

Section 4

Subchapter 5N

Pelagic domain

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Key points

The pelagic domain encompasses the entire water column and is the largest oceanic region. Due to its vastness and limited accessibility, it remains less studied and understood than its benthic and intertidal counterparts. The existing knowledge underscores its biological richness and essential contribution to ecosystem functions. It also offers significant potential for humans, providing valuable ecosystem services such as living resources, energy and climate regulation.

1. Introduction

Key components and structure

From the Latin *pelagus*, the pelagic domain refers to the open ocean environment, consisting of all the organisms that live within the water column, rather than on the ocean floor or near the coast. A key characteristic is the high mobility and dynamism of its organisms, which are not anchored to substrate and move through the water column. Their movements link habitats and drive processes like benthopelagic coupling (see figure I). An exception to that mobility is some mesopelagic species that are non-migratory, particularly the *Cyclothone* genus that are largely responsible for what are known as the deep scattering layers, ubiquitous features of the mesopelagic (Sarmiento-Lezcano and others, 2023) and bathypelagic depths (Peña and others, 2021).

The pelagic domain is influenced by physical and biogeochemical factors that create distinct and dynamic habitats for marine life at different depths (see figure I). It is subdivided into zones based on light penetration: epipelagic (0-200m), mesopelagic (200-1,000m), bathypelagic (1,000-4,000m), abyssopelagic (4,000-6,000m) and hadalpelagic (more than 6,000m) zones. This classification aids its description although oversimplification may misrepresent ecosystem processes (Eduardo and others, 2024).

Past drivers and pressures

Since the 1800s, the key factors controlling the pelagic domain underwent significant shifts, driven by human-induced climate change. These changes are altering species distributions and productivity, biodiversity and the overall health of the oceans (Williamson and Guinder, 2021), with significant socioecological and economic consequences. Human activities like intense fishing, energy production and global trade are also increasingly affecting the pelagic zone (see figure I), with rising impacts now reaching even remote and once-pristine areas (Paolo and others, 2024).

2. Scientific advances since the first and second *World Ocean Assessment*

New discoveries and technological advances

Advancements in observational technologies have enhanced the ability to monitor Earth and wildlife, utilizing high-resolution data from sensors in various environments (Joo and others, 2022; McCauley and others, 2024). Research vessels now serve as motherships for robots, enabling extensive data collection and multidisciplinary studies (Miller and Virmani, 2023). The Biogeochemical Argo programme has expanded global insights into ocean productivity and dissolved oxygen (Izett and others, 2024; Jemai and others, 2021; Stoer and others, 2023).

Environmental DNA techniques have enhanced biodiversity understanding across ecosystems (Deeg and others, 2023; Zhang and others, 2020). They provide new insights into the diets of pelagic species, particularly informing the contribution of gelatinous zooplankton (Dischereit and others, 2024). On the other hand, advancements in the study of trophic ecology and ecosystem functioning include compound-specific stable isotope analyses (Gimenez and others, 2023; Stahl and others, 2023).

New assessments and modelling efforts

The latest Earth system models from the Coupled Model Intercomparison Project have projected greater warming, acidification, deoxygenation and nitrate reductions in the ocean, with smaller declines in primary production compared with the previous model (Kwiatkowski and others, 2020). The latest models also better capture extreme events like marine heatwaves (Qiu and others, 2021). Species distribution models and marine ecosystem models now integrate complex datasets and environmental dynamics, simulating marine biomass on a global scale (Lotze and others, 2019; Tittensor and others, 2018). These models have revealed uncertainties and help project ecosystem responses to climate changes (Blanchard and Novaglio, 2024; Heneghan and others, 2021; Tittensor and others, 2021). Recent advancements in functional trait standardization have aided environmental DNA and their applications in ecosystem modelling, connecting ecosystem components based on functional roles and properties (Green and others, 2022; Heneghan and others, 2020; Pata and Hunt, 2023).

Emergent drivers and effects

Recent analyses have shown how changes in energy transfer efficiency due to ocean warming may lead to reduced biomass of fish and marine mammals, a phenomenon known as trophic amplification (Atkinson and others, 2024; Lotze and others, 2019).

Extreme ocean events have received increased attention due to their abrupt nature and severe impacts. Studies show spatial overlap and temporal synchronicity of compound extreme events, which exacerbate their effects (Amaya and others, 2023; Li and others, 2024). Recent advancements in ocean reanalysis models enable the analysis of vertical structures of these events (Wong and others, 2024; Zhang and others, 2023).

Emergent pollutants, transported through oceanic and atmospheric means, also pose an increasing risk to pelagic systems. Global levels may be exceeding planetary boundaries (Richardson and others, 2023).

3. Description of the current state and recent trends

Changes in physical and chemical states

Global ocean temperatures are rising, especially at high latitudes (see figure II) (Garcia-Soto and others, 2021; Storto and Yang, 2024) (see sect. 4, chap. 3). In addition, natural variability, such as the Pacific Decadal Oscillation and El Niño Southern Oscillation, affects regional trends (Johnson and Lyman, 2020). The 2023 El Niño led to record sea surface temperatures, with the global average 0.23°C higher than in 2022, while Antarctic sea ice extent reached unprecedented lows (Copernicus, 2023).¹

Warming trends also increase the frequency and intensity of marine heatwaves (Collins and others, 2022; Oliver and others, 2021) (see figure III). Marine heatwaves affect marine ecosystems by altering species distributions and food web efficiency (Smith and others, 2023). They can trigger low-oxygen events, worsening ocean deoxygenation (Li and others, 2024), leading to habitat compression (Jorda and others, 2020).

The ocean absorbs anthropogenic CO₂, leading to increased acidity (decreased pH) and decrease aragonite saturation state (Bednaršek and others, 2023; Garcia-Soto and others, 2021; Ma and others, 2023) (see sect. 4, chap. 3). Ocean salinity and circulation are also changing (see sect. 4, chap. 3) impacting the pelagic domain (see figure II) (Bograd and others, 2023; Ditlevsen and Ditlevsen, 2023; Douville and Cheng, 2024; Fox and others, 2023; Gutierrez-Guerra and others, 2024; Rahmstorf, 2024).

Changes in marine productivity and chlorophyll-a concentration

Marine productivity has declined across ocean basins, primarily due to ocean warming, increased stratification and reduced oxygen and nutrient fluxes (Boyce and others, 2010) (see sect. 4, chap. 3). Recent satellite data indicate ongoing declines in chlorophyll-a concentrations, affecting the reproductive performance of marine predators, in particular in the Northern Hemisphere (Sydeman and others, 2021). While strong natural variability masks climate-change effects on phytoplankton, trends in ocean colour reflectance are more detectable, revealing that low-latitude oceans have become greener (Cael and others, 2023). Negative extreme events decrease at high latitudes, while positive extremes intensify, especially along the circumpolar current (see figure IV).

Human activities

Plastic debris is increasingly found in marine organisms (Liu and others, 2023; Marmara and others, 2023; Wiczorek and others, 2018). Plastics affect marine ecosystems by influencing carbon sinking rates and oxygen levels (Kvale and others, 2023). Humans are exposed to plastics through contaminated seafood (Akhbarizadeh and others, 2020; Leslie and others, 2022; Marmara and others, 2023).

While small-scale trials for mesopelagic fish exist, they are not a significant target for commercial fishing, with total reported catches at 2.7 million tons since the 1950s (Pauly and others, 2021). Economic viability is limited by distance to fishing areas, high fuel costs, rapid fish deterioration and low fish density (Kourantidou and Jin, 2022; Paoletti and others, 2021; Vastenhoud and others, 2023). Rising demand for fishmeal and improved storage methods may make mesopelagic fisheries profitable in the future (Paoletti and others, 2021).

¹See: <https://marine.copernicus.eu/news/2023-northern-hemisphere-summer-record-breaking-oceanic-events>.

Key zones

The mesopelagic zone (200–1,000 m) covers 60% of the surface of the Earth and accounts for 20% of the ocean's volume. This community is vital to the biological carbon pump and the global carbon cycle, transporting carbon to depth through diel vertical migration (Anderson and others, 2019; Kiko and others, 2020) and mediating the flux of sinking carbon-containing particles (Baumas and others, 2021) (subsect. 5B, chap. 1). Mesopelagic fish and zooplankton contribute 16% each to the global biological carbon pump, corresponding to the sinking particulate organic carbon (POC) flux from surface waters (Archibald and others, 2019; Saba and others, 2021). Climate-driven changes are altering mesopelagic communities, impacting the biological carbon pump (Kiko and others, 2020).

Primary production in eastern boundary upwelling systems is disrupted by climate change, as sea surface temperatures rise and upwelling winds intensify. Shifts in pelagic species are observed in upwelling systems, such as the California Current and Southern Benguela (Blamey and others, 2015; Fiechter and others, 2021).

The Arctic and Antarctic regions are highly vulnerable to climate change, in particular in their oceans and cryosphere. Changes in sea ice conditions are leading to profound shifts in the magnitude and phenology of pelagic marine productivity pulses, typical of highly seasonal polar systems, with far-reaching implications for polar ecosystems and their roles in global biogeochemical cycles (see sect. 4, chap. 3 and subchap. 5K) (Willis and others, 2023).

Key species groups

Climate-driven declines in phytoplankton size and biomass have led to greater losses in higher trophic organisms like fish and marine mammals across the open ocean (Henson and others, 2022; Lotze and others, 2019). Ocean warming has also shifted zooplankton distribution, favoured smaller species and altered seasonal patterns of productivity (Benedetti and others, 2021; Ratnarajah and others, 2023). These shifts have large impacts on fish recruitment (Beaugrand and others, 2003; Jaspers and others, 2023; Johnston and others, 2022; Pinchuk and others, 2021; Steinberg and Landry, 2017) (see sect. 4, subchap. 4A).

Small pelagic fish contribute over 15% of energy flowing to top predators, supporting 22% of seabirds and 15% of marine mammals in assessed ecosystems (Ruzicka and others, 2024). Small pelagic fish represent 43% of total fish production and 18% of global catches, (Ruzicka and others, 2024). Their worldwide status is complex and regionally variable (FAO, 2024). Historically, fluctuations in small pelagic fish populations have been linked to environmental variability, while high fishing pressure and competition among pelagic organisms play crucial roles (Alheit and Peck, 2019; Coll and others, 2024; Hilborn and others, 2022). These fluctuations significantly affect fisheries and predatory species of conservation concern. In 2023, El Niño conditions reduced the habitats of cold-water species like Peruvian anchoveta (*Engraulis ringens*), the world's largest monospecific fishery, leading to a 50% reduction in industrial landings compared with 2022. Such losses impacted local economies and global aquaculture due to the fishery's role in producing fishmeal and fish oil (see sect. 4, chap. 4).

Deep-pelagic fish are crucial for oceanic carbon sequestration (Eduardo and others, 2024; Klevjer and others, 2016; Saba and others, 2021) but they face threats from pollutants (Ferreira and others, 2023; Justino and others, 2022), potential exploitation from fisheries (Hidalgo and Browman, 2019; Pauly and

others, 2021), the offshore oil and gas industry (Hawkins and others, 2023) and from the emerging practice of deep-sea mining (Kung and others, 2021).

The open ocean catch was estimated at 11 million tons per year in 2022, primarily consisting of species with open ocean distributions (FAO, 2024). Global tuna catches reached 8.3 million tons in 2022, with 87% of world tuna stocks considered sustainably fished (FAO, 2024). Skipjack tuna (*Katsuwonus pelamis*) is the third-largest catch among harvested species, while some previously overfished stocks, like bluefin tuna (*Thunnus thynnus*), have recovered, demonstrating the benefits of effective management (Juan-Jordá and others, 2022). Not all species and stocks are assessed, however, in particular small tunas (Lucena-Frédou and others, 2021).

Chondrichthyans are highly vulnerable to overfishing and bycatch due to slow growth and low reproductive rates (Dulvy and others, 2021). Recent trends do not indicate major recoveries (Juan-Jordá and others, 2022) and many shark species are threatened with extinction, with three quarters of studied species being at risk (Dulvy and others, 2021).

Despite recent recoveries (Duarte and others, 2020), marine mammals in pelagic ecosystems face significant conservation challenges from human activities and climate change (see sect. 4, subchap. 4E). Key threats include bycatch, vessel collisions, plastic and noise pollution and habitat degradation that affects food availability and migratory patterns (Avila and others, 2018; Fortuna and others, 2024). Many seabird species are also in decline (BirdLife International, 2018), with invasive species, overfishing and climate change as the primary threats (Dias and others, 2019; Gimeno and others, 2024; Sydeman and others, 2021) (see chap. 4, subchap. 4G). The pelagic phase of marine turtles is largely under-studied (Robinson and others, 2023) and while many populations are declining, a few are increasing (Hays and others, 2024) (see sect. 4, subchap. 4F).

Effects of changes for humans

Catches from wild-capture fisheries have remained at around 90 million tons per year since the 1980s (FAO, 2024), while commercial fisheries now cover nearly all pelagic ocean areas (Rousseau and others, 2024) (see subsect. 5A, subchaps. 1A and 1B). This expansion may obscure warming-induced shifts in species richness from equatorial waters since the 1970s (Chust and others, 2024). With global demand for marine protein expected to double by 2050, pressure on pelagic ecosystems will likely increase and move northwards (Cruz and others, 2024).

The blue economy is projected to grow to \$3 trillion annually by 2030 (Jolly, 2016), while facing challenges due to insufficient ocean knowledge (Narwal and others, 2024). It heavily relies on fisheries, with small pelagic fish and tuna comprising a significant portion of catches (FAO, 2024). Intensive fisheries management has generally improved abundance of several stocks (Hilborn and others, 2020). However, increased interest in exploiting deeper waters could jeopardize essential species, leading to declines in biomass and diversity (Ariza and others, 2022; Eduardo and others, 2024; Lin and others, 2023).

Pelagic ecosystems suffer from accumulated pollutants, particularly persistent ones like polychlorinated biphenyls and per- and polyfluoroalkyl substances (PFASs), which do not decompose naturally and cause carcinogenesis, teratogenesis and endocrine disruption (Worm and others, 2017). Nanoplastics and microplastics are of concern, contaminating marine organisms and posing health risks to humans as they

bioaccumulate in the food web (Fauvelle and others, 2021; Sala and others, 2022). Risks to the open ocean include light and noise pollution and sediment discharges from mining operations, which contain harmful particulates and chemical additives (Christiansen and Bräger, 2023; Duarte and others, 2021). Mining plumes may impact fisheries (Van Der Grient and Drazen, 2021) and human health through the bioaccumulation of toxins.

Evolution of management and conservation

Managing the high seas is challenging because of their vast and dynamic nature and the complex impact of climate change. Regional fishery management organizations (RFMOs) play crucial roles in managing pelagic species and addressing bycatch, and they are expanding to incorporate ecosystem and climate change considerations (see subsect. 5A, subchap. 1A) (SCRS-ICCAT, 2024). Proposing marine protected areas (MPAs) in the pelagic zone faces obstacles due to species' migratory behaviour, impacts of climate change, technological gaps and enforcement difficulties. Recent technological advances have improved monitoring capabilities, although the observation of biological variables and processes still presents important challenges (see sect. 4, chap. 2).

The International Seabed Authority (ISA) is responsible for the regulation of deep-sea exploration and exploitation for minerals in areas beyond national jurisdiction but has yet to adopt a regulatory code for exploitation activities. In 2023, the Authority's Assembly adopted a road map with a view to the adoption during its thirtieth session. (ISA, 2024). The full regulatory framework and time-frame for ISA approval are uncertain (Pickens and others, 2024). The unprecedented geographic scale of deep-sea mining, along with new technologies and poorly understood ecosystems, complicates environmental impact assessments.

The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction aims to protect marine biodiversity in international waters by area-based management tools, including MPAs, and mandate environmental impact assessments. It establishes a framework for sustainable use of ocean resources, enhancing global cooperation to manage the unique challenges of pelagic ecosystems. The Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction was adopted on 19 June 2023 by the Intergovernmental Conference on Marine Biodiversity of Areas Beyond National Jurisdiction convened under the auspices of the United Nations, and ratified on 19 September 2025. The Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction becomes the third implementing agreement to the United Nations Convention on the Law of the Sea, which marked a significant step in ocean conservation and governance.

4. Region-specific issues

Arctic Ocean

The Arctic is experiencing rapid climate transformations, known as Arctic Amplification (Carmack and others, 2015), fuelled by sea ice loss and radiative feedbacks (Jenkins and Dai, 2021). Sea ice extent has significantly declined (Ivanov, 2023) and the Barents Sea has become a "hot spot" for climate change, marked by intensified inflow of warmer, saltier Atlantic waters, known as "Atlantification", which further accelerates sea ice loss (Skagseth and others, 2020) (see sect. 4, subchap. 5K). These changes affect biodiversity and abundance of marine communities (Gordó-Vilaseca and others, 2024; Gordó-Vilaseca

and others, 2023). The region seems to be a sink for contaminants and litter from global sources, transported from lower latitudes (ICES, 2022).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

The North Atlantic faced strong to severe marine heatwaves in the summer of 2023, causing a significant decrease in chlorophyll-a concentration (up to 50 to 60%) in the Eastern North Atlantic, which had a notable impact on ocean productivity. A persistent cold anomaly in the subpolar gyre and low salinity along the Greenland coast, likely due to increased precipitation and ice sheet melting, have altered the distribution of several species (mackerels, bluefin tuna, humpback whales, common eiders, great cormorants) (Josey and others, 2018). In the North Sea, warming surface waters are affecting plankton, fish, and fisheries distribution, with the 0 to 200 m depth zone heavily trawled. While most commercial fish stocks are stable, seabird populations are declining and seal numbers are increasing. In the Baltic Sea, climate-driven changes are reshaping ecosystem. While most pelagic fish stocks are increasing, with the exception of the Baltic herring, non-indigenous species (NIS) are spreading. The Baltic population of the harbour porpoise is critically endangered and presently confined to the western basin, with a dramatic population decline caused by bycatch in fishing gear, underwater noise, chemical pollution and prey depletion.² Mediterranean sea surface temperatures have shown positive anomalies (Salat and others, 2019), with February 2023 reaching a record high of 1.2°C. Rising temperatures and declining primary productivity have affected small pelagic fish, altering their distribution and reducing catches (Coll and others, 2024) and the spread of non-native pelagic species is changing the biodiversity (Zenetos and others, 2022). In the Black Sea, the situation remains poorly assessed, but some large pelagic species, like bluefin tuna and swordfish, were slowly returning before recent extreme events.

South Atlantic Ocean and Wider Caribbean

The Southwestern Atlantic Ocean is highly vulnerable to marine heatwaves (Artana and others, 2024). These marine heatwaves contributed to massive fish mortality and toxic algal blooms in the summer of 2017 (Manta and others, 2018). Moreover, on particular occasions, marine heatwaves coincided with a severe drought in Southeast Brazil such as in January 2014 (Rodrigues and others, 2019). In South Africa, management trade-offs between the conservation needs of the endangered African penguin and small pelagic purse seine fisheries have sparked intense debate and legal battles (Cochrane and others, 2024; McInnes and others, 2024).

The increase in *Sargassum* seaweed blooms (see sect. 4, subchap. 4I) is now stretching across the great Atlantic Sargassum belt from the Gulf of Mexico to the western Atlantic. These blooms are exacerbated by warmer sea temperatures and nutrients runoff from coastal areas and create hypoxic zones affecting marine species, local tourism and fisheries (Marsh and others, 2023; Robledo and others, 2021).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Warming ocean temperatures and oxygen depletion in the Indian Ocean affect pelagic species, leading to shifts in the distribution of tuna, sardines and mackerel, with species moving towards cooler southern waters (Waller and others, 2024). For example, in the Arabian Sea, low-oxygen zones are expanding, reducing habitat for pelagic organisms such as Indian mackerel and scads (Lachkar and others, 2023). The

² See <https://www.ascobans.org/en/species/phocoena-phocoena>.

Bay of Bengal faces increased hypoxia, threatening key pelagic fish species due to changing monsoon patterns (Vidhya and others, 2022). In the Persian Gulf, the effects of climate change impacts pelagic fish populations (Khalfeh Nilsaz and others, 2024).

North Pacific Ocean

This region is increasingly contaminated by microplastics (Van Seville and others, 2015; Yu and Singh, 2023). In the western North Pacific, plankton and small pelagic fish biomass fluctuations respond to the Pacific Decadal Oscillation at a multidecadal scale. However, the sea surface temperatures regime has been unconventional in the last decade (Kuroda and others, 2020). Despite a negative Pacific Decadal Oscillation phase around 2010, lower sea surface temperatures were recorded in some seasons and small pelagic fish population dynamics have not followed past trends.

South Pacific Ocean

Global warming and rising sea surface temperatures affects marine life, leading to major changes in currents and upwelling zones (Bograd and others, 2023; Sutton and others, 2024; Wang and others, 2023). These changes affect the distribution, reproduction and behavior of many marine animals (Avila and others, 2020; Montalva and others, 2022; Peters and others, 2022). Concerns about anthropogenic stressors persist, including fisheries (Ortiz and Hermosillo-Núñez, 2024). The ubiquity of microplastics (Bakir and others, 2020; Bleszynski and Clark, 2023) and the spread of the H5N1 avian influenza virus are affecting seabirds and marine mammals (Gamarra-Toledo and others, 2023; Leguia and others, 2023; Stokstad, 2023).

Southern Ocean

Circumpolar deep-water warms and CO₂ concentrations have been rising (Morley and others, 2020). Atmospheric warming and declining sea-ice extent is most pronounced around the Antarctic Peninsula (Gimeno and others, 2024) (see sect. 4, subchap. 5K). This affects the recruitment success of Antarctic krill, a keystone species (Johnston and others, 2022). While current and future physical and biogeochemical changes may increase primary production (Pinkerton and others, 2021), the food web responses will depend on zooplankton reactions to warming and acidification, affecting higher trophic levels (Johnston and others, 2022; Swadling and others, 2023).

The long history of resource exploitation, primarily driven by Antarctic krill and toothfish fisheries, remains low compared to global averages (Paolo and others, 2024). However, advancements in technology and favourable environmental conditions could increase the accessibility and pressure on these resources (Rogers and others, 2020). Climate change exacerbates these challenges (Gimeno and others, 2024), alongside rising tourism, pollution, pathogens and disturbances from invasive species (Becker and others, 2024). The growing vulnerability of marine life in the Antarctic has sparked a recent initiative aiming to strengthen humankind's duty in supporting Southern Ocean ecosystems.³

³ <https://antarcticrights.org/>.

5. Key knowledge and capacity gaps

Gaps in key processes

Although there has been progress (Eduardo and others, 2024; Egorova and others, 2024), the mesopelagic zone remains data poor. Increased interest in deep-water ecosystems highlights their ecological significance, alongside significant knowledge gaps and rising threats. Much of the biodiversity below 1,000 m also remains undiscovered, with gaps in taxonomy (smaller organisms being less studied) and species interactions.

Little is known about species movements and ecological interactions among organisms across trophic levels and regions, hindering the understanding of species distribution, ecosystem changes and effective management and conservation effects. Understanding these interactions is crucial for advancing the comprehension of ocean ecosystems and the impact of management actions (Schaber and others, 2022). Technological advancements like in situ imaging and environmental DNA are starting to address some of these important gaps.

The cumulative impact of extreme climate events is becoming a critical research focus, particularly regarding compound events and their influence on ocean dynamics, biodiversity and human livelihoods. Moreover, these events are exacerbated by other anthropogenic impacts on ocean ecosystems, such as pollution and fishing. As the frequency and intensity of extreme events rise, it is essential to understand their effects at various spatiotemporal scales. For instance, the interplay of global warming (centennial scale), Atlantic Multidecadal Oscillation (multidecadal scale), Pacific Decadal Oscillation, and El Niño and La Niña events, along with marine heatwaves (annual scale), could intricately affect organism and community dynamics in ocean ecosystems.

The start of deep-sea mining operations may soon pose a new threat to the deep pelagic communities of the open ocean that play a crucial role as prey for higher trophic levels and in the global biological carbon pump. Assessing the severity of this threat is challenging. Moreover, the interactive effects of multiple stressors on pelagic organisms, populations and communities (and dependencies with benthic counterparts) present a key knowledge gap that requires further research (Pinsky and others, 2020; Van de Waal and Litchman, 2020). Fisheries impacts and value chains and food nutrition with a pelagic origin, are important knowledge gaps, going beyond the impacts of climate change on fish production (Heneghan and others, 2023; Van de Waal and Litchman, 2020).

Technological gaps

The pelagic domain remains among the least explored areas on Earth. There is still a critical need for enhanced observational data. Biogeochemical parameters are poorly sampled compared to physical variables. Most monitoring efforts focus on surface-level measurements, limiting understanding of the deep ocean's role in heat and carbon storage, especially below 2,000 m. Recent studies using deep Argo floats reveal that decadal heat content trends are significant in these underexplored regions (Johnson and Purkey, 2024). Gaps remain in measuring vertical ocean velocities, particularly in sub-mesoscale processes. The launch of the Surface Water and Ocean Topography satellite in December 2022 is a significant advancement (Fu and others, 2024).

Challenges remain in obtaining quantitative estimates of fish and plankton biomass. An estimated 81% of zooplankton monitoring data are either unavailable or only partially accessible (Ratnarajah and others, 2023). There is a pressing need to implement findable, accessible, interoperable and reusable data standards in pelagic data (Wilkinson and others, 2016) for biodiversity assessments (Becker and others, 2024; Ramírez and others, 2022). Further efforts on environmental DNA techniques are needed to build reference libraries (Ratnarajah and others, 2023).

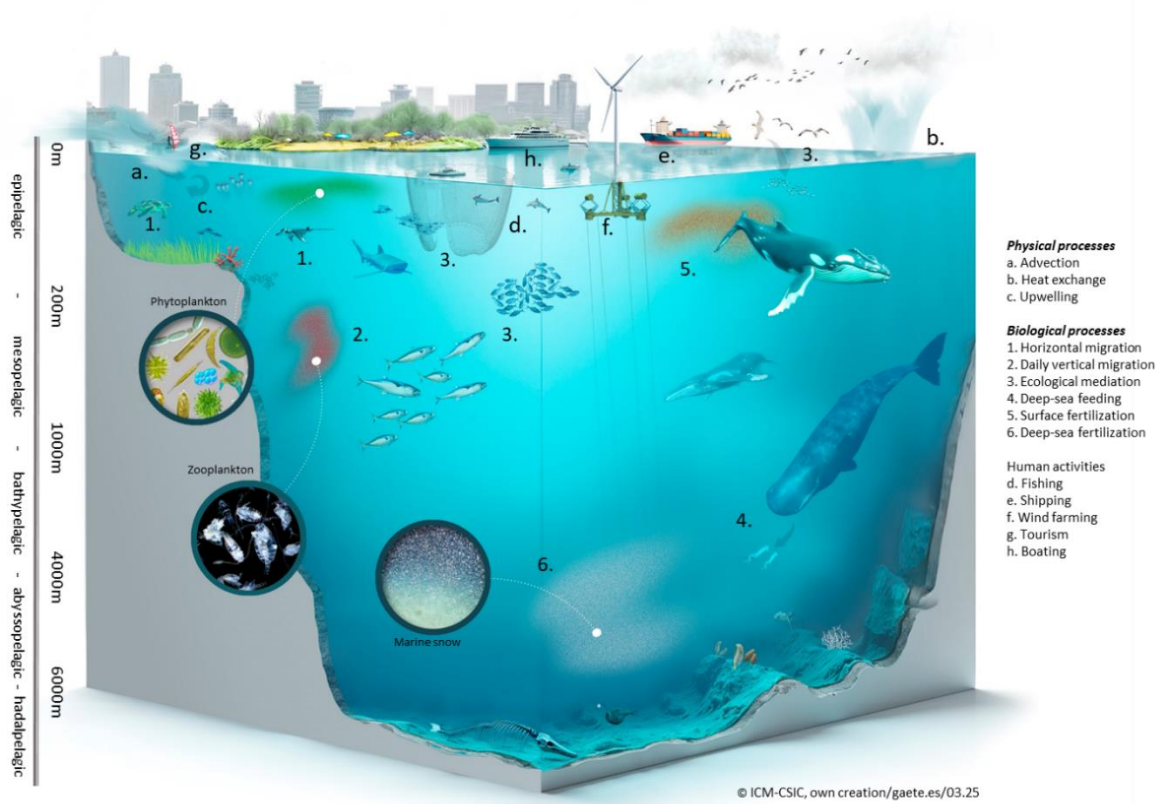
Capacity-building needs

Another challenge is about digitizing and mobilizing existing data and knowledge (Meyer and others, 2015; Rogers and others, 2022). Enhancing the collaboration in international data-sharing programmes through partnerships and capacity-building can improve marine biodiversity monitoring. Taxonomic training, especially for less-known non-vertebrate groups, should remain a priority, as the value of digitized collections depends on accurate species identifications and taxonomic completeness.

Quantitative socioecological assessments are essential for analysing pelagic systems and understanding human impacts. Socioecological models must be scientifically robust yet accessible to managers and decision-makers (Heymans and others, 2020). Despite progress in quantifying marine modelling uncertainty (Rynne and others, 2025; Steenbeek and others, 2024), further development is still needed.

Figure I

Schematic representation of the pelagic domain

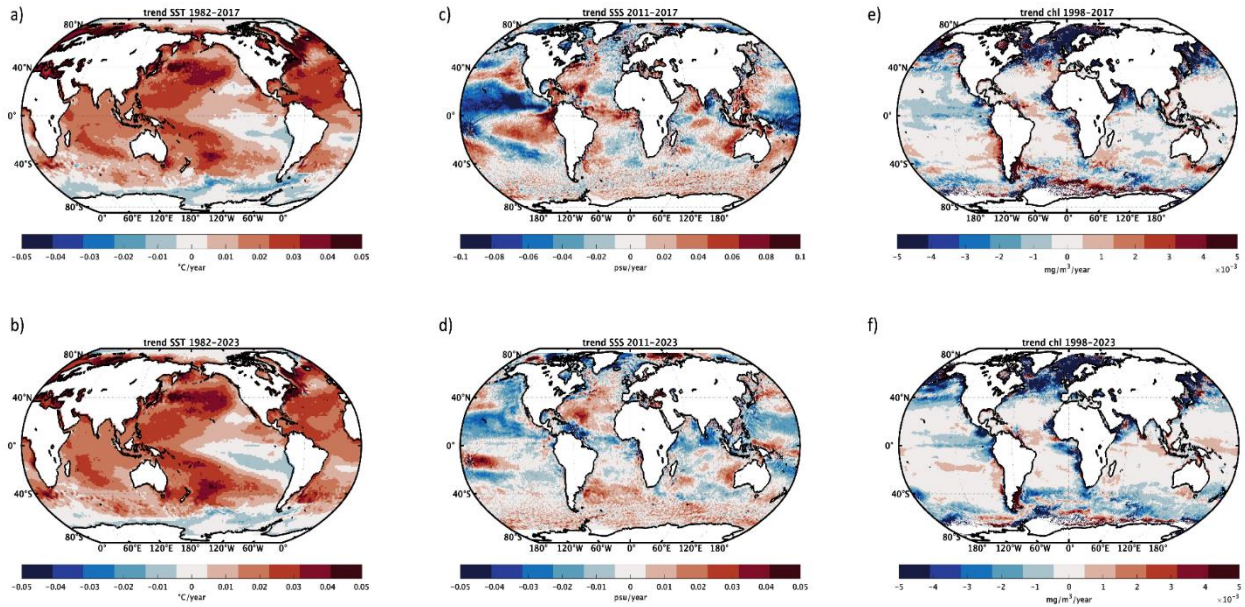


Source: Image: ICM-CSIC, own creation/gaete.es/03.25.

Note: Main regions and species type are represented, along with some key ecological processes and human activities that accumulate in the pelagic domain.

Figure II

Temperature trend for the period (a) 1982-2017 and (b) 1982-2023; salinity trend for the period (c) 2011-2017 and (d) 2011-2023; chlorophyll-a trend for the period (e) 1998-2017 and (f) 1998-2023



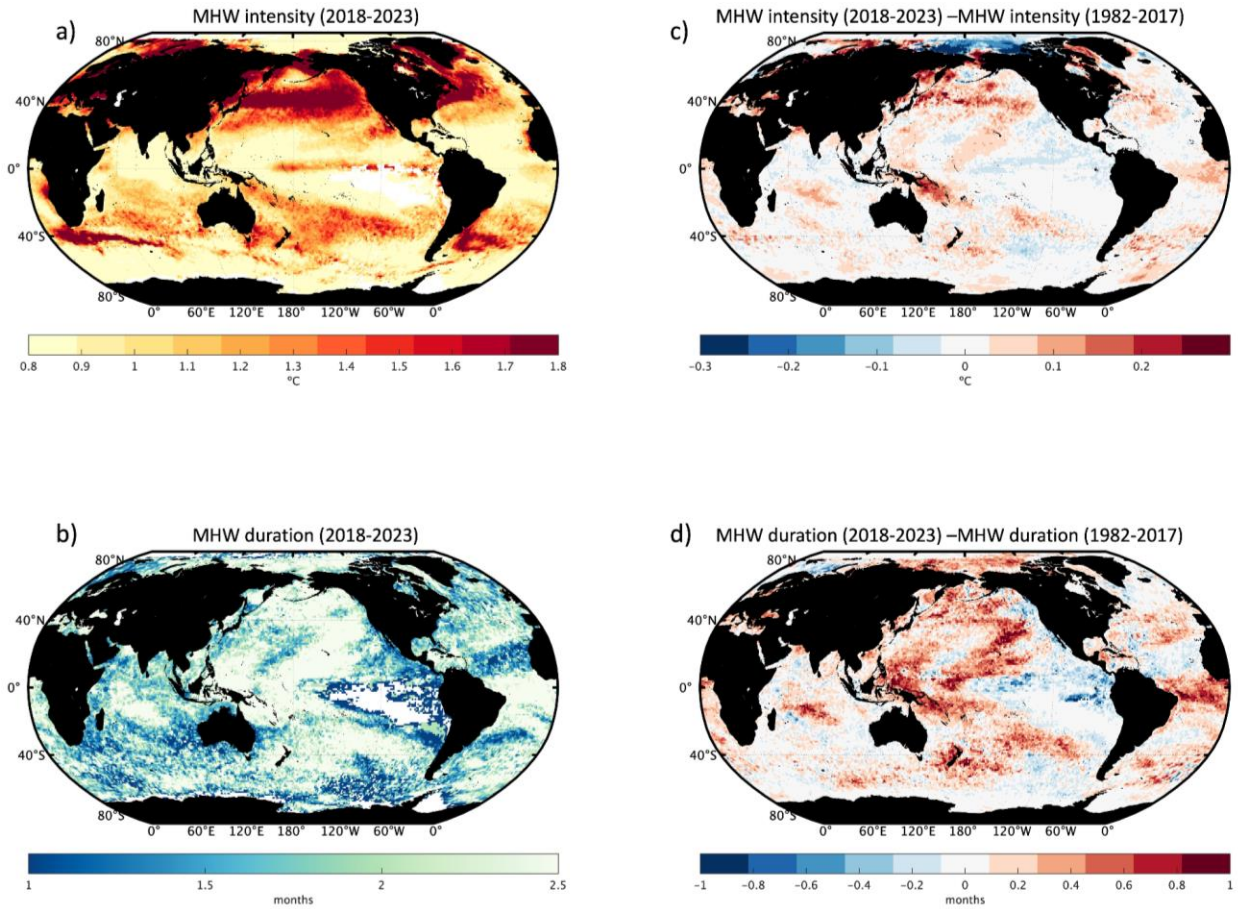
Source: Salinity data from Kolodziejczyk and others, 2021; chlorophyll-a data downloaded from the Copernicus marine service website;^a temperature data from NOAA OISSTv2.176 product, obtained from NOAA/OAR/PSL.^b

^a See <https://data.marine.copernicus.eu/products>.

^b See <https://psl.noaa.gov/>.

Figure III

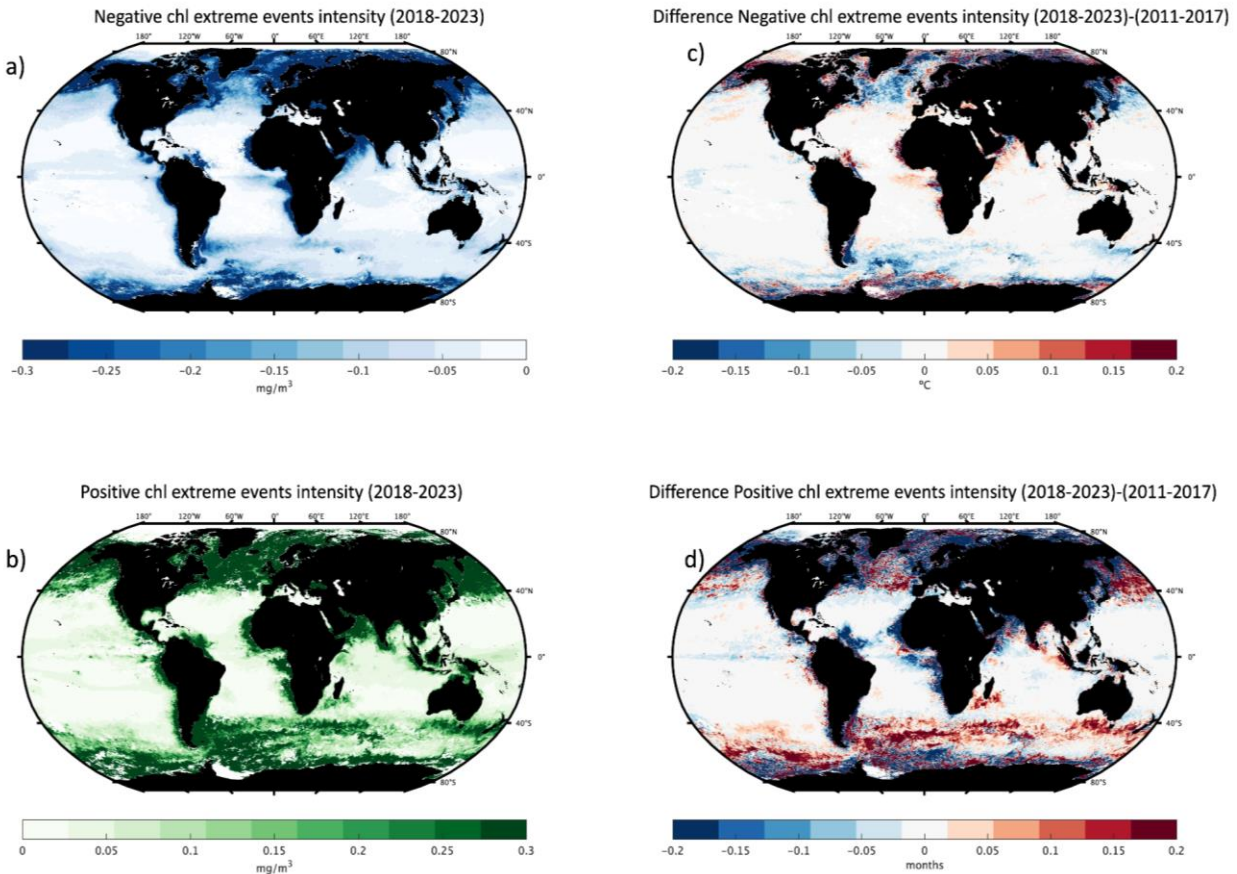
(a) Mean marine heatwave intensity for the period 2018-2023; (b) same as (a) but for marine heatwave duration; (c) difference between mean marine heatwaves intensity computed over the period 2018-2023 and mean marine heatwave intensity computed over the period 1982-2017; (d) same as (c) but for marine heatwave duration



Source: Temperature data from NOAA OISSTv2.176 product, obtained from NOAA/OAR/PSL <https://psl.noaa.gov/>.

Figure IV

(a) Negative and (b) positive extreme events of Chlorophyll-a intensity for the period 2018-2023: (c) differences between negative extreme events of chlorophyll computed over the period 2018-2023 and 2011-2017. Blue colours indicate that negative extreme events were more intense during 2011-2017. (d) Same as (c) but for positive extreme events of chlorophyll.



Source: Chlorophyll-a data from <https://doi.org/10.48670/moi-00281> downloaded from the Copernicus marine service website: <https://data.marine.copernicus.eu/products>.

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