differently, particularly in semi-enclosed seas such as the Baltic Sea, the Black Sea, and the Mediterranean Sea. The findings stress the urgency of timely action and the need to strengthen evidence-based and strategic ocean knowledge transfer at the science and policy interface for informed decision-making that balances environmental sustainability, economic resilience, and social inclusivity to address the growing challenges of ocean change in the northeastern Atlantic and its adjacent seas.

1 Introduction

The ocean plays a central role in Europe's climate, environment, and society. It acts as a climate regulator by absorbing heat and carbon dioxide (IPCC, 2021), helps drive weather and climate patterns, and supports diverse marine ecosystems that are essential to biodiversity and food security (IOC-UNESCO, 2024; IPBES, 2019; IPCC, 2022). Coastal regions and economies across Europe and abroad rely on the ocean for e.g. fisheries, tourism, transport, and renewable energy (Cramer et al., 2020; Martínez-Vázquez et al., 2021; Mejjad et al., 2022). In addition to its ecological and economic importance, the ocean is deeply connected to European culture and heritage (Delaney and Frangoudes, 2024). As a dynamic and interconnected system, the health and environmental balance of Europe's seas is critical – not only for marine life but also for the wellbeing and resilience of communities across the continent. The ocean in the northeastern Atlantic and its surrounding seas is undergoing rapid and profound change (von Schuckmann et al., 2024). As outlined in the previous Copernicus Ocean State Report, issue 8, temperatures are rising at more than twice the global average, especially in the Baltic, Black, and Mediterranean seas, where warming has become a persistent trend. Sea levels are steadily increasing, ocean waters are growing more acidic, and marine heatwaves (MHWs) are becoming more frequent, intense, and widespread.

Focusing on regional ocean indicators, rather than solely global ones, is essential because ocean conditions can vary significantly across different areas due to factors such as climate variability patterns, currents, and other region-specific ocean and atmospheric dynamics. Regional indicators pro-

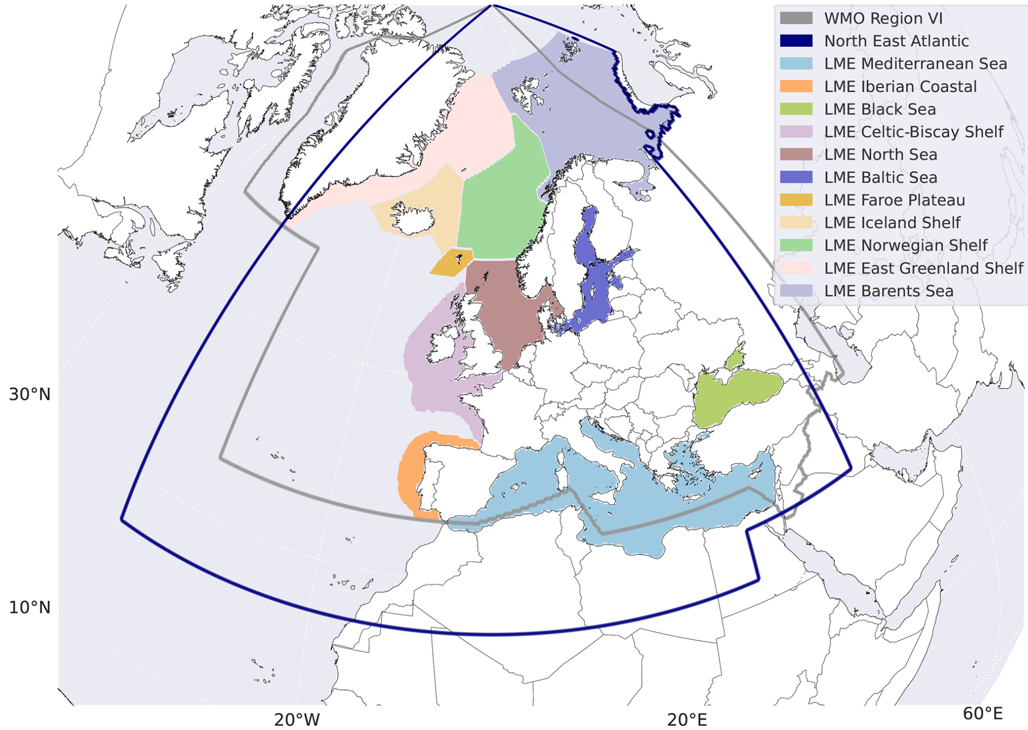

Figure 1. Illustration of the definition of the northeastern Atlantic and adjacent seas (inside the blue polygon, as in the OSR8), the WMO's delineation of Europe (inside the grey polygon), and large marine ecosystems (LMEs; Sherman, 2005; product ref. no. 1, in colours).

vide a more detailed picture of how the ocean is changing in a specific area, which is crucial for e.g. efficient regional to national management and adaptation strategies (Winther et al., 2020). The regionalization approach can vary (Fig. 1), ranging from multilateral frameworks, such as the World Meteorological Organization (WMO; WMO Regions, 2025) or the Copernicus Ocean State Report (von Schuckmann et al., 2024), to more specific models, such as large marine ecosystems (LMEs) (Sherman, 2005). LMEs encompass coastal areas, from river basins and estuaries to the seaward boundaries of continental shelves, and enclosed and semi-enclosed seas and the outer margins of major current systems. They are of significant socioeconomic importance, as they account for the majority of global fisheries biomass (Guiet et al., 2025; Sherman et al., 2009). However, these ecosystems also face challenges, including ocean pollution, overexploitation, and the alteration of coastal habitats, all of which occur within their boundaries (Sherman, 2005).

Here, we provide an ocean narrative to tell a compelling story that communicates the ongoing change in the northeastern Atlantic and adjacent seas in relation to people and the planet. It connects scientific understanding with social, economic, and cultural dimensions, helping audiences grasp why changes in the ocean matter. By connecting these dimensions, the ocean narrative helps make complex changes in the marine environment more relatable and relevant. It aims not only to raise awareness but also to shape how we perceive risks, responsibilities, and opportunities – ultimately encouraging informed decisions and collective action for a sustainable ocean future.

2 Method

This study employs a structured multi-indicator approach to describe and assess the state of the ocean in the northeastern Atlantic and adjacent seas. The analysis is grounded in a core set of ocean indicators, which include surface and subsurface ocean warming, surface ocean acidification, sea level rise, and marine heatwaves. These indicators are derived using scientifically validated methods and form part of the Copernicus Ocean Indicator Framework (see Product Table, Supplement).

Primary data sources include products from the Copernicus Marine Service, which are supplemented, where available, by additional publicly accessible datasets to enhance spatial and temporal coverage. A multi-product methodology is applied wherever feasible, combining data from different ocean products. This approach enables an assessment of internal consistency and uncertainty by comparing the spread across product ensembles. Uncertainty ranges are obtained using standard deviation at the 95 % confidence level. A regional trend amplified compared to the global trend implies that the 95 % range of the local trend exceeds the global trend. All datasets utilized are documented and referenced in the product table, including links to associated metadata and scientific publications (see Supplement). Each ocean indicator has been updated with the most recent data available at the time of analysis, subject to product-specific update frequencies and data availability constraints.

To integrate the physical changes in the marine environment with broader sustainable development perspectives, additional datasets from the economic and social domains were included. This integrative approach reflects the three pillars of sustainability: environmental, economic, and social. Only data that are publicly available and accompanied by appropriate metadata were used. Metadata documentation and source references are provided in the product table. The three domains – environment, economy, and society – were then brought together to develop an ocean narrative, supported by peer-reviewed scientific knowledge with analysis interlinking ocean and biodiversity change to socioeconomic evidence, aimed at contextualizing observed and reported changes. This narrative is not intended as a new quantitative scientific analysis, but rather as a synthesis of available evidence-based and scientific information to support decision-making and communication. Scientific rigour is maintained by basing this synthesis on peer-reviewed literature and established datasets, ensuring an evidence-based narrative framework.

3 An ocean narrative for the northeastern Atlantic and adjacent seas

Ocean change in the northeastern Atlantic and adjacent seas is widespread from the surface to the ocean abyss. Regional mean sea surface and subsurface ocean warming are higher than the global trends, with rates of $+0.27 \pm 0.04$ °C per decade between 1982–2024 and $+0.41 \pm 0.03\,\mathrm{W\,m^{-2}}$ per decade between 1960–2024 (Fig. 2a, b). Ocean acidification in the northeastern Atlantic and adjacent seas continues at a rate comparable to the global trend, with a pH decline of -0.017 ± 0.001 units per decade between 1985 and 2023 (Fig. 2c). The warming and acidification trends are consistent across various large-scale regional definitions, whether based on the WMO's delineation of Europe or the aggregation of Europe's LMEs (Fig. 2c). Sea level is rising in this area at an average trend of $+3.7 \pm 0.8\,\mathrm{mm\,yr^{-1}}$ between 1999–2024 (EU Copernicus Marine Service Information, 2024), affecting the entire area. Since 1982, marine heatwaves in the northeastern Atlantic and adjacent seas have become more frequent, intense, and widespread (von Schuckmann et al., 2024). Marine heatwaves of categories extreme and severe over that period (see Hobday et al., 2016, for definitions) lasting at least 5 d have barely increased in mean duration (+11 %), from an average of 8 d per event in the 1990s (1993–2002) to 9 d per event over the past decade (2015–2024) (Fig. 2e).

Ocean change is not uniform. Semi-enclosed basins, such as the Baltic, Black, and Mediterranean seas, are experiencing the most rapid warming due to limited exchange with the open ocean (Fig. 2a). The Faroe Plateau, Iberian coast, and Celtic-Biscay Shelf show lower warming rates compared to other European seas, though they still exceed the global average (Fig. 2a). These regions lie close to the open Atlantic, where long-term warming interacts with pronounced natural variability (Årthun et al., 2021; Jackson et al., 2022). Also, ocean acidification patterns vary locally, with the Mediterranean Sea and the subtropical Atlantic showing a more rapid decline in pH, indicating intensified acidification in these areas (Fig. 3).

Ocean warming and acidification are well-documented stressors that exceed tolerance thresholds for many marine species, driving habitat loss, population declines, and disruptions to ecosystem functioning and services (Bindoff et al., 2019; Cooley et al., 2022). All United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage marine sites in the northeastern Atlantic and adjacent seas are experiencing rapid ocean surface warming at rates exceeding the global average (Fig. 3), which are recognized for their unique marine biodiversity, exceptional ecosystems, remarkable geological processes, or unparalleled beauty, with the aim of ensuring their conservation for future generations (UNESCO, 1972). They represent some of the most iconic and fragile marine environments on Earth, and their status provides the potential for a comprehensive policy framework that allows their identification, management, governance, and protection (Abdulla et al., 2014). However, their conservation status remains relatively unknown (Kuempel et al., 2022), although ocean changes from global warming are putting pressure in these unique environments (Fig. 3).

The years 2023 and 2024 stand out in the historical record (Guinaldo et al., 2025; Terhaar et al., 2025), marking the longest average duration of marine heatwaves observed across the northeastern Atlantic and adjacent seas (Fig. 4). In 2023 alone, around one-third of these waters experienced severe to extreme marine heatwaves, with prolonged events lasting up to 4 months (von Schuckmann et al., 2024). In 2024, the eastern Mediterranean and Black seas, the Bay of Biscay, and the subtropical Atlantic were hit by severe to extreme marine heatwave events (Fig. 4). The northern Mediterranean Sea, Black Sea, and Baltic Sea have experienced recurring (three times or more since 1982) persistent (> 38 d duration and mean sea surface temperature (SST) anomaly exceeding 2.3 °C; Mignot et al., 2022) MHWs that can harm marine life by causing mass die-offs, pushing species to new areas, and disrupting the balance of ocean ecosystems when temperatures get too high (Garrabou et al., 2022; Scannell et al., 2024).

About 17 % of the cold-water corals and 50 % of seagrass in the northeastern Atlantic and adjacent seas experienced extreme and long-lasting MHWs in 2024 (Fig. 4). Marine

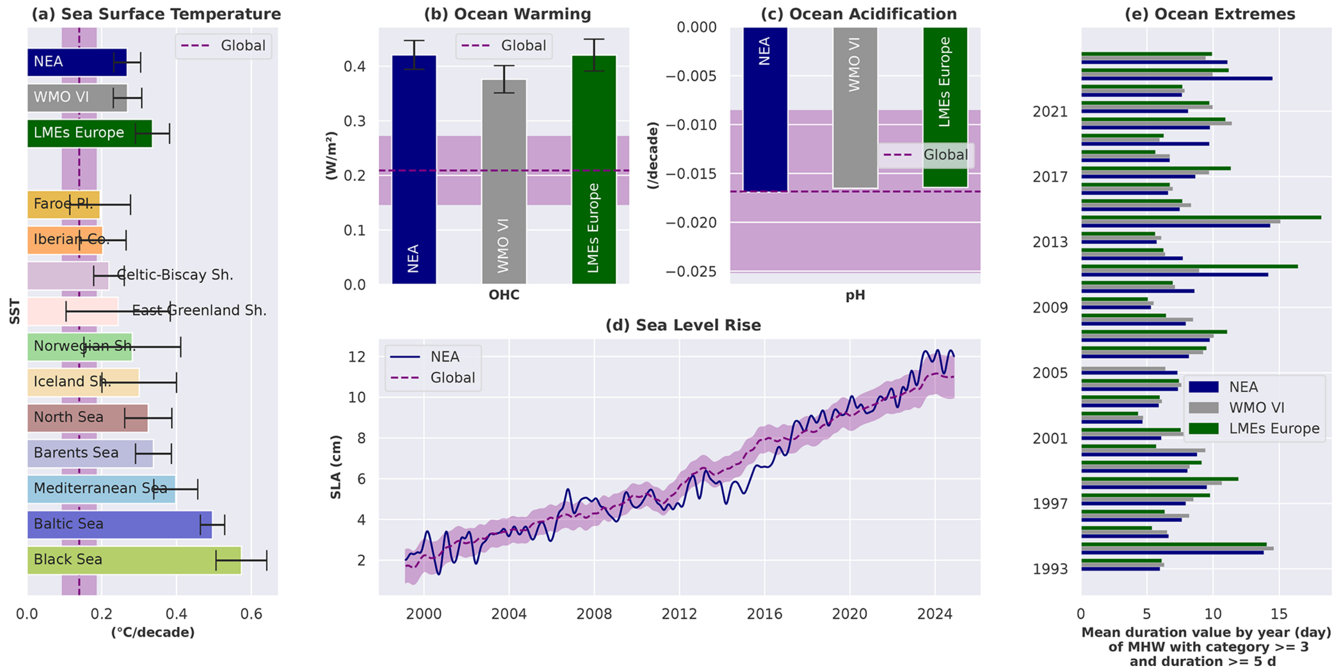

Figure 2. Current state of the northeastern Atlantic and adjacent seas based on a core set of ocean indicators. **(a)** Decadal trends in sea surface temperature (SST; product ref. nos. 2 and 3) anomalies (relative to 1991–2020) for the northeastern Atlantic and adjacent seas (blue), the WMO's delineation of Europe (grey), all large marine ecosystems (LMEs; product ref. no. 1) taken together (green), and each LME taken alone (other colours) for the period 1982–2024. Whiskers indicate the 95 % uncertainty range obtained by considering product ref. nos. 2–5, 28, and 29. The dashed purple line and shadow indicate the global average and its uncertainty envelope. **(b)** Same as panel **(a)** for the trends in ocean heat content (OHC; product ref. nos. 6 and 7) anomalies (relative to 1991–2020) integrated over the upper 300 m depth for the period 1960–2024. Whiskers indicate the 95 % obtained by considering product ref. nos. 6–10. The dashed purple line and shadow indicate the global average and its uncertainty envelope. **(c)** Same as panel **(a)** for the trends in pH for the period 1985–2022 for the global, and 1985–2023 for all regions, based on product ref. nos. 11 and 12. The dashed purple line and shadow indicate the global average and its uncertainty envelope. **(d)** Sea level rise (SLR; product ref. nos. 13 and 14) in the northeastern Atlantic and adjacent seas (blue) and at the global scale (purple and its uncertainty envelope shaded) for the period 1999–2024. **(e)** Annual mean duration of marine heat waves (MHWs) of category 3 and above, lasting at least 5 d, in the northeastern Atlantic and adjacent seas (blue), the WMO's delineation of Europe (grey), and all large marine ecosystems (LMEs) taken together (green) for the period 1993–2024 (climatology 1993–2022) based on product ref. nos. 15 and 16.

heatwaves, particularly the most persistent ones, induce loss of seagrass canopy and severe coral bleaching (Chapron et al., 2021; Corinaldesi et al., 2022; Frölicher et al., 2018; Gómez et al., 2022; Marzonie et al., 2023; Orenes-Salazar et al., 2023; Serrano et al., 2021; Strydom et al., 2020). Cold-water corals – which live in many areas of the northeastern Atlantic and adjacent seas – create habitat structure, host endemic species, sequester carbon, and provide many other ecosystem services (Cordes et al., 2023). Seagrass is a natural attribute of World Heritage properties (UNESCO, 2008), and seagrass habitats are one of the largest natural carbon sinks on the planet (Losciale et al., 2024). Since the start of the century, approximately 19 % of global seagrass coverage has been lost due to the cumulative impacts of direct anthropogenic and climate stressors (Dunic et al., 2021; Dunic and Côté, 2023).

All ocean regions adjacent to countries producing over 5000 t of aquaculture annually are undergoing rates of surface ocean warming and acidification faster than the global average (Fig. 3). Countries bordering the Mediterranean, southern Baltic, and southern North seas and the Bay of Biscay – where aquaculture production of fish, crustaceans, molluscs, and other aquatic organisms is high – are experiencing simultaneous rapid ocean warming and acidification, putting this economically important sector at increasing risk from climate change (Stewart-Sinclair et al., 2020). Altogether, 17 % of shellfish farms along European coasts are located in seas that experienced severe to extreme marine heatwaves in 2024 (Fig. 4). In particular, areas around shellfish farms in the eastern Mediterranean Sea, in the Bay of Biscay, and along the coast of Norway experienced extreme conditions. Marine heatwaves induce stress in species, leading to weight loss, impaired nutrient absorption, and disrupted physiological functions, which adversely affect shellfish welfare and reduce the productivity of the affected aquaculture industry (Kajtar et al., 2024; De Marco et al., 2023; Masanja et al.,

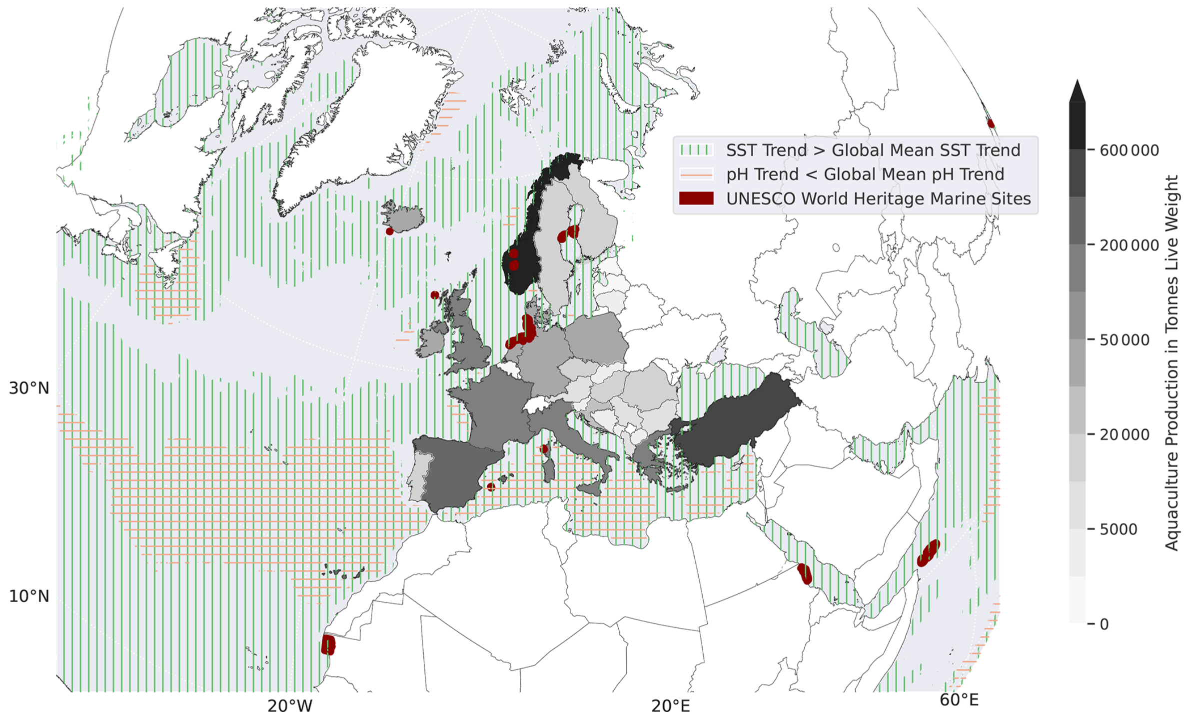

Figure 3. Aquaculture production and UNESCO World Heritage marine sites in a warmed and acidified ocean. Total production of fish, crustaceans, molluscs, and other aquatic organisms from aquaculture, excluding hatcheries and nurseries, in European countries (shown on land) in 2023 (or latest available data; see product ref. no. 17 for more information) (grey gradient). Vertical hatching represents where 95 % of the local sea surface temperature (SST) trend range surpasses the global average trend for the period 1982–2024 based on the product ref. nos. 2–5, 28, and 29. Horizontal hatching is the same but for the pH trend for the period 1985–2022 based on product ref. no. 18. Brown dots and polygons represent marine UNESCO sites (product ref. no. 19).

2023). Monitoring and forecasting marine heatwaves helps aquaculture adapt by allowing early action to reduce losses and protect vulnerable food systems and coastal communities (Masanja et al., 2024).

In the northeastern Atlantic and adjacent seas in 2024, major marine heatwave events of extreme to severe category were located adjacent to countries where 40 %–80 % of blue economy employment relies on coastal tourism (Fig. 4). Marine industries, such as fisheries, aquaculture, and tourism, face increasing risk from extreme climate events such as marine heatwaves, as they disrupt ecosystem functions and services and human–ocean interactions and lead to economic losses (Schaeffer et al., 2023; Smith et al., 2021). For example, loss of marine habitats (Garrabou et al., 2022) or invasive species as observed during marine heatwave events is one of the most profound implications on coastal and marine tourism, as it reduces the destination's attractiveness and degradation of landscapes, particularly where the natural attributes are of high value (Arabadzhyan et al., 2020; Cuttler et al., 2018; Marshall et al., 2013; Scott et al., 2012a, b; Wong et al., 2024; Zeppel and Beaumont, 2012). This in turn induces changes in tourism flows, leading to substantial geospatial shifts in economic costs and benefits associated with tourism revenue and coastal infrastructure protection, repair, and restoration (Arabadzhyan et al., 2020; Bayraktarov et al., 2016; Weatherdon et al., 2016). Regular monitoring and seasonal forecasts of marine heatwaves provide a powerful tool to reduce risks, enabling economy actors to act early and build resilience (Hartog et al., 2023; McAdam et al., 2023).

Fast-rising sea levels increase flood and erosion risks, and hence the loss of property and livelihoods, in areas where about 200 million people live on European coasts (Eurostat, 2025). All European countries with high near-coastal population densities (> 200 persons km^{-2}) border ocean areas where THE sea level is rising faster than the global average, particularly affecting some of the continent's most densely populated and vulnerable regions, such as the Netherlands (Fig. 5). Ocean change is also affecting cultural heritage. Numerous cultural UNESCO World Heritage sites are in low-lying coastal regions, and many of these sites will be partially or totally flooded in the coming centuries/millennia (Cazenave, 2014; Marzeion and Levermann, 2014). Several UNESCO-listed ancient coastal heritage sites in the Mediterranean Sea face sea level rise rates above the global average (Fig. 5) and are projected to be increasingly at risk from coastal hazards (flooding, erosion) due to sea level rise (Reimann et al., 2018).

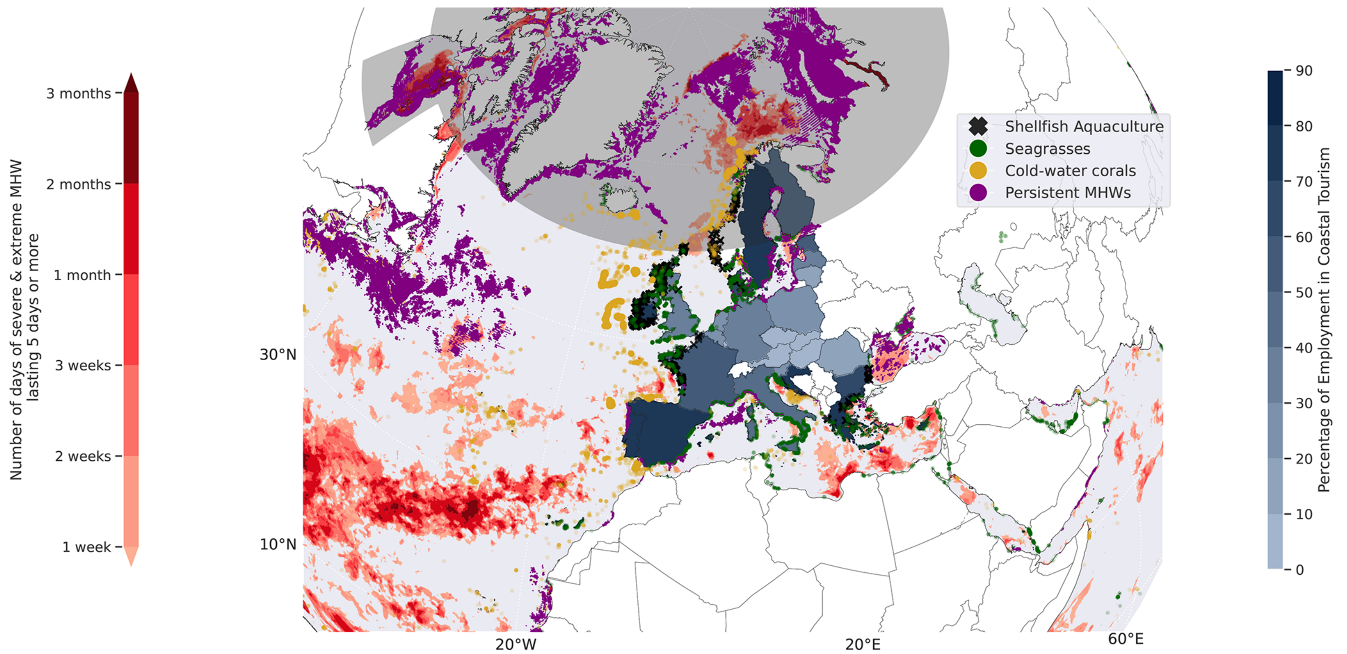

Figure 4. Biodiversity and coastal employment exposition to marine heat waves. Cumulative number of marine heatwave (MHW) days (method following Hobday et al., 2016), considering categories 3 and above, lasting 5 d or more in 2024 based on the product ref. nos. 15 and 16 (red graduation). Purple shading represents satellite sea surface temperature (SST) grid points that have experienced at least three persistent marine heat waves (PMHWs) from 1993 to 2024 based on product ref. nos. 15 and 16. Grey shading represents the area above 60° N and the Hudson Bay, where the surface is partially and temporally covered by ice, implying potentially less accurate MHW detection. Percentage of employment in coastal tourism in European countries (shown on land) in 2017 based on product ref. no. 21. Black crosses show shellfish aquaculture (product ref. no. 22). Green dots show seagrasses (product ref. no. 23). Yellow dots show cold-water corals (product ref. no. 24). A cut-off criterion of 10 km (due to the data grid; product ref. nos. 15 and 16) has been used to obtain % estimates linking seagrass, cold-water corals, and shellfish aquaculture to extreme and long-lasting MHWs in 2024 (see text for more detail).

Lastly, this ocean narrative provides a valuable framework for connecting different regional indicators. For example, in the Aegean Sea, multiple facets of ocean change are intensifying, with increasing sea surface temperatures (SST), ocean acidification (pH), and sea level rise (SLR) and prolonged marine heatwave (MHW) durations. This region, rich in culture (home to coastal and marine UNESCO sites), environment (seagrass meadows), and economy (aquaculture, coastal tourism), faces an increasing imperative to adapt to these local changes. Similarly, the Cantabrian Sea illustrates how regional indicators can collectively signal alarming trends, threatening coral reefs, coastal UNESCO sites, and the livelihoods of the local population. The urgency to address these changes is amplified in areas where the environment, culture, and economy are intricately linked.

4 Conclusion

The northeastern Atlantic and adjacent seas are undergoing rapid and widespread ocean changes driven by warming, acidification, sea level rise, and intensifying marine heatwaves. These transformations present a critical barometer for Europe's ability to align environmental protection, economic resilience, and societal wellbeing within a forward-looking ocean strategy. Regional disparities, particularly in semi-enclosed basins such as the Baltic, Black, and Mediterranean seas, show that local conditions can significantly amplify global and large-scale ocean trends, highlighting the need for locally tailored responses within broader European ocean and climate strategies.

The impacts extend across all dimensions of sustainable development. Marine ecosystems are increasingly vulnerable, with important habitats, such as cold-water corals and seagrass beds, exposed to extreme and prolonged thermal stress. This not only undermines biodiversity and ecosystem services but also affects carbon sequestration and the ecological integrity of protected areas, including UNESCO World Heritage marine sites. Similarly, the risk to cultural heritage is rising, especially in low-lying coastal zones of the Mediterranean, where several UNESCO-listed sites face long-term threats from coastal hazards driven by sea level rise.

The economic implications are equally significant. Aquaculture and tourism – both cornerstones of the coastal blue economy – are already experiencing the consequences of ocean extremes. Without strengthened early warning systems and climate-smart adaptation, these sectors face growing un-

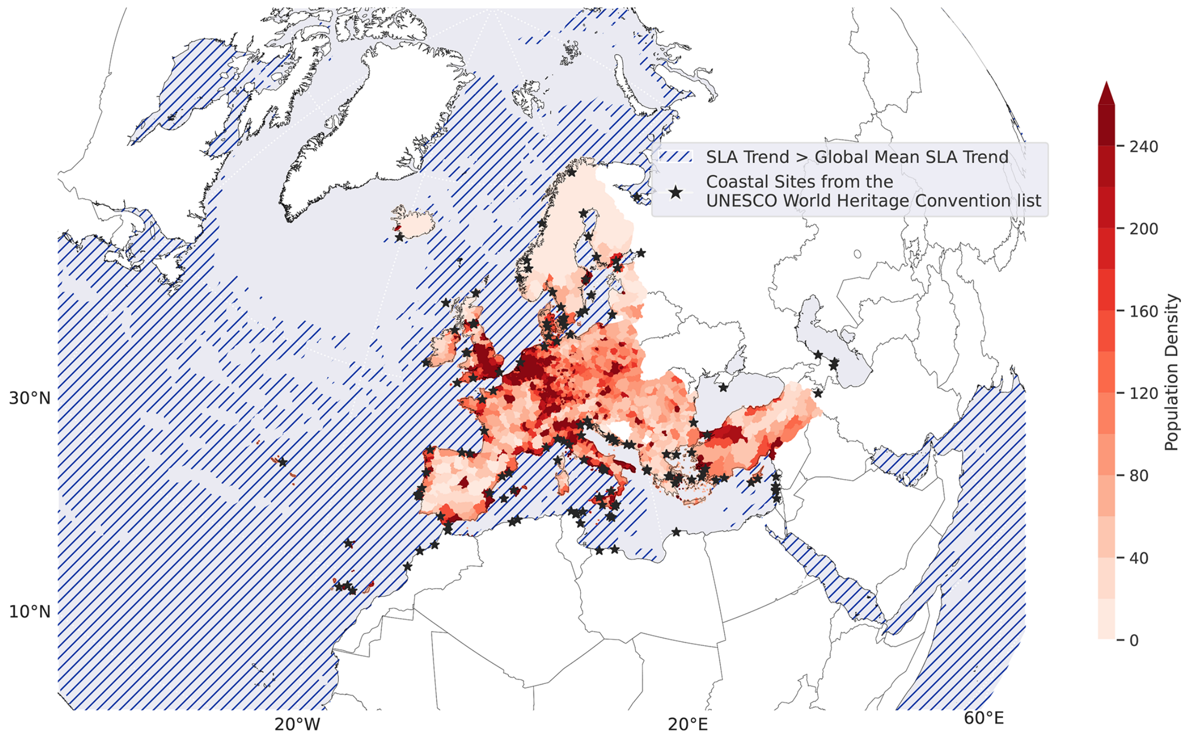

Figure 5. Sea level rise and impacted coasts. Population density (unit of measurement: persons per square kilometre (persons km^{-2})) in European countries in 2023 (or latest available data; see product ref. no. 25 for more details) (red gradient). Oblique hatching shows where the local sea level rise (SLR; product ref. no. 26) trend surpasses the global trend for the period 1999–2024. Black stars represent coastal UNESCO sites (product ref. no. 27).

certainty that could endanger jobs, food security, and coastal livelihoods.

Taken together, these findings highlight the critical need for coordinated, timely action. Climate resilience should be a core component of conservation, economic planning, and marine governance. Safeguarding biodiversity, supporting vulnerable communities, and protecting cultural and natural heritage must serve as key priorities in Europe's strategy for addressing the growing challenges of ocean change. The northeastern Atlantic stands not only as a prominent climate hotspot but also as an essential region for shaping comprehensive ocean policies that balance environmental sustainability, economic resilience, and social inclusivity.

Code availability. All codes are available upon request.

Data availability. All data used are available, and their sources are listed in the Supplement.

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