OSPAR COMMISSION

Climate Change Thematic Assessment

OSPAR QUALITY STATUS REPORT 2023

2023

OSPAR's Quality Status Report 2023

Climate Change Thematic Assessment

OSPAR Convention

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the “OSPAR Convention”) was opened for signature at the Ministerial Meeting of the former Oslo and Paris Commissions in Paris on 22 September 1992. The Convention entered into force on 25 March 1998. The Contracting Parties are Belgium, Denmark, the European Union, Finland, France, Germany, Iceland, Ireland, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

Convention OSPAR

La Convention pour la protection du milieu marin de l´Atlantique du Nord-Est, dite Convention OSPAR, a été ouverte à la signature à la réunion ministérielle des anciennes Commissions d´Oslo et de Paris, à Paris le 22 septembre 1992. La Convention est entrée en vigueur le 25 mars 1998. Les Parties contractantes sont l´Allemagne, la Belgique, le Danemark, l´Espagne, la Finlande, la France, l´Irlande, l´Islande, le Luxembourg, la Norvège, les Pays-Bas, le Portugal, le Royaume- Uni de Grande Bretagne et d´Irlande du Nord, la Suède, la Suisse et l´Union européenne

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Contents

Contributors 1

Citation 1

Executive Summary 3

Q1. Identify the problems? Are they the same in all OSPAR regions? 3

Q2. What has been done? 5

Q3. Did it work? Developments since QSR2010 and NEAES 2020 6

Q4. How does this field affect the overall quality status? 7

Q5. What do we do next? 7

D - Drivers 8

A – Activities 9

P – Pressures 13

S – State 25

I – Impact (on Ecosystem Services) 35

R – Response 37

Cumulative Effects 47

Thematic metadata 48

References 49

Executive Summary

The Climate Change Thematic Assessment summarises the information on climate change and ocean acidification in the OSPAR Maritime Area. The ocean is critical in regulating the Earth's climate: it has absorbed 89% of the excess heat trapped inside the atmosphere since the 1970s, and every year absorbs at least a quarter of the carbon dioxide (CO_2) released by human activities.

Their ability to absorb heat and CO_2 means that marine ecosystems, and the human activities within them, are particularly vulnerable to climate change. Rising sea level and temperatures, reduced pH values, changes in rainfall amounts and reduced sea ice coverage, among others, are all effects of the rising atmospheric greenhouse gas concentrations. These pressures have resulted in documented changes to marine ecosystems, for example in the distribution of species and the timing of key life stage events. Local and regional impacts can vary, and some regions are experiencing changes at a much faster rate (for example, in the Arctic Waters (Region I)). Climate extremes, such as marine heatwaves, storms and waves are also becoming more prevalent.

Increased atmospheric greenhouse gas concentrations and the related impacts on the marine environment are influenced by almost all socio-economic drivers and by a wide-ranging number of associated human activities, both on land and at sea.

Human activities in the marine environment and marine ecosystems will need to adapt to both the observed and anticipated changes. In addition, the coastal and marine environment offer opportunities for reducing anthropogenic greenhouse gas emissions, (e.g. through the production of offshore wind and wave energy), for protecting and restoring natural greenhouse gas sinks (such as blue carbon and sedimentary carbon) and for establishing anthropogenic carbon storage, often referred to as carbon capture and storage (CCS). These opportunities need to be fully explored and maximised to support climate action.

Q1. Identify the problems? Are they the same in all OSPAR regions?

Since the industrial revolution, greenhouse gases emitted by human activities have caused the Earth's climate (the long-term average prevailing conditions) to change. These greenhouse gases have originated from the combustion of fossil fuels (such as coal, oil and gas) and from changes in agriculture, forestry and other land use. Greenhouse gases are effective at trapping the heat inside the Earth's atmosphere, like layers of blankets to keep your body warm on a cold night. This additional energy in the Earth system has led to global warming, with impacts for terrestrial environments and the ocean. The majority of this heat has been absorbed by the ocean, highlighting the importance of the ocean in regulating the Earth's climate.

In the ocean, climate change has led to warming, decreased oxygen concentrations, marine heatwaves and sea-level rise, with many further related impacts across marine ecosystems and the services they provide. Moreover, the excess CO_2 released into the atmosphere by human activities is being drawn down into the ocean, leading to acidification (see: Climate Change and Ocean Acidifcation - An Explainer.pdf). Climate change is also triggering widespread change in the water cycle by changing the prevailing atmospheric conditions and causing changes to other parameters such as stratification and ocean circulation. Climate extremes, such as storms and waves are becoming more prevalent.

Kongsfjord glacier Norway. © Tony Morris

These changes in the physical and chemical conditions of the marine environment are affecting marine habitats and ecosystems across the OSPAR Maritime Area, although there are regional and local variations in these pressures. The root cause is global, but the effects, such as storms and floods or changes in rainfall, are felt at more local scales. There are also regional variations in the rate of change, for example the higher rates of sea temperature warming in Arctic Waters.

These localised effects can trigger changes in other regions. Some studies have suggested that losses of Arctic sea-ice may affect the position and strength of strong winds such as the polar vortex and the jet stream, which may then cause extreme weather at mid-latitudes.

Not all pressures are changing at the same rate across the OSPAR Maritime Area, and some regions are experiencing changes at a much faster rate (Arctic Waters). Changes in sea-level rise and in the frequency and intensity of the strongest storms may impact lower lying areas in OSPAR countries more significantly. The eventual climate risk, a combination of vulnerability and exposure, emerges on a much more local scale, requiring a national response.

Because of the connectivity between land and sea, land-based impacts may also lead to pressures on the coastal and marine environment, for example from intense rainfall events.

Changes in the physical and chemical conditions of the marine environment are affecting marine habitats and ecosystems across the OSPAR Maritime Area, floods are felt at local scales pictured here in Germany. © Shutterstock

Q2. What has been done?

The topics of marine climate change and ocean acidification (OA) have increasingly gained prominence within OSPAR's work. At the same time, the interconnection between ocean and climate has also received greater recognition on the global policy scene, for example at the UN Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) in Madrid in 2019, and more recently in the COP26 Glasgow Climate Pact, in which the parties agree to integrate and strengthen ocean action across the UNFCCC and to establish an annual ocean dialogue, providing an opportunity to permanently embed the ocean into climate change responses.

The OSPAR Convention already provides some measures intended to help Contracting Parties reduce atmospheric greenhouse gas concentrations (mitigation), live with the consequences of climate change (adaptation), or increase the resilience of their natural and socio-economic systems to climate change impacts. These include OSPAR Decisions 2007/1 and 2007/2, both relating to the storage of CO_2 streams. The OSPAR network of Marine Protected Areas (MPAs) may also be regarded as supporting increased ecosystem resilience. However, OSPAR still needs to adopt further specific measures in order to tackle climate change and ocean acidification.

The Quality Status Report 2010 identified climate change impacts as an increasing pressure on marine ecosystems. It also found that the pressures from human activities would alter as societies mitigated against and adapted to climate change. The assessment recommended that OSPAR Contracting Parties should cooperate in reducing existing pressures, managing sea-based renewable energy and carbon capture and storage developments, and, inter alia, in monitoring and assessing ocean acidification and climate change.

The QSR 2010 noted the key vulnerability of the Arctic region and its marine ecosystems to climate change and ocean acidification. The focus that OSPAR places on the protection of Arctic waters has resonance beyond the region itself. For example, the Arctic Monitoring and Assessment Programme (AMAP) reported in 2017 that the Arctic "*also plays an important role in global climate and weather, sea level rise and world commerce, which means that impacts in the Arctic resonate far south of the Arctic Circle*".

This assessment informed OSPAR's commitments on climate change and ocean acidification under the North-East Atlantic Environmental Strategy for 2020 (NEAES 2020). These included the monitoring and assessment of the effects of climate change and ocean acidification, incorporating the impacts of, and responses to, climate change and ocean acidification in integrated management, and improving knowledge on the interactions between climate change and eutrophication.

OSPAR's Intermediate Assessment 2017 (IA 2017) made further progress on assessing marine climate and climate change (including ocean acidification) in the OSPAR Maritime Area, while recognising that more progress needed to be made. The IA 2017 also recommended placing prevailing ocean conditions within the cumulative effects framework (which has been further advanced by the application of the DAPSIR framework in QSR 2023).

Ocean acidification received little consideration under QSR 2010 but has gained increasing prominence since then. OA monitoring became a voluntary parameter reported under OSPAR's Coordinated Environmental Monitoring Programme (CEMP) following the work done by the Joint Study Group on Ocean Acidification (SGOA, 2012-2014) and the report it delivered (ICES, 2014). Subsequently, an intersessional correspondence group (ICG) on OA was established and first met in 2019. This group was tasked with the delivery of an ocean acidification assessment for QSR 2023.

As set out in NEAES 2020, OSPAR has focused on managing many of the human pressures that affect the marine environment, although there has been increasing recognition of the importance of climate change and ocean acidification in understanding changes in marine biodiversity and ecosystem functioning. In accordance with this strategy, OSPAR has committed to monitor and assess the nature, rate and extent of the effects of climate change and ocean acidification on the marine environment and to consider appropriate ways to mitigate and adapt to these impacts. Strengthening the OSPAR network of MPAs was also emphasised as part of the strategic direction under NEAES 2020. However, more work will be needed before the resulting increase in the resilience of the marine ecosystem to climate change can be quantified.

Q3. Did it work? Developments since QSR2010 and NEAES 2020

OSPAR has recognised the need to emphasise climate change and ocean acidification more strongly in its work. Although these topics gained prominence in NEAES 2020, the evaluation of this strategy (OSPAR, 2021) reveals that progress on climate change and ocean acidification has been limited. A regional, coordinated monitoring and assessment programme for climate change and ocean acidification has not been achieved to the same degree as for the marine biodiversity and ecosystem function. Good progress has been made towards the monitoring and assessment of ocean acidification, through the establishment of the ICG-OA in 2018 and the group's subsequent work.

Climate change signals are apparent in several of the assessments completed in the framework of the QSR 2023, but a more developed understanding of the fundamental links between ecosystem responses, climate and other anthropogenic drivers is required.

The NEAES 2020 had ambitions to monitor and assess the current and future impacts of climate change and ocean acidification on species, habitats and ecosystem functioning, determine the timescale(s) for such impacts to take effect and their possible extent, and to consider management options suitable for mitigating and adapting to such impacts. While this has not been achieved, OSPAR's North-East Atlantic Environment Strategy (NEAES) 2030 has confirmed the continued intention to support progress towards these goals in the forthcoming assessment cycle, with three of its 12 strategic objectives focused specifically on climate change and ocean acidification.

Q4. How does this field affect the overall quality status?

It is clear that changes in the prevailing physico-chemical conditions of the marine environment in the OSPAR Maritime Area have been caused by climate change and ocean acidification. Thematic assessments produced for QSR 2023 indicate that climate change and ocean acidification are already having an effect on the marine ecosystem and all human activities in the OSPAR Maritime Area. However, there remains the difficulty of quantifying these impacts and fully integrating them in order to determine the resulting change in overall quality status. This mainly stems from the difficulty in distinguishing with confidence the impacts of climate change and ocean acidification from the impacts of other processes that are either primary or managed drivers. Such strong causal links and identified mechanisms are currently lacking, but future developments may bring improvement in directly attributing changes in the quality status of marine ecosystem and human activities to climate change. To address this, OSPAR should further explore how indicators change in response to changes in the climate pressures identified in this thematic assessment.

Q5. What do we do next?

Addressing climate change will require action at all levels of society. This action needs to focus on three aspects: (i) preparing for and adapting to the hazards exacerbated by climate change, (ii) building up resilience across the system by managing pressures, and (iii) reducing greenhouse gas emissions and increasing their uptake and storage. Although many of the levers for achieving this lie outside of the OSPAR mandate, we will contribute to international progress towards a climate-ready and low-carbon society, under the North-East Atlantic Environment Strategy (NEAES) 2030. As part of this work, OSPAR should proactively adopt specific measures to address climate change and ocean acidification.

Resilience to the impacts of climate change and ocean acidification is one of the four themes encompassed by NEAES 2030. This theme has three strategic objectives:

- OSPAR will raise awareness of climate change and ocean acidification by monitoring, analysing and communicating their effects (Strategic Objective 10);
- OSPAR will facilitate adaptation to the impacts of climate change and ocean acidification by considering additional pressures when developing programmes, actions and measures (Strategic Objective 11); and
- OSPAR will mitigate climate change and ocean acidification by contributing to global efforts, including by safeguarding the marine environment's role as a natural carbon store (Strategic Objective 12).

The Climate Change Expert Group, established to deliver the Climate Change thematic assessment for QSR 2023, will propose that OSPAR consider establishing a permanent working group on climate change to address these objectives. This group's work would include regular assessments of current and projected impacts and support the work of other Committees in integrating climate change into their assessments and policy work. To progress the work of attributing changes in the overall quality status of marine ecosystem and human activities to climate change, OSPAR should explore further how indicators reflect changes in climate pressures. In future assessments, OSPAR might also consider the assessment of physico-chemical pressures within a more formal framework; these could then be included in the Joint Assessment & Monitoring Programme (JAMP).

The work programme on climate change and ocean acidification would also inform the future implementation of nature-based solutions for different habitat types in the OSPAR Maritime Area. The multiple benefits of these nature-based solutions include carbon uptake and storage through natural processes, the reversal of biodiversity loss, and improved ecosystem resilience.

Strengthened collaboration between the OSPAR experts on ocean acidification and climate change will be central to addressing these strategic objectives and progressing the necessary underlying tasks.

D - Drivers

Drivers of climate change in the marine environment

Almost all social and economic drivers have the potential to influence climate change. Many drivers, through the emissions of greenhouse gases to the atmosphere, cause both climate change and ocean acidification.

Almost all social and economic drivers have the potential to influence climate change. Emissions of greenhouse gases to the atmosphere lead to climate change and ocean acidification. As societies seek to reduce these emissions and adapt to climate change impacts, the activities they undertake in response are likely to emit greenhouse gases, and therefore some responses are also included here as drivers. This closes the circle in the DAPSIR framework.

Society's responses for addressing climate change, both by reducing greenhouse gas emissions and adapting to climate change impacts, include:

- Reductions in fossil fuel consumption (and extraction); reductions in greenhouse gas emissions; increased reliance on and expansion of renewable energy technologies; increased carbon capture and storage activity and a focus on protection and restoration of natural carbon stores;
- In response to threats to society: coastal and flood protection; sea defences; levees; dikes; relocation of at-risk communities; shifts in the wild capture and aquaculture species for human consumption due to range shifts and other impacts; a shift to low-carbon heating, transport and power for homes, businesses, and industry. Activities to adapt to climate change impacts will also emit greenhouse gases, thus contributing further to climate change;
- Building climate-proof economic and social systems to create resilience to extremes such as floods, storms, winds, and temperature changes; constructions designed to withstand extreme weather events; sustainable consumption of natural resources; assessment of environment, habitat and biodiversity changes to allow management responses for sustainable ecosystems;
- In response to growing energy demand as the global population increases: shifts in policies towards low carbon economies, which will require a significant expansion of renewable energy development (including marine); oil and gas as part of the energy mix (albeit declining) of many countries, and a continuing need to manage emissions. Nuclear energy will be a source for some countries. Market forces will drive energy prices.

Policy responses for managing climate change need to consider all these driving forces in order to reduce greenhouse gas emissions, reduce reliance on non-renewable energy technologies, mitigate risks and facilitate societal change.

A – Activities

Human activities and climate change

A great number of land-based and sea-based human activities emit greenhouse gases, causing climate change and ocean acidification. The following table provides an overview of the key human activities and their trends, as assessed by the OSPAR Quality Status Report 2023.

Table A.1: Overview of human activities, as assessed by the OSPAR Quality Status Report, and their key trends. Cell entries represent intensity (high, medium, low), trend since QSR 2010, and forecast trend to 2030. Symbols used: ↓ = decreasing trend, ↑ = increasing trend, ↔ = little change in intensity since QSR 2010; ? = future trends are uncertain. *Note that not all human activities are currently assessed directly by OSPAR

Main activities	Arctic Waters (Region I)	Greater North Sea (Region II)	Celtic Sea (Region III)	Bay of Biscay and Iberian Coast (Region IV)	Wider Atlantic (Region V)
Aggregates extraction *Intensity* *Trend since QSR2010* *Trend to 2030*	L ↔ ?	H ↓ ?	M ↔ ?	M ↑ ?	L ↔ ?
Agriculture *Intensity* *Trend since QSR2010* *Trend to 2030*	L ↔ ↔	H ↔ ↔	M ↔ ↔	M ↔ ↔	L ↔ ↔
Aquaculture *Intensity* *Trend since QSR2010* *Trend to 2030*	H ↑ ↑	H ↑ ↑	M ↔ ↑	M ↑ ↑	L ↑ ↑
Fisheries *Intensity* *Trend since QSR2010* *Trend to 2030*	H ↓ ?	H ↑ ?	H ↑ ?	M ↔ ?	L ↔ ?
Oil/gas production *Intensity* *Trend since QSR2010* *Trend to 2030*	M ↔ ↔	H ↔ ↔	M ↔ ↔	L ↔ ↔	L ↔ ↔
Renewable energy *Intensity* *Trend since QSR2010* *Trend to 2030*	L ↑ ↑	H ↑ ↑	M ↑ ↑	L ↑ ↑	L ↔ ↔
Shipping *Intensity* *Trend since QSR2010* *Trend to 2030*	M ↔ ?	H ↔ ?	H ↔ ?	H ↔ ?	L ↔ ?
Tourism *Intensity* *Trend since QSR2010* *Trend to 2030*	L ↑ ↑	H ↑ ↑	M ↔ ↔	H ↑ ↑	L ↑ ↑

Activities emitting greenhouse gases

A great number of land-based and sea-based human activities emit greenhouse gases, causing climate change and ocean acidification. Globally, greenhouse gas emissions continued to rise between 2010 and 2018 (Lamb *et al.*, 2021). Atmospheric greenhouse gas emissions are not covered by OSPAR measures or reported by harmonised OSPAR methodologies, but are dealt with by the UNFCCC, the International Maritime Organization (IMO), the International Civil Aviation Organization (ICAO), the EU -where applicable- and national legislation.

Over the period 2009-2019, the Extraction of oil and gas sector (see:Offshore Industry Thematic Assessment) identified a decreasing trend in emissions. The offshore oil and gas industry continues to make improvements to the methodologies for quantifying these emissions, as well as develop initiatives to reduce its contribution to climate change (e.g. the World Bank's 'Zero Routine Flaring by 2030' initiative).

An Oil platform. The Extraction of oil and gas sector identified a decreasing trend in emissions. © Shutterstock

Fuel combustion by maritime vessels is a major source of greenhouse gas emissions (see: Human Activities Thematic Assessment). Maritime vessels include those used in Transport – shipping, Fish and shellfish harvesting, Extraction of minerals and Tourism and leisure. Inputs include discharges from exhaust gas cleaning systems, discharges of contaminated water, and pollution from the oil or other noxious substances that can arise from accidents and operational activities such as the washing of cargo tanks or the use of antifouling paints.

Similarly, the combustion of fossil fuels in the Transport – air, Transport – land, Agriculture, Aquaculture, Urban and industrial uses (including the generation of electricity and heating) and Tourism and leisure activities and infrastructure sectors also emits greenhouse gases (see: Human Activity Thematic Assessment).

Changes in methods of energy generation

see: Human Activity Thematic Assessment

As Contracting Parties transition to low-carbon energy generation and use, there will be significant changes to the main sources of energy generation. Offshore wind installations (and other technologies, such as wave, tidal stream and tidal range) in the OSPAR Maritime Area are expected to increase greatly in the next decade and beyond, primarily in the Greater North Sea and Celtic Seas Regions. The amount of offshore wind energy capacity has increased substantially since QSR 2010; turbine size, wind farm size and average distance to shore have also increased. Offshore wind energy capacity is anticipated to expand at an accelerated pace in the coming decade, and further expansion beyond 2030 is also planned. While most of this will involve fixed turbines, floating installations are now past the proof-of-concept stage and may become more prevalent. Some increase in wave and tidal energy installations, including pilot projects, is anticipated up to 2030, but significant cost reductions would be needed for these to play a significant role in energy generation. Nuclear technologies are also considered by some Contracting Parties to have a role to play in the energy transition (see: Radioactive Substances Thematic Assessment).

Activities to limit exposure to climate risk

Despite the focus on avoiding and reducing greenhouse gas emissions so as to mitigate climate change, some of future impacts of global warming will occur as the inevitable result of past and current emissions (also known as committed warming), and further impacts will emerge as long as greenhouse gas concentrations in the atmosphere increase. Activities in the marine and coastal environment may support adaptation to climate change impacts and reduce the exposure to climate risks such as sea level rise, coastal flooding and erosion. To address the exposure to climate risks of coastal and marine infrastructure, activities related to Coastal defence and flood protection are anticipated to increase.

The Thames Barrier is an example of a Flood Barrier. © Craig Allen

Non-marine activities and their influence on the marine environment

Forests play an integral part in the carbon cycle and help to stabilise the climate (IUCN). Each year, deforestation and forest degradation account for 5 to10 billion tonnes of CO_2-equivalent emissions. CO_2-equivalent, or CO_2e, is a measure used to standardise the climate effect of various greenhouse gases; it adjusts for the fact that each greenhouse gas has a different warming potential and atmospheric lifetime. This metric expresses emissions to an equivalent of the most common greenhouse gas (CO_2). Forestry management is thus an important factor in addressing the effects of climate change. In addition to contributing to climate change, agriculture can itself be affected by climate change (temperature change, rainfall, spread of pests and diseases). Changes to agriculture due to shifts in societal demands for plant- and animal-based products are increasingly becoming apparent. Any changes in activities in freshwater and terrestrial environments may have an influence on conditions in the coastal and marine environments.

Marine-based activities providing climate solutions

There is increasing recognition of “working with nature” to address climate risks and increase the uptake and storage of greenhouse gases in natural stores. Nature-based solutions such as the conservation and restoration of biogenic reefs, salt marshes and sea- grass beds may provide solutions to coastal flooding and coastline erosion by acting as floodplains or reducing wave exposure. Other benefits of nature-based solutions may be their ability to take up and store carbon (climate change mitigation) and their biodiversity functions. This will be revisited in the Response section.

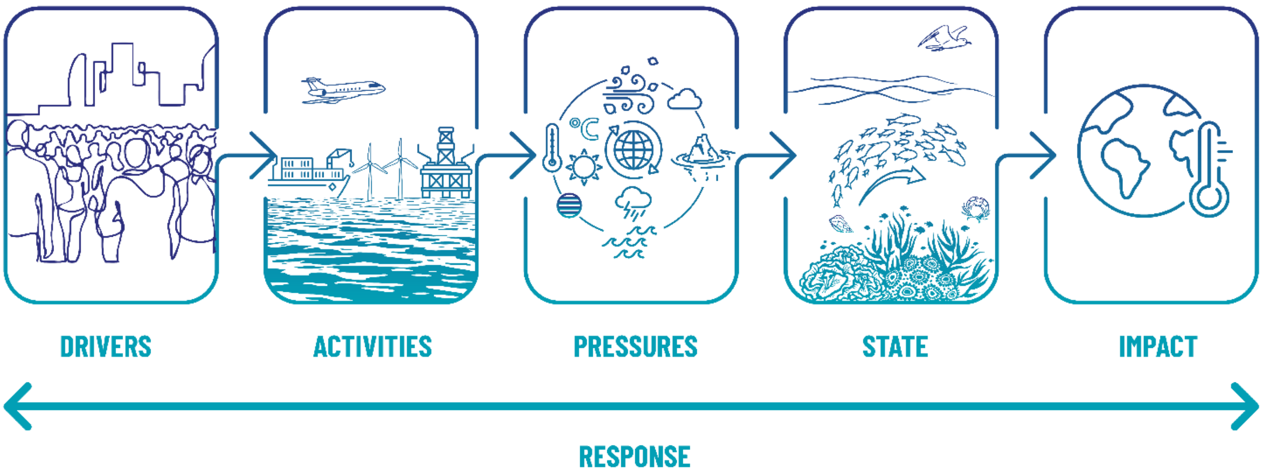
P – Pressures

Marine climate change as a pressure

Anthropogenic greenhouse gas emissions are causing changes in the ocean climate. These can be seen as pressures on marine biodiversity and human activities. Across the OSPAR Maritime Area, these pressures are mounting: increased sea temperature, shrinking sea ice, increased freshwater input, changed salinity, changes in large-scale ocean circulation, shelf sea and open ocean stratification, increased storms and waves, rising sea level, reduced uptake of CO_2, acidification, nutrient enrichment, reduction in dissolved oxygen, changes in upwelling intensity and marine heatwaves. Changes in these pressures have been identified in all OSPAR Regions, although Arctic Waters in particular are experiencing changes at much faster rates.

Note on confidence assessment: Due to the specific nature of the climate change Thematic Assessment, which is not backed by the assessment of agreed OSPAR indicators, adding an assessment of the confidence was considered irrelevant.

Human activities have caused major changes in the Earth's climate system, with warming observed in the atmosphere, in the ocean and on land. The scale and rate of change is unprecedented in thousands of years. The ocean has absorbed 89% of the excess heat (von Schuckmann *et al.*, 2020), and every year it absorbs at least a quarter of the carbon dioxide (CO_2) released to the atmosphere (see: Ocean Acidification – Other Assessment). Due to human influence, the marine environment is warming, its dissolved oxygen concentration reducing and its pH content decreasing (acidification). This is also causing widespread change in the water cycle (changing prevailing atmospheric conditions) and causing changes in other parameters such as stratification. Climate extremes, including marine heatwaves and extreme weather events, are also becoming more prevalent. These changes in the physical and chemical conditions act as pressures on marine habitats and ecosystems, and on the human activities taking place across the OSPAR Maritime Area. Consequently, ecosystem service impacts due to climate change and ocean acidification will also occur. The following paragraphs provide further details of these pressures and how they have changed and may change in future, across the North-East Atlantic Ocean. They have also been summarised in the following infographic.



Increased sea temperatures

Increasing sea temperatures show the imprints of the global warming trend associated with anthropogenic climate change, as well as variability, on inter-annual to multi-decadal time scales, due to natural cycles, and differences between regions. Examination of the changes in temperature at regional scale in the North Atlantic, whether over the past century or the past 30 years, reveals that the temperature evolution at any particular location does not follow a smooth, continuously upward path (**Figure P.1**). Records show short periods of rapid warming, periods of little change, and periods of cooler conditions. Changes in sea surface temperature are presented below, followed by a more complex presentation of temperature change in the upper, intermediate and deep layers of the north-east Atlantic.

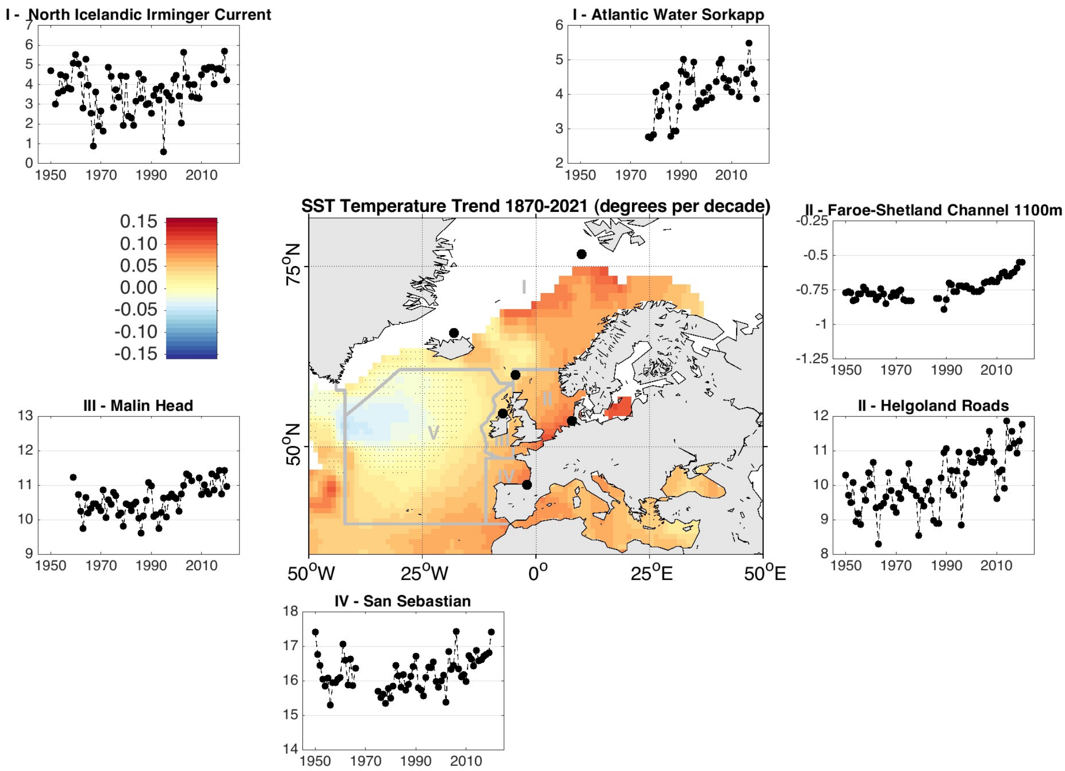


Figure P.1: Sea temperature trends at key locations in the OSPAR Maritime Area from HadSST sea surface temperature (Rayner *et al.*, 2003), and selected time series from the ICES Report on Ocean Climate (Gonzalez-Pola *et al.*, 2020). Statistical significance of trends determined by Kendall rank correlation. Stippled areas show trend is not statistically significant. Data provided by Met Office – UK, Hafrannsoknastofnun - Marine Research Institute - Iceland, Institute of Marine Research - Norway, Marine Scotland Science – UK, Alfred-Wegener Institut Helmholtz-Zentrum für Polar- und Meeresforschung – Germany, Aquarium of San Sebastian (Oceanographic Society of Gipuzkoa and Oceanographic Foundation of Gipuzkoa) – Spain, Marine Institute/Met Eireann - Ireland)

The recent Intergovernmental Panel on Climate Change (IPCC) assessment report has stated: *"it is certain that global sea surface temperature (SST) has increased since the beginning of the 20th century"* (Fox-Kemper *et al.*, 2021). Estimates from the 5th issue of the Ocean State Report (von Schuckmann *et al.*, 2021) suggest that the global ocean has warmed by 0,015 ± 0,001 °C/year between 1993 and 2019. The north-west shelf region of Europe broadly mirrors the global trend of warming in sea surface temperature (0,017 ± 0,001 °C/year).

The International Council for the Exploration of the Sea (ICES) Working Group on Oceanic Hydrography provides more regional context for changes in ocean temperature based on long-established ocean sections, some of which are a century or more in duration (**Figure P.1**). In the Greenland Sea, the upper 100 m of the ocean warmed over the 2013 to 2018 period, and relative cooling has been observed since 2018. By contrast, the Norwegian basin experienced a strong influence of warm and saline Atlantic waters between 2006 and 2016, with the Atlantic waters becoming fresher since 2016 (Skagseth *et al.*, 2022). That predominance of Atlantic waters is consistent with "Atlantification" and associated reduced sea-ice cover in the Atlantic sector of the Arctic Ocean (Barents Sea, Fram Strait) (Asbjørnsen *et al.*, 2020; von Schuckmann *et al.*, 2021). Temperature time series derived from ocean quahog clam shells for coastal regions of Norway in the Barents Sea imply a warming of at least 2 °C from the mid-18th century to 2014 (Mette *et al.*, 2021). The Irminger Basin (south-west of Iceland) has exhibited warming since 2018, reversing the previous trend associated with the subpolar North Atlantic cold anomaly between 2013 and 2016 (Josey *et al.*, 2018).

The eastern Atlantic region has shown a decrease in upper ocean temperatures in recent years (ICES Working Group on Oceanic Hydrography). Those cooler surface temperatures were also recorded in the western Iberian margin upwelling region (OSPAR Region IV) and in the Canary upwelling region, although the long-term trend between 1982 and 2019 indicates warming in both regions with a rate of +0,0105 °C / year in OSPAR Region IV (Siemer *et al.* 2021). The underlying long-term warming trend is already leading to tropicalization of shallow marine communities in the southern areas of OSPAR Regions IV and V (e.g. Vergés *et al.*, 2014; Schäfer *et al.*, 2019). Temperatures around the Azores (Region V) have increased since 1982, reaching a maximum rate of 0,027 °C / year (Siemer *et al.*, 2021). This trend was also recorded at subsurface level, with waters in the upper 240 m warming since 1998 and those at 500 m depth since 2006 (Fründt *et al.*, 2013). Warmer (and more saline) central waters (200 to 400 m) have also been observed in OSPAR Region IV since 2008 (Valente *et al.*, 2019).

Contrary to the ascertained global ocean trend of warming down to 2000 m water depth since 1971 (Bindoff *et al.*, 2019) and a likely warming trend below 2000 m water depth since 1992 (Fox-Kemper *et al.*, 2021), the Irminger Sea has seen cooling of around 0,3° C in the 700 to 1500 m depth range. That cooling between 2016 and2021 interrupted the warming phase that had prevailed since 1990 (Desbruyères *et al.*, 2022) and might be related to the North Atlantic cold anomaly. The Greenland Sea has seen a positive warming trend since 2002.

Slight cooling has been apparent in the sub-tropical gyre (OSPAR Region V) since 2012 at depths between 700 and 1500 m (Gonzalez-Pola *et al.*, 2020) and could be related to the long-term cooling trend observed in the Mediterranean Outflow Water since 1981 (Frazão and Waniek, 2021). Comparison of data from the 1980s to the 2000s shows, however, significant moderate warming at depths of 1000 and 1600 m in the south-eastern sector of OSPAR Region V, but no change at 3000 m (Frazão *et al.*, 2021).

Reducing sea ice

Global warming is causing a reduction in sea ice in OSPAR Region I. The Arctic sea ice extent, the area covered at a particular time of year, has continued to show a decreasing trend (a 43% decline between 1979 and 2019; AMAP, 2021a). These declines have been significant in all months, although the largest reductions have been seen in September when the Arctic sea ice is at its lowest (Eyring *et al.*, 2021). In the seasonal sea ice zone, the earlier onset of surface melt in spring and delay in the autumn freeze-up are lengthening the open water season, although exact quantification of regional trends is difficult owing to differences between observational products) (Fox-Kemper *et al.*, 2021).

At least half of the change in the Arctic sea ice can be attributed directly to human greenhouse gas emissions, with other causes including increased surface heat flux and increased Atlantic water influence (Hwang *et al.*, 2020). Sea-ice thickness has been more difficult to monitor, but observations show that in the central Arctic Ocean it reduced by 65% over the period 1975 to2012 (AMAP, 2017). Sea ice cover has also been thinning and reducing in age since the 1980s (AMAP, 2021a). Changes in the polar sea ice extent will create enhanced warming in the region (since water absorbs more sunlight than ice) and cause changes to the ecosystem, from primary producers to species composition, spatial distribution and abundance of species across the marine food web (Meredith *et al.*, 2019).

Changes in the extent of the Arctic sea ice may also impact conditions beyond the Arctic Circle, including north-west Europe (Screen, 2021). The precise extent of and processes behind these changes remain active areas of research, with observational evidence and computer models showing low consensus (Cohen *et al.*, 2020). One potential effect of sea-ice loss could be weakening and greater instability of the polar vortex and jet stream (two important strong winds in the atmosphere), which may cause extreme regional weather in the OSPAR Contracting Parties.

Elsewhere in the OSPAR Maritime Area, sea ice has been known to form in shallow parts of the southern North Sea under specific atmospheric conditions in wintertime. There has been a general decreasing trend in occurrences of North Sea ice winters since the mid-20th century, although conditions in the winters of 2010, 2011, 2012 resulted in some ice cover following a decade in which it had been absent (Brander *et al.*, 2016; BSH, 2021).

Global warming is causing a reduction in sea ice. © Pexels

Increased freshwater input

Global warming causes changes to the water cycle: in a warmer climate, the amount and intensity of rainfall events will increase and therefore freshwater inputs from precipitation and river run-off will increase. The melting of land-based ice (e.g. Greenland ice sheet and glaciers) will also increase freshwater input to the marine environment.

Observed precipitation trends across Europe since 1979 are not consistent across datasets, but analysis of longer records shows significant increases in precipitation for much of Scandinavia and north-western Europe (Fox-Kemper *et al.*, 2021). Model-based estimates of river flow (European Environment Agency, 2016) show increased annual flows from land areas adjacent to Regions I (Arctic Waters), II (Greater North Sea) and III (Celtic Sea), but decreased river flow from those adjacent to Region IV (Bay of Biscay & Iberian Coast). Increased annual river flows are mainly associated with wetter winters, while decreasing trends in annual river flow are associated with drier spring and summer seasons. Under future climate change scenarios, these trends are expected to continue, with generally lower annual mean river flow in Region IV and higher annual mean river flow in Regions I, II and III. River discharges from the surrounding land increased in Region I between 1976 and 2017 (Meredith *et al.*, 2019), and these trends are projected to continue.

Extreme rainfall events, such as those seen in parts of Germany, Belgium and the Netherlands in July 2021, have been attributed to climate change. As global warming continues, both the intensity and likelihood of occurrence of these rainfall extremes will continue to change. Although catchment dynamics, urbanisation, water management and other factors will influence how these rainfall events translate to river flow changes, it is probable that the likelihood and intensity of freshwater pulses in the marine environment will increase, particularly for Regions II and III, but also the coastal regions of Region I.

The contribution of freshwater from the melting of land-based ice will particularly influence Region I of the OSPAR Maritime Area. Reductions in land ice have been observed across Region I, with an increase in the rate of loss in recent decades (AMAP, 2021a). This loss of land ice in Region I is the largest regional contribution to global sea-level rise (AMAP, 2021b).

The melting of land-based ice like that seen here in Greenland will also increase freshwater input to the marine environment

Changed salinity

On a global scale, regions of higher salinity and evaporation (the tropics and subtropics) have become saltier, whereas regions of low salinity and greater precipitation have trended fresher since the 1950s (Durack, 2015; Bindoff *et al.*, 2019). Those trends will continue into the 21st century (medium confidence) and reflect the increased intensity of the Earth's hydrologic cycle (Durack, 2015; Eyring *et al.*, 2021).

Freshening is observed in and forecast for the Arctic (Region I) due to increased freshwater flux from land (Bindoff *et al.*, 2019; Fox-Kemper *et al.*, 2021). There is high confidence that, at annual to decadal time scales, regional salinity changes are being driven by ocean circulation change superimposed on longer-term trends. Due to prevailing ocean currents, the salinities in the OSPAR Maritime Area have been strongly influenced by oceanic variability in the wider North Atlantic basin. For example, between the early 1990s and early 2010s, northward transport of warmer and saltier Atlantic waters from OSPAR Region V (Wider Atlantic) into the subpolar gyre (NW sector of Region V) and into Region I (Daniault *et al.*, 2016; Lozier *et al.*, 2019; Li *et al.*, 2021) compensated for the salinity decrease expected from increased Greenland freshwater run-off in the subpolar North Atlantic (Fox-Kemper *et al.* 2021; Gonzalez-Pola *et al.* 2020). Salinities across the eastern subpolar North Atlantic Ocean have become fresher since 2015 (Holliday *et al.*, 2020; Gonzalez-Pola *et al.*, 2020), and this pattern is reflected in the observational records across the OSPAR Maritime Area (e.g. Norwegian Sea, Skagseth *et al.*, 2022).

At depth, there is less of a consistent pattern across the OSPAR Maritime Area, again due to prevailing oceanographic circulation. The deep outflow from the Norwegian Sea recorded at the Faroe Bank Channel became saltier (and warmer) during the period 1995-2015 (Hansen *et al.*, 2016). On the other hand, the deep water formed in 2015 and 2016 in the Irminger Sea (NW sector of Region V) resulted in lower salinities at depths between 1500 m and 2000 m in the Irminger Sea and the Labrador Sea (Lozier *et al.*, 2019), in line with observed cooling. In the south-eastern sector of Region V, the intermediate depth (700 to 1500 m) Mediterranean Outflow Water not only became cooler, but also fresher, in the 1981 to 2018 period (Frazão and Waniek, 2021).

Changes in large-scale ocean circulation (incl. overturning)

The ocean's circulation and its transport of heat, salt and other properties are critical components of the Earth's climate system. Within the OSPAR Maritime Area, the Atlantic Ocean's surface and deep ocean currents and their exchanges with the Arctic Mediterranean (i.e. the Arctic Ocean, Nordic Seas and adjacent shelf seas) play an important role in the climate of north-western Europe, as well as the productivity of the marine ecosystem. This is also called the Atlantic Meridional Overturning Circulation (AMOC). Based on palaeoceanographic reconstructions, the AMOC appears to have remained relatively stable during the past 8 000 years (IPCC AR6 WG1, 2021; medium confidence). The AMOC appears to be weaker than in the pre-industrial era, although there is no evidence to identify the magnitude of this weakening or to attribute it to anthropogenic greenhouse gas emissions (Garcia-Soto *et al.*, 2021). More recently, historical ship-based hydrographic estimates of the AMOC (1980s onwards) show no overall decline in AMOC strength (Fu *et al.*, 2020; Worthington *et al.*, 2021). Since the mid-2000s, direct observational evidence of AMOC strength in the sub-tropical North Atlantic Ocean (RAPID-MOCHA-26N) has increased our understanding of the AMOC's variability over shorter time scales (seasonal to decadal). These direct observations have identified a reduction in AMOC strength over decadal time scales (e.g. Mercier *et al.*, 2015; Smeed *et al.*, 2018). The directly observed weakening in the AMOC cannot be attributed to a long-term trend (high confidence; Moat *et al.*, 2020). Based on the latest evidence, it is very likely that the AMOC will decline during the 21st century, but there is low confidence in the expected timing and magnitude. This weakening could be further enhanced by increased melting of the Greenland Ice Sheet (Fox-Kemper *et al.*, 2021). The collapse of the AMOC is regarded as a climate tipping point (Collins *et al.*, 2019), although considered very unlikely but plausible.

Since 2014, new direct measurements of the overturning circulation in the subpolar North Atlantic (part of the Overturning in the Subpolar North Atlantic Program; OSNAP) have improved our understanding of the overturning circulation in the subpolar North Atlantic (OSPAR Region V). Variability in the AMOC is strongly influenced by the conversion of surface to deep waters in the region between Greenland and Scotland (Lozier *et al.*, 2019, Li *et al.*, 2021). The large-scale circulation of the North Atlantic subpolar gyre (both in terms of the overturning and the horizontal gyre circulation) is important in setting the prevailing ocean climate across much of the OSPAR Maritime Area. Past changes in salinity and temperature across the region (see above) have been linked to changes in the strength of the subpolar gyre (for example, Häkkinen *et al.*, 2011). Between the mid-2000s and mid-2010s, the subpolar gyre appeared to be in a weaker state, but in the past decade the circulation has been stronger (Berx, in prep; Gonzalez-Pola *et al.*, 2020).

Changes in shelf sea stratification

Seasonally, the imbalance between mixing due to natural processes (such as tides and winds) and buoyancy changes from surface heating or freshwater results in some areas of shelf seas becoming stratified (a layer of more buoyant water overlies denser waters) and others becoming fully mixed. This process is most relevant in the shallow shelf regions of OSPAR Regions II and III. These areas of stratification have an impact on circulation and on many components of the ecosystem, for example by limiting the dispersal of larvae or by reducing nutrient supply between the near-surface and deeper layers. Seasonal stratification, both in terms of strength and duration, has been identified as important for our understanding of changes in the dissolved oxygen concentrations of seawater close to the seabed. In stratified areas, oxygen exchange from the atmosphere to this deep layer may be limited, leading to reduced dissolved oxygen concentrations (Sharples *et al.*, 2020). There is no further update available on observed changes to strength and duration in shelf sea stratification. There is currently also no direct monitoring programme of shelf sea stratification taking place in the OSPAR Maritime Area. Models of future stratification in Regions II and III consistently project an increase in both the strength of stratification and in its seasonal duration as the regional climate changes through the 21st century (Lowe *et al.*, 2009; Holt *et al.*, 2010; Sharples *et al.*, 2013).

Changes in open ocean stratification

Although studies focused on observed changes in open ocean stratification have been lacking until very recently, new works have increased our confidence in the rate of stratification change (Somavilla *et al.*, 2017; Yamaguchi and Suga, 2019; Li *et al.*, 2020; Sallée *et al.*, 2021). The estimated density contrast across the mixed layer base, one metric of stratification, has been increasing during the past 60 years at varying global mean rates of 1 to 9% per decade (Yamaguchi and Suga, 2019; Li *et al.*, 2020a; Sallée *et al.*, 2021), while the mixed layer has deepened at a rate of several metres per decade (Somavilla *et al.*, 2017; Sallée *et al.*, 2021). Similar patterns of increasing stratification together with deepening of mixed layer depths have been observed in the open ocean across Region V and the wider North Atlantic. However, in the North Atlantic, stratification is increasing at slower rates (approximately half of the global average). This is due to the global signal being dominated by contributions from tropical regions (Yamaguchi and Suga, 2019; Li *et al.*, 2020; Sallée *et al.*, 2021), while the mixed-layer depth is deepening at trends similar to the global ocean at rates between 5 and 8 m per decade (Somavilla *et al.*, 2017; Sallée *et al.*, 2021).

Increased storms and waves

The observational evidence of the trends in atmospheric patterns and storminess reveals mixed results. There is low confidence in long-term (centennial) changes in storminess, although analysis of the observational evidence since the mid-1970s has identified increases in the frequency and intensity of the strongest storms in the North Atlantic (Wolf *et al.*, 2020). Models and observations show an associated increase in annual and winter mean significant wave heights in the North-East Atlantic since the 1950s. Climate models show a low level of agreement on the future response of the North Atlantic storm track, although a continued poleward shift is likely. This is mainly due to the challenges of accurately representing the winter storm track into Europe, due to model biases and large natural variability. Under a high-emissions scenario, there could be an overall reduction in mean significant wave height in the North Atlantic by 2100, although the most severe waves could increase in height (Wolf *et al.*, 2020).

In Region I, increases in high latitude storminess have been detected (AMAP, 2021b), the changes being associated with increased storminess in late autumn and winter due to a northward shift of the prevailing storm track. Owing to the difficulty in resolving and documenting polar lows, there is little evidence of a significant change in their occurrence. Future projections of climate change do not show a consistent signal of increases in storminess across Region I (AMAP, 2021b). However, given the suggested northward shift of the storm tracks, and the projected increases in heat and moisture, increased storm activity in Region I is plausible (AMAP, 2021b). The increase in the ice-free area may affect storms and weather at lower latitudes, due to increased wind and wave fetch and moisture exchange to the atmosphere (AMAP, 2021b).

Analysis of the observational evidence since the mid-1970s has identified increases in the frequency and intensity of the strongest storms in the North Atlantic. © Shutterstock

Rising sea level

Global mean sea level rose by 0,2 m between 1901 and 2018. Between 1901 and 1971 the rate of sea level rise was 1,3 mm/year, and a higher rate of 3,7 mm/year has been observed by satellites in the recent two decades (2006 to 2018) (IPCC, 2021). The rise in sea level since 1900 has been faster than in any century over the last 3 000 years. This is reflected across European coastlines, albeit generally to a lower extent in northern areas that are experiencing a higher rate of post-glacial land rebound. Sea-level rise is estimated to be 3,6 ± 0,82 mm/year along the coasts of the Iberian peninsula, the Bay of Biscay and Ireland (Region IV and part of Region III) and 2,9 ± 0,83 mm/year between 1993 and 2020 for Europe's north-west shelf (Regions II and III; von Schuckmann *et al.*, 2021).

The impact of rising sea level is most evident when the local sea level combines with tidal, wave and weather conditions in an extreme high water level event. Increased occurrence of extreme high water level events in many locations is due to rise in local sea levels, rather than any change in storm or surge activity (EEA, 2014). North-west Europe in particular is projected to be a "hotspot" for significant changes in episodic flooding by 2100 (Kirezci *et al.*, 2020).

In the period 2006 to 2015, meltwater from land-based ice in the Arctic (glaciers and ice caps) was the largest regional source of global sea-level rise (i.e. when not considering thermal expansion globally) (AMAP, 2021b; Oppenheimer *et al.*, 2019). The rate of loss in the last two decades has been almost twice that prior to the mid-2000s (Meredith *et al.*, 2019).

Global mean sea-level rise is projected to range from 0,37 to 0,86 m (5th-95th percentile range) by 2100 under the highest future CO_2 emission scenario (IPCC, AR6). Due to factors such as vertical land motion, ocean circulation and water density changes, different regional patterns in local sea-level rise will occur around the OSPAR Maritime Area's coastline. Vousdoukas *et al.* (2017) reported average projected increases of 0,57 to0, 81 m in a 100-year extreme sea-level event for Europe under varying emission pathways, including the OSPAR Maritime Area from Gibraltar to the Barents Sea coast of Norway. The North Sea region could face the highest increase in extreme sea levels (approximately 1 m under a high emissions climate scenario by 2100), followed by the Baltic Sea and the Atlantic coasts of the United Kingdom and Ireland. The projected sea-level rise within the IPCC's sixth assessment cycle is higher than that it had reported previously, and therefore higher than the estimates reported in QSR 2010 and IA 2017. This is due to an improved understanding and representation of the key processes.

Reduced uptake of CO_2

The ocean mitigates climate change by taking up anthropogenic CO_2. A high-quality assessment of the ocean carbon sink is critical for assessing changes in the contemporary carbon cycle and for a robust projection of its future evolution. Sudden changes in the ocean carbon sink would immediately affect the allowable emissions for limiting global warming to well below 2 °C (Hauck *et al.*, 2020). For the Nordic Seas, Olafsson *et al.* (2009) and Skjelvan *et al.* (2008; 2021) have shown that the sea surface pCO_2 undersaturation is weakening and thus that the CO_2 uptake from the atmosphere is reduced.

The ocean CO_2 sink has been estimated at 2,8 ± 0,4 GtC yr^{-1} for the decade 2011 to2020 (26% of total CO_2 emissions), and the preliminary estimate for 2021 is approximately 2,9 GtC yr^{-1} (Friedlingstein *et al.*, 2021). Observational data from Ships of Opportunity shows that the mid-latitude North Atlantic Ocean around the Porcupine Abyssal Plain (a long-term monitoring site in Region V) has remained a sink for atmospheric CO_2 in recent years. (Macovei et.al., 2020).

Ocean circulation variability has been the primary driver of these changes in oceanic CO_2 uptake over the past several decades. Multiple factors influence ocean CO_2 uptake rates, including sea surface temperature (SST) and chemistry, biological CO_2 utilization, and ocean circulation patterns. Measured sea surface CO_2 concentrations integrate all these factors, making it difficult to disentangle the influence of each on the changing oceanic CO_2 sink (De Vries *et al.*, 2017).

Acidification

The ocean's uptake of approximately one quarter of the CO_2 released to the atmosphere by human activities each year results in a chemical reaction that reduces pH and aragonite saturation state, also called ocean acidification. The rate of acidification is highly local, with differences both between and within regions.

Open water pH has decreased by -0,001 to -0,002 yr^{-1}, but coastal time series in the English Channel (Region II) and Bay of Biscay (Region IV) show declining pH rates of -0,03 yr^{-1}. Short-term variability is large, especially in coastal regions, due to both natural and anthropogenic processes. These may mask the long-term signal owing to anthropogenic CO_2 emissions. Sustained time series remain limited, and OSPAR will implement an ocean acidification monitoring strategy as part of NEAES 2030 (S10.O1).

The most effective way to limit future ocean acidification is to reduce CO_2 emissions. Future climate projections estimate the average trend of ocean acidification to be -0,0017 yr^{-1} in Region I, and between -0,0021 and -0,0023 yr^{-1} elsewhere in the OSPAR Maritime Area, under a medium emissions scenario (see:to Ocean Acidification Other Assessment). These climate projections also estimate that a small part of the shallow shelf will be corrosive for unprotected calcareous organisms. Under a high emissions scenario, these acidification rates will be higher, and the corrosive waters will expand to a large part of the seafloor.

A more detailed assessment of acidification in the OSPAR Maritime Area, current state and future trends, can be found in the Ocean Acidification Other Assessment.

Nutrient enrichment

Good status was achieved in the majority of the OSPAR Maritime Area (see: Eutrophication Thematic Assessment), although the overall 'not good' status assessment for river plumes in Regions II and IV demonstrates the continued need to reduce eutrophication effects. With respect to management, reductions in point source inputs from sewage treatment plants are proving increasingly successful. However, controlling the inputs from diffuse sources remains a challenging problem. This requires sustained, integrated research and monitoring, as well as repeated assessments of nutrient loading and impacts (Malone & Newton, 2020). Global climate changes will likely result in higher water temperatures and stronger stratification, and increased inflows of freshwater and nutrients to coastal waters may increase the inputs of nutrients to the marine and coastal environment, with consequences for eutrophication and marine biota. These resulting changes are not straightforward to predict, in part due to uncertainties about future land use and socio-economic developments.

Reducing dissolved oxygen

Climate change has an impact on the amount of oxygen that can be dissolved in seawater: ocean warming reduces the amount of oxygen that can be held, and ocean stratification limits the oxygen concentration in deeper layers. Increased levels of carbon dioxide can also promote phytoplankton growth, which, when it decays and is consumed beneath the thermocline, can further decrease oxygen concentrations (see: Dissolved Oxygen near the Seafloor Indicator Assessment).

There is a growing consensus that between 1970 and 2010 the open ocean very likely lost 0,5 to3,3% of its dissolved oxygen in the upper 1 000 m, and that oxygen minimum zones in the global ocean are expanding (Bindoff *et al.*, 2019; Canadell *et al.*, 2021). In coastal ocean regions, anthropogenic eutrophication via continental run-off and atmospheric nutrient deposition, as well as ocean warming, are very likely the main drivers of deoxygenation (Bindoff *et al.*, 2019; Canadell *et al.*, 2021).

In European shelf seas, most areas (except for the Baltic Sea) become vertically well mixed in winter every year. This resets oxygen concentrations to the surface values. As oxygen consumption is mainly driven from close to the seabed, the regions which suffer from low oxygen concentrations are those which have a relatively small volume of water beneath the thermocline. If climate change extends the length of time that regions remain isolated from the atmosphere (i.e. a longer time between the onset of stratification and the breakdown of stratification), this will also increase oxygen utilisation.

There is no observed widespread oxygen deficiency across most of the OSPAR Maritime Area, although more localised areas of oxygen deficiency are present in Regions II and IV (see: Dissolved Oxygen near the Seafloor Indicator Assessment). There are statistically significant trends of reducing oxygen concentration in five regions (Atlantic, Atlantic Seasonally Stratified, Meuse, Scheldt Plume, Norwegian Trench) and of increasing oxygen concentration in one (Kattegat Coastal). Among these, it is only the Atlantic Seasonally Stratified region where reduced solubility due to increased sea temperature is the dominant effect (see: Dissolved Oxygen near the Seafloor Indicator Assessment).

Changes in upwelling intensity

Within the OSPAR Maritime Area, wind-driven upwelling is particularly important along the western margin of Iberia in Region IV, where it exerts strong control over productivity, with wide-ranging effects across the trophic levels of the region's marine ecosystem. The changes in productivity have been described for the last 1 000 years (e.g. Abrantes *et al.*, 2011), but there is contradictory evidence as to the direction of changes in recent times and the projections for the future. Recent intensification in upwelling has been described for the African coast (McGregor *et al.*, 2007), but other analyses of wind data have shown differences in trends at sub-regional scale (Alvarez *et al.*, 2008; Pérez *et al.*, 2010; Santos *et al.*, 2011), a general weakening in the region (Pardo *et al.*, 2011; Siemer *et al.*, 2021) or no clear evidence of upwelling decrease (Barton *et al.*, 2013; Benazzouz *et al.*, 2015). Indeed, estimations based on regional climate models predict an increase in upwelling-favourable winds in the region (Casabella *et al.*, 2014). Satellite-derived chlorophyll series have not revealed a consistent trend through the region (Bode *et al.*, 2011; Alvarez *et al.*, 2012: Benazzouz *et al.*, 2015), but in situ determinations near the coast suggest large year-on-year variations (Bode *et al.*, 2011), or even increases at decadal time scales (Pérez *et al.*, 2010).

Marine heatwaves

Marine heatwaves are defined as periods of extreme high sea surface temperature relative to the long-term mean seasonal cycle (Hobday *et al.*, 2016). Such events can have negative impacts on marine ecosystems, including mortality events and plankton blooms and, over longer time scales, can cause shifts in species distribution and declines in commercial fishery catches (Collins *et al.*, 2019). Marine heatwaves can also extend widely in both geographic (millions of km^2) and temporal terms (weeks to months). Collins *et al.* (2019) have highlighted that large-scale climate models can either amplify or supress the occurrence of marine heatwaves. They report that marine heatwaves doubled in frequency between 1982 and 2016, increasing in intensity by 0,04° C per decade and in spatial extent by 19% per decade. Climate projections suggest that marine heat-waves will become more frequent in the future under most shared socio-economic pathway scenarios and may last significantly longer. The Arctic region is likely to be one of the regions impacted by increased frequency and intensity in future marine heatwaves. There are very limited studies available to date on marine heatwaves in the OSPAR Maritime Area. A recent study in Region II (Wakelin *et al.*, 2021) found evidence of widespread heatwaves in the southern North Sea over the last 30 years, but no evidence of a trend in extent or strength. Even during this period of general warming, they also found no significant trend in winter cold snaps.

S – State

Impacts of marine climate change on biodiversity and human activities

The changes in physical and chemical conditions in the marine environment are causing changes in the state of the marine ecosystem and in the human activities taking place in the marine environment. Changes in state have been reported from across the OSPAR Maritime Area and have been identified across the three non-climate themes in NEAES 2030: clean seas, biologically diverse and healthy seas and productive and sustainably used seas. In Arctic Waters (Region I), changes are occurring at an accelerated rate, with changes in state affecting many aspects including pelagic habitats, marine mammals, and a range of human activities. Low-lying areas, particularly those surrounding the Greater North Sea (Region II) are at greater risk of impact from rising sea levels. The impacts of climate change on biodiversity and human activities are now widespread across the OSPAR Maritime Area. Although, for some, the processes and attribution are only tentatively described (often due to a relatively short time series or lack of understanding of the complex processes and interactions between cumulative pressures), there is a growing body of evidence that these impacts are caused by climate change. As the climate continues to change, further impacts are likely to emerge, as well as become progressively more severe.

The physical and chemical pressures produced by climate change are affecting the state of the marine ecosystem and its habitats, and of the human activities taking place, across the OSPAR Maritime Area. The following paragraphs outline the changes in state linked to climate change for the three remaining themes in NEAES 2030.

Clean seas

There is limited evidence of direct causal changes to levels of hazardous substances, marine litter, eutrophication or radioactive substances due to climate change and ocean acidification. However, the links between them are generally well identified. Increasingly, there is good evidence that there are co-benefits to be derived from climate action alongside direct interventions on source contaminants. The climate impacts on these four parameters can be placed in the following three categories: (1) changes in the toxicology of contaminants at warmer temperatures; (2) changes in the pathways of contaminants; and (3) changes in the frequency of weather conditions that lead to episodic inputs of contaminants from land and rivers and to the remobilisation of historic pollutants. In particular, the episodic inputs and remobilisation may originate from changing precipitation patterns, including more extreme precipitation events, resulting in increased run-off. These could lead to greater inputs of litter, hazardous substances, nutrients and radioactive substances from the terrestrial environment. Changes in oceanic transport due to climate change could then further affect the distribution of these inputs across the OSPAR Maritime Area.

Marine litter

The Marine Litter Thematic Assessment identifies a number of ways in which climate change could affect the quantities of marine litter entering the marine environment, especially from rivers, and then the subsequent distribution and deposition of the litter. While there may be a need to adapt to some of the changes, it is not currently a major factor influencing OSPAR's marine litter objectives or the selection of actions for OSPAR's Regional Action Plan on Marine Litter.

The exact effects that climate change will have on marine litter pollution in the North-East Atlantic are relatively unstudied and still difficult to predict. Therefore, the potential effects described within that Thematic Assessment are generally hypothetical and highly uncertain, but form a starting point for further exploration of the issue. In general, climate change will not directly affect marine litter or its impact on biota per se, but its influence on atmospheric and ocean circulation may affect some of the pathways for and retention of litter. By managing marine litter, the cumulative impacts on marine biota may also be reduced, thus supporting increased resilience to climate change.

Hazardous substances

There is substantial evidence that increases in temperature and extreme events may enhance the release, transportation, and mobilisation of both hydrophobic and hydrophilic pollutants in the marine environment. Also, the toxicity of pollutants may increase with increasing temperatures. Climate change also contributes to oxygen depletion (hypoxia and anoxia) in the marine environment, which can increase the uptake of methylmercury in food webs and in several cases has also been found to increase the toxicity of contaminants. Changes involving extreme storms and waves may also increase the likelihood of accidents, including those where hazardous substances are released into the marine environment (see: Offshore Industry Thematic Assessment).

The risks of climate change-induced increases in pressures and in contaminant concentration levels are reducing the impact of the responses made to reduce inputs, particularly those from the historic contaminants stored in sediments, and could be a contributing factor in the lack of progress made towards a better status for the effects of hazardous substances in the marine environment. Further work on attributing the changes in contaminant concentrations to ocean climate changes may be needed in order to understand and address this aspect.

Radioactive substances

There is little evidence that climate change is having any impact on radioactive substances within the OSPAR Maritime Area at present. Increased levels of naturally occurring radionuclides in the Arctic Ocean have been linked to a reduction in the depth of permafrost and increased mobility of these radionuclides in soils (Kipp *et al.*, 2018). However, there is potential for predicted climate change effects (IPCC, 2021) to influence many aspects of radioactive substances in the marine environment, and this could have an impact on the assessments currently being carried out by OSPAR, as well as on the underlying parameters of such assessments. Warming seas may also affect the uptake of radionuclides by marine biota and food web structures, leading to changes in the biological transfer of radionuclides.

Climate change may have the potential to affect the sources of radioactive substances in the OSPAR Maritime Area, owing to predicted increasing sea levels and storm surge events leading to increased remobilisation of radionuclides from coastal sediments, as well as threatening the safety of coastal nuclear facilities.

The potential contribution of nuclear technologies in mitigating climate change is discussed in the Response section. Some Contracting Parties consider that nuclear fission and, potentially, nuclear fusion have a role to play in fulfilling this need and have developed national policies that incorporate the use of nuclear energy to further their decarbonisation objectives.

Eutrophication

The Eutrophication Thematic Assessment does not highlight climate change as a primary cause of current changes in eutrophication status, but does note that the effects of eutrophication are increased by climate change. This co-occurrence derives from the activities (e.g. burning of fossil fuels, agriculture, deforestation) that contribute to climate change, as well as the associated changes in prevailing climatic conditions (pressures) that are linked to eutrophication (e.g. changes in rainfall and run-off, storms, stratification, ocean acidification).

Climate change may also have an impact on levels of nutrient enrichment, in that it could lead to changes in circulation patterns and the occurrence and duration of stratification, which could then impact nutrient levels and primary production. Expectations about the direction of the effects are uncertain (Holt *et al.*, 2016, Schrum *et al.*, 2016).

Increased nutrient loading could be expected if river discharges increased, but this also depends to a large extent on future land use and socio-economic developments (Arheimer *et al.*, 2012, Bartosova *et al.*, 2019).

Climate change may also have an impact on the direct and indirect effects of nutrient enrichment. Increased water temperatures have been shown to lead to phenological shifts, biogeographical changes and changes in abundance of plankton (see Brander *et al.*, 2016, for an overview). With changes in phytoplankton composition, changes in chlorophyll concentrations and primary production can be expected.

Climate change can impact upon dissolved oxygen concentration in many ways, most evidently via the direct effect on solubility. However, it can also increase metabolic rates and oxygen demand and increase stratification, which inhibits the supply of oxygenated waters to lower levels. The duration of seasonal stratification in shelf seas is expected to increase and regions that show oxygen depletion are expected to become larger (Wakelin *et al.*, 2020).

NASA Satellite imagery of bloom in Skaggerak and Kattegat Seas © NASA

Biologically diverse and healthy seas

There is increasing evidence of the impacts of climate change on the marine ecosystem, its function and biodiversity. These can generally be categorised as: (1) habitat loss; (2) shifts in distribution; (3) changes to species composition and food webs; and (4) changes to life history events.

Habitat loss

Changes in environmental conditions driven by climate change are likely to have impacts on marine biodiversity by influencing the availability of suitable habitats.

Mammals and birds

Sea-level rise and extreme weather events are the main climate-related factors impacting mammals and birds. Sea-level rise leads to increased mortality of juvenile mammals. Mammals breeding along low-lying coastal areas are particularly vulnerable to storm surges (Evans & Bjorge, 2013; Zicos *et al.*, 2018), with reported extremes of up to 75% of grey seal pups being lost after severe storms (SCOS, 2018). Additionally, reduced area and ice condition may impact seals through loss of birthing habitat and of refuge habitat from predators such as killer whales (ICES, 2018; ICES, 2021; ICES, 2022; [Marine Mammals Thematic Assessment]). Increased storm frequency plays an important role in waterbirds' nest survival and the survival of adults trying to forage during storms. In addition, climate change may affect the extent and quality of waterbirds' breeding and wintering grounds as well as their migration stopovers. However, short-term extreme weather events (i.e. storms) are, to date, less impactful on seabird population size than climate-mediated changes in prey availability (Johnston *et al.*, 2021). On the other hand, there is growing evidence that short term extreme weather events will become more frequent and have increasingly significant effect (Mitchell *et al.*, 2020; Marine Birds Thematic Assessment).

Sea-level rise and extreme weather events are the main climate-related factors impacting mammals such as orcas. © Shutterstock

Fish

Temperature, the main factor impacting the suitability of fish habitats, can affect fish in different ways. For cod and haddock, earlier spawning in warmer years at the northern edge of their distributional range increases their survival during the subsequent winter months (Ottersen, 2000). On the other hand, Arctic and boreal fish are predicted to be particularly impacted (Poloczanska *et al.*, 2013) by warming climate, and the wolffish *Anarhichas lupus* has been declining in abundance (Bluemel *et al.*, 2022). The observations are more contradictory for herring: according to Lyashevska *et al.* (2020), herring might be more susceptible to climate warming at the southern limit of the distribution range, compared with northerly populations. By contrast, recruitment, body size and spawning stock biomass for Norwegian spring-spawning herring have been found to be positively correlated with temperature (Graham & Harrod, 2009). In addition, increasing bottom water temperatures have caused a deepening response among some fish species (Dulvy *et al.*, 2008) and the availability of suitable habitat at increasing depth may limit species range shifts under future climate scenarios (Rutterford *et al.*, 2015; Fish Thematic Assessment).

Benthos

Ocean warming, acidification, changes in oxygen fluxes, increased water turbidity/reduced light penetration and sediment resuspension have been reported to impact all benthic habitats, habitat suitability for sensitive benthic species, community structures and diversity patterns (Harley *et al.*, 2006; Hoegh-Guldberg & Bruno 2010; Poloczanska *et al.*, 2013; Gattuso *et al.*, 2015; Nagelkerken & Connell, 2015; Poloczanska *et al.*, 2016; Weinert *et al.*, 2016). However, each habitat is susceptible to different main impacts (Krause-Jensen *et al.*, 2021).

Increased sea temperature and changes in coastal development, in terms of coastal protection due to sea level rise, are expected to have a particularly strong effect on coastal areas such as the littoral zone, infralittoral rocks, biogenic reefs, *Zostera* beds and mud flats (Birchenough *et al.*, 2015, Garrard & Tyler-Walters 2020). These habitats are unable to migrate landwards and are particularly threatened by increasing water depths, which leads to risks of habitat loss and coastal squeeze through impacts such as oxygen depletion caused by nutrient enrichment (Painting *et al.*, 2013).

Extreme events involving sea level and altered hydrological and sediment dynamics along the shoreline affect benthic biodiversity (Spreybroeck *et al.*, 2006). This may be further increased by storms and storm surges which translocate and disperse large sediment volumes, thus altering sediment properties and reducing habitat heterogeneity. The impact on benthic habitats will increase with the magnitude, frequency and spatial scale of storm events (Corte *et al.*, 2017). On the other hand, sedimentary habitats are liable to adapt to a gradual sea level rise and compensate for alterations by extra sedimentation. Stratification effects may cause changes to deep sea benthic habitats, though the impacts here are unclear (Sweetman *et al.*, 2017). Acidification can impact the integrity of coral reefs and cause ecosystem-scale habitat loss (Hennige *et al.*, 2020; Benthic Habitats Thematic Assessment)

Pelagic

The impacts of increasing temperature, acidification and light attenuation increase on the abundance of plankton lifeforms have been most frequently detected in shelf and oceanic pelagic habitats. In the North-East Atlantic, the ocean climate-related stressors with the greatest impact on plankton communities are sea surface temperature warming (e.g. Harris *et al.*, 2014, Costoya *et al.*, 2015) and ocean acidification (e.g. Beaugrand *et al.*, 2013). Furthermore, climate can alter wind speed and precipitation, potentially affecting the light attenuation coefficient (Cappuzzo *et al.*, 2015) and sea surface salinity (Holt *et al.*, 2010). The abundances of dinoflagellates and small and large copepods have been found to decline across the North-East Atlantic, while meroplankton abundance has been observed to increase throughout the Greater North Sea. Although meroplankton in the coastal and shelf areas of the Greater North Sea have increased in abundance, simultaneously the abundance of holoplankton is declining in the shelf regions (see: Pelagic Habitats Thematic Assessment). Observations of North Atlantic krill show a squeeze in habitat due to a northward shift in warm isotherms that is not matched by movement of the polar front (Edwards *et al.*, 2021).

Food webs

Depletion of the territory and ice conditions under which seals give birth and whales avoid predators, the greatest fear being killer whales, will lead to major changes in food webs (ICES, 2018; ICES, 2021; ICES, 2022).

Understanding the extent and magnitude of all the different impacts is important, because they could result in reductions of sensitive habitats and species as well as continued declines in biodiversity.

Distribution shift

Increasing evidence indicates that geographic shifts of marine biodiversity towards northern ranges are largely driven by changes in sea surface temperature and associated changes in primary production, as species adjust to changes in environmental conditions and in the abundance and distribution of prey (ICES, 2016). These may be categorised as tropicalization (Horta e Costa *et al.*, 2014), meridionalization (Punzón *et al.*, 2016) and borealization (Fossheim *et al.*, 2015). The high latitude regions have become increasingly dominated by species with warmer affinities (ICES, 2008; Lenoir *et al.*, 2014; Simpson *et al.*, 2011). Climate change impacts are expected to be more pronounced in Region I, where species are more restricted in their ability to adapt and move further north (see: Marine Mammals Thematic Assessment and Fish Thematic Assessment).

Pelagic

Latitudinal shifts have been observed in a wide range of pelagic species, particularly the zooplankton taxa. For example, range shifts of *Calanus* zooplankton taxa have been observed, with *Calanus helgolandicus* (associated with warmer water habitat) replacing *Calanus finmarchicus* (associated with colder waters) (Beaugrand, 2003) (see: Pelagic Habitat Thematic Assessment).

Birds

Temperature-mediated shifts in distribution and earlier departures of seabirds (change in timing of life events) have been observed within the OSPAR Maritime Area, with some species becoming increasingly concentrated in north-eastern areas during winter and fewer reaching south-western parts of their former range (so-called "short-stopping"). The effects are often species- and region-specific, thus contributing to the difficulties in attributing broad-scale changes (see: Birds Thematic Assessment).

Marine mammals

Shifts in the range of some cetacean species have been observed (see: Marine Mammal Thematic Assessment). For example, Williamson *et al.* (2021) found a northward shift in the occurrence of strandings of warm-water adapted species (short-beaked common and striped dolphins) related to changes in sea-surface temperature, in OSPAR Regions II and III.

Fish

Recent assessments of the long-term distributional shifts of key commercial fish stocks in Europe have found distributional shifts for all examined species (Baudron *et al.*, 2020; ICES, 2016). Species identified as 'big movers' include anchovy, white anglerfish, cod, megrim, haddock, hake and plaice (ICES, 2016). Increases in abundance and biomass are predicted for fish stocks in high latitude regions (Arctic and subarctic) and the poleward tips of the continental shelf margin, while declines are anticipated within the tropics and at the southern margins of semi-enclosed bodies of water (e.g. the Celtic Sea and the Bay of Biscay; Cheung *et al.*, 2010) (see: Fish Thematic Assessment).

Benthos and NIS

The effect of seawater warming is related to expectations of a general northward expansion of marine species (Pinsky *et al.*, 2013; Poloczanska *et al.*, 2016), with some evidence and indications of climate-related changes affecting increasing abundances of non-indigenous species (NIS) in marine systems (García-Gómez *et al.*, 2020; Sorte *et al.*, 2010; Staehr *et al.*, 2020). The northernmost regions of the North Atlantic are predicted to experience the greatest impacts under worst-case climate scenario predictions. Increased temperature and lower pH will lead to declines in population densities, loss of biodiversity and reduced biogeographic distribution that might compromise connectivity across large time scales as well as long-term survival. Nowadays, warm-water benthic taxa are more common in the Barents Sea (ICES, 2021; Jørgensen *et al.*, 2022). Considering the different pathways of NIS introduction, a northward expansion seems most relevant in the case of secondary introductions, as NIS introduction hotspots in southern seas would introduce new NIS to northerly regions where temperature conditions gradually became favourable. Secondary introductions (~spread) have, however, accounted for only 5% of the NIS introductions in the OSPAR Regions. Overall, there is currently no strong evidence of climate change-related northward spread of NIS.

Climate change influences marine species composition and food-webs

Changes in species composition driven by climate change have been observed for marine organisms of every habitat, triggering further changes in trophic interactions. As the base of the food web, the changing phytoplankton and zooplankton communities have consequent effects on the benthic and pelagic organisms which rely on them for food, and in turn on their top predators, such as seabirds and marine mammals. These changes often take place on a local or regional scale and their characteristics differ between the OSPAR Regions (Baird *et al.*, 2019).

Phytoplankton are highly sensitive to changes in physical and chemical conditions, namely temperature, salinity, light, nutrients, pH, storminess and currents, as well as to the availability of oxygen and CO_2. Each of these factors is influenced by changing climate (see: Pressures section). Changes in ice-associated biota communities are strongly linked to the thinning and reduction of sea ice cover in OSPAR Region I (AMAP, 2017).

More generally, changes in prey species within marine food webs may result in distribution range shifts of the mobile predator species which follow them, or may have effects on predator population density and size as prey becomes less valuable or available, leading to lower species performance, e.g. for example breeding failure or reduced biomass (for further details and examples see (for further details and examples see the Food Webs Thematic Assessment).

Primary productivity from phytoplankton may be augmented by nutrient enrichment due to climate change-induced increased riverine input after extreme rainfall events, and, in colder regions, from loss of sea ice. However, other human impacts may interact with these impacts, and there may also be increased potential for harmful algal blooms as a result of climate change. Decreasing sea surface salinity impacts zooplankton diversity in shelf habitats of the Celtic Seas (OSPAR Region III), but also in oceanic habitats of the Bay of Biscay and the Iberian coast (OSPAR Region IV). While changes in plankton communities (encompassing lifeforms, biomass, abundance and diversity) may also be influenced by anthropogenic factors, climate change – which is associated with changing light attenuation, increasing temperature and sea surface salinity and their combined influence on stratification – has a strong impact on plankton communities. The effects of ocean acidification may then be an added stress factor. In all areas, predator-prey decoupling – between primary and secondary production – is expected to cause increased sinking of phytoplankton to the sea bottom (Morrison *et al.*, 2019) (for further details and examples see the Pelagic Habitats Thematic Assessment).

Like the pelagic ecosystem, benthic communities will be affected by climate change, resulting in changing species composition and predator-prey decoupling. In shallow water or coastal areas, sea-level rise, storminess and extreme weather events may change the community structure. The impacts on deep sea benthic habitats remain unclear: stratification may hinder the input of nutrients and, as with seasonal shelf sea stratification, productivity may be limited in summer. Winter storms may promote water-column mixing in winter (for further details and examples see Benthic Habitats Thematic Assessment).

Warming could create environmental conditions that help introduced species to become established and spread, especially northwards (cf. Occhipinti-Ambrogi, 2021; Townhill *et al.*, 2017; Poloczanska *et al.*, 2016; Dukes & Mooney, 1999). While the NIS introduction rate is probably underestimated, higher NIS arrivals have been observed on southern European coasts (Tsiamis *et al.*, 2019). The expected increases in biomass and abundance of NIS will change food web structure and functioning in all OSPAR Regions (Jung *et al.*, 2020). However, there is only limited scientific documentation of causal effects from climate change on NIS (for further details and examples see Non Indigenous Species Thematic Assessment).

The climate change impacts on seabirds include increased foraging difficulty due to extreme weather, changes in prey availability, increased predation and/or competition, increased heat stress on adults/chicks/eggs, and in some cases nest destruction caused by extreme climate events (see Marine Birds Thematic Assessment). As an example, lower over-winter survival and lower breeding success have been observed in black-legged kittiwake (Frederiksen *et al.*, 2004, 2005, 2007; Frederiksen, 2014). This is due to the species' dependence on sand eels, which in turn depend on copepod prey that have seen a northward shift at the time of peak abundance due to increased sea surface temperature. As sand eels are an important food for many seabirds, similar effects are expected to be observed for other species. In addition, extreme events are expected to have more impact in the future (Mitchell *et al.*, 2020). Changes in food supply are evaluated as the major threat to seabirds by seabird conservation practitioners (Hakkinen *et al.*, 2022). This changing relationship is also valid for other prey species like herring (Durant *et al.*, 2003) and sprat (Österblom *et al.*, 2006). Changing food availability not only impacts birds, but also marine mammals. Minke whales, for example, are observed to have declined near Iceland, probably because of lower food availability and a decrease in preferred prey species (Víkingsson *et al.*,2015; ICES, 2018).

The consequences described above, such as reduced or different prey availability, breeding failure due to habitat changes and changes in size and biomass, are also changes of concern for fishes (see: Fish Thematic Assessment) and marine mammals (see: Marine Mammals Thematic Assessment) in all OSPAR Regions.

(Eco)physiological alterations and changes in life history within species
As described above, altered timing in plankton growth may result in mismatches between prey and predators that are especially relevant for juvenile fish and their development. Increased physiological energy demand due to increased water temperature coincident with lower food supply – both due to climate change – may also explain reductions in fish biomass (Lotze *et al.*, 2019). As juvenile fish are likely to grow more rapidly due to the ecophysiological effects of temperature, adult maximum sizes are expected to be reduced for metabolic reasons and adaptive life history traits (Genner *et al.*, 2010, Ikpewe *et al.*, 2021; see also Fish Thematic Assessment). Climate change-induced higher water temperatures will also raise the metabolic demands of omnivorous zooplankton (Capuzzo *et al.*, 2017; Thorpe *et al.*, 2022; see also Pelagic Habitats Thematic Assessment). Additionally, physiological heat intolerance is predicted to create regions that are unsuitable for species, causing local extinction in specific regions. For example, Arctic skua are expected to become less abundant in the British Isles (moderate confidence) and may even become entirely absent (low confidence; Pearce-Higgins *et al.*, 2021; see also Marine Birds Thematic Assessment). For top predators like sea birds and marine mammals, the melting of the Arctic ice also generates leakage from reservoirs of persistent chemicals, which bioaccumulate in the food web and interact with physiological processes (see: Marine Mammals Thematic Assessment).

Other linkages

The reductions in sea ice cover in the Arctic due to climate change may exacerbate other human pressures on the ecosystem. These include increased disturbance from cargo vessels, expansion of wild capture fisheries into the region, and other industrial effects. These activities may cause further disturbance to Arctic mammal species and could lead to the introduction of NIS. Other cumulative impacts could be increased collision risk and by-catch and additional exposure to underwater noise.

Productive and sustainably used seas

Change in productivity or resilience of the ecosystem

The stress from climate change might exacerbate pressures from human activities and may further weaken ecosystem resilience. The changes will affect physical, chemical and biological cycles and may affect the ocean's ability to stabilise the climate.

Stock distributions and/or sizes of fish and other seafood groups may change, for example through increased catch potential in high latitude areas (although impacts on commercially important stocks are uncertain) and decreases further south. The assessment, allocation, and transboundary management of catches may become increasingly complex and contentious. Fishers may need to adapt their practices, for example to address changes in the frequency of extreme events or to ensure resilience of fish stocks.

Climate change may also cause loss of aquacultural production or infrastructure due to increased intensity or frequency of extreme weather events. Diseases, harmful blooms, parasites and other negative effects on fish and shellfish production might increase due to physical/chemical changes in the environment. There will also be an increased risk of microbial pathogens and non-native species spreading from aquaculture systems into the environment and becoming established, if climate change creates more favourable conditions for them. The potential expansion of this sector into large-scale inshore and offshore facilities can potentially magnify some of the above issues. However, there is some possibility of positive impacts such as higher growth rates in certain warm-water finfish or shellfish aquaculture.

Change in ability to conduct the activity

Climate change has already led to other environmental changes such as increased frequency of storm events or the reduction in Arctic sea-ice coverage. These alterations will intensify in the coming years and alter the way human activities can be conducted.

Reduced ice coverage in the Arctic Waters Region could lead to further increases in shipping activity in some parts. How significant this will be remains uncertain, and depends on factors such as the length of the Arctic shipping season and the economic viability of trans-Arctic routes. Reduced ice cover and thus increased access may also result in the expansion of the offshore oil and gas industry in the Arctic, see Human Activities Thematic Assessment .

Changes in rainfall, extreme weather events, sea-level rise, increasing risk of marine pathogens and beach erosion could all affect marine and coastal tourism. Any associated recreational activities such as boating, coastal walking and water sports may also experience increased exposure to extreme, unsafe conditions (see: Human Activities Thematic Assessment).

Change of the activity/pressure due to climate change

Several human activities are experiencing changes due to climate change, often altering their pressure footprint on the marine environment. These changes are likely to continue and, in some cases, accelerate.

Sea-level rise will increase the demand for sand for coastal reinforcement and maintenance, and thus increase aggregates extraction. It will also have an effect on the dredging activities which help to maintain shipping routes and facilitate harbour access, see Human Activities Thematic Assessment.

Extreme wind and wave events, shifting seafloor sediments and rising sea levels also present a changing hazard in the long term to offshore assets such as oil and gas installations, renewable energy infrastructure and subsea pipelines and cables. The vulnerabilities that can result from extreme storms and high wave events include the destabilization, scouring or degradation of offshore and subsea structures, health and safety risks to staff, reduced operating periods and reduced access for maintenance and inspection activities, thereby increasing the likelihood of accidents, including spill and pollution incidents (see: Human Activities Thematic Assessment and Offshore Industry Thematic Assessment).

The expected large-scale development of offshore renewable energy capacity over coming decades may have impacts on local wind, wave, tide and sediment dynamics. There may be impacts on marine life, particularly on benthic environments surrounding the structures. To date, it is unclear how the expansion of offshore renewable energy, particularly wind energy structures, will interact with the impacts from climate change. This will depend on the region, time frame and scale of each development (see: Human Activities Thematic Assessment).

Environmental changes in the physical properties of the ocean will influence levels of ambient underwater noise and the propagation of sound underwater. Climate-driven shifts in some activities, such as the relocation of shipping routes and fishing grounds and the expansion of offshore renewable energy, together with other potential effects from changes to, for example, vessel specifications and fishing fleet size and coverage will, in line with decarbonisation policies, result in different levels of anthropogenic underwater noise in the future. Activity restrictions, noise abatement and other mitigation measures may become more widely used to limit underwater noise levels (Faulkner *et al.*, 2018), although these measures are likely to be focused on sensitive habitats/species and therefore be localised in their effect (see: Underwater Noise Thematic Assessment).

Changing rainfall patterns and the impacts from extreme rainfall events will affect hydrological connectivity and the mobilisation of sediments, nutrients and contaminants (including microplastics) from agricultural land to waterways and in turn to marine waters. Sewer networks could become overloaded, leading to surface water flooding and overflow at urban waste water treatment plants, with untreated sewage along with litter flowing into waterways and/or coastal areas (see: Human Activities Thematic Assessment).

There is also evidence of climate-related increases in the occurrence and spread of non-indigenous species in marine systems. The greatest risk here is predicted for the northernmost regions of the North Atlantic. Changes to shipping routes, for example as year-round trans-Arctic routes emerge, coupled with warming temperatures, will increase the risk of non-indigenous species being introduced through ballast water exchange and transport on ships' hulls. Similarly, offshore man-made structures may act as stepping-stones for non-native invasive marine species (see: Non Indigenous Species Thematic Assessment).

I – Impact (on Ecosystem Services)

Impact of marine climate change on ecosystem services

Marine climate change has an impact on most ecosystem services. In many cases, this is directly due to climate change, while in some cases the impacts may be more indirectly due to humanity's response to the climate emergency (for example, offshore renewable energy developments and mineral extraction).

The marine environment provides goods and services that are valued by our society, either in a direct monetary way or intrinsically. These ecosystem services originate from both living and non-living processes within the marine environment and can be divided into four categories: provisioning, regulation, maintenance and cultural (see: Ecosystem Services Descriptions). Recent reports by the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have concluded that globally, ecosystem services from the ocean will be negatively impacted by climate change, with greater losses anticipated at higher levels of global warming (Pörtner *et al.*, 2014; Hoegh-Guldberg *et al.*, 2018; Bindoff *et al.*, 2019; IPBES, 2019).

The ocean provides arguably the greatest ecosystem service in the climate- change context by alleviating the impacts of global warming across all components of the Earth system (climate regulation). The extent of the biotic and abiotic climate regulation achieved by the ocean in absorbing the greenhouse gas CO_2 and absorbing the excess heat in the Earth system cannot be overstated: it has absorbed 89% of the excess heat since the 1970s (von Schuckmann *et al.*, 2020) and every year absorbs at least a quarter of the carbon dioxide (CO_2) released to the atmosphere from human activities (see: Ocean Acidification Other Assessment).

While climate regulation may be the ecosystem service linked most directly to climate change, ecosystem impacts have been described in almost every Thematic Assessment of the QSR 2023, and therefore climate change will likely have an overarching impact on all ecosystem services. The following two examples illustrate potential impacts on ecosystem services, although many more could be listed. First, the anticipated rise in local sea levels will increase requirements for coastal protection. Local sea-level rise may, however, reduce the ability of existing habitats to provide adequate protection. Second, changes in the ocean climate may cause distributional shifts in fish species. This may lead to a reduction in the provision of wild fish biomass.

A recent climate change assessment in the adjacent Baltic Sea (Climate Change in the Baltic Sea, 2021) found that most ecosystem services are expected to reduce because of climate change, although the exact changes in ecosystem services due to climate change are difficult to predict due to uncertainty about future non-climate pressures. The exception to these negative impacts are cultural services related to marine and coastal recreation and tourism, which could benefit to some extent from the impacts of climate change through higher air and sea temperatures and longer seasons. The cumulative effects of other anthropogenic pressures (such as eutrophication, pollution, fishing and aquaculture) have the potential to further reduce ecosystem services by offsetting opportunities or strengthening impacts. Efforts to increase resilience (e.g. protection and restoration) could help maintain or even improve ecosystem services under global warming.

While other Thematic Assessments have applied a link-based methodology, this would have resulted in unclear linkages in the case of climate change owing to the countless interconnections. Therefore, the methodology in this Thematic Assessment does not follow the harmonised approach adopted in others. Instead, in order to further investigate the impacts on ecosystem services, a more general scoring system was attempted by the OSPAR Climate Change Expert Group, based on expert opinion.

A workshop was held on 19 August 2022, with representatives from Belgium, Iceland, Ireland, Sweden and the United Kingdom, and observers, who were all members of the OSPAR Climate Change Expert Group. During the workshop, the 11 participants were asked to select one of the following six categories to describe the response to climate change by each ecosystem service (these were assigned a score between 0 and 5 in the subsequent analysis): no response (0), unknown (1), no impact (2), some indirect impact (3), some direct impact (4) or strong impact (5). **Table I.1** shows the responses for each category as a percentage of respondents (columns 3 to 8), as well as the weighted average score (second column). An example of direct impact from climate change on the ecosystem service under consideration would be where increased temperatures changed finfish distributions or sea level rise caused a change in coastal protection. Indirect impacts were those where the ecosystem service was affected by a sequence of processes (e.g. sea-level rise would create a need for greater coastal protection, which would require more marine aggregate extraction). Future work could further explore how to quantify the impacts of climate change on ecosystem services in the OSPAR Maritime Area, and should draw on a larger participant pool if done through expert opinion.

Experts from the OSPAR Contracting Parties consider climate change to have a direct or strong impact on most of the ecosystem services (**Table I.1**). Seven ecosystem services were seen as being impacted directly by climate change (average score of 4 or above – blue shaded rows in the table), namely coastal protection by coastal habitats, wild fish and other natural aquatic biomass and related raw materials, nursery population and habitat maintenance, (global) climate regulation, regulation and maintenance of marine food webs, water quality regulation, and mediation of waste, toxics and other nuisances by non-living processes. Cultural ecosystem services were not considered to be so strongly impacted, although this could be due to the bias of expertise (natural sciences, rather than social sciences). The group agreed by consensus that the impact of climate change on the provision of genetic material constituted a knowledge gap.

Table I.1: Expert opinion on the impacts of climate change on Ecosystem Services (n=11). Participants could select one of six categories to describe the response to climate change by each ecosystem service (and these were assigned a score between 0 and 5 in the subsequent analysis): no response (0), unknown (1), no impact (2), some indirect impact (3), some direct impact (4) or strong impact (5). Percentage of participants for each category and each ecosystem service are shown in columns 3 to8. The average score (column 2) is the weighted mean of the scores.

Ecosystem Service	Average Score	No response (0)	Un-known (1)	No impact (2)	Some indirect impact (3)	Some direct impact (4)	Strong impact (5)
Coastal protection	4,91	0%	0%	0%	0%	9%	91%
Wild fish and other natural aquatic biomass and related raw materials	4,82	0%	0%	0%	0%	18%	82%
Nursery population and habitat maintenance	4,73	0%	0%	0%	0%	27%	73%
(Global) climate regulation	4,73	0%	0%	0%	9%	9%	82%
Regulation and maintenance of marine food webs	4,64	0%	0%	0%	9%	18%	73%
Water quality regulation	4,27	0%	0%	0%	9%	55%	36%
Mediation of waste, toxics, and other nuisances by non-living processes	4,09	0%	0%	0%	0%	91%	9%
Biomass and raw materials from in-situ aquaculture	3,91	0%	9%	0%	9%	55%	27%
Recreation related services	3,91	0%	0%	0%	18%	73%	9%
Education, scientific, and research services	3,82	0%	0%	0%	45%	27%	27%
Pest control	3,64	9%	0%	0%	18%	55%	18%
Sediment quality regulation	3,64	0%	0%	0%	45%	45%	9%
Ecosystem and species appreciation	3,55	0%	18%	0%	18%	36%	27%
Visual amenity services	3,27	0%	0%	9%	64%	18%	9%
Mineral substances used for material purposes	2,91	0%	9%	18%	55%	9%	9%
Spiritual, artistic, and symbolic services	2,73	0%	27%	0%	45%	27%	0%
Genetic material	2,18	9%	36%	0%	36%	18%	0%

R – Response

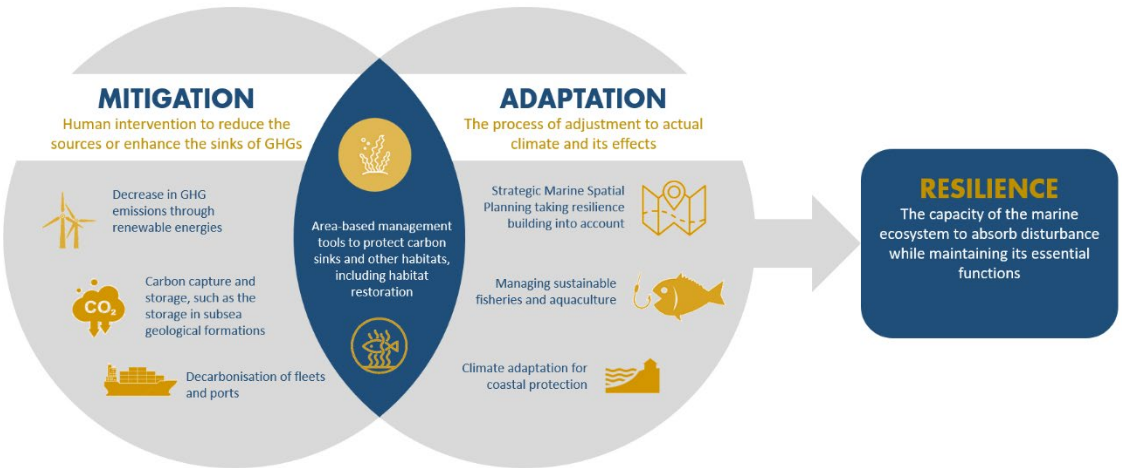
Responding to the climate emergency: mitigation, resilience, and adaptation

The OSPAR Contracting Parties will need to take action to reduce global warming in order to comply with the UNFCCC Paris Agreement (i.e. to limit the rise of global average temperatures to well below 2 ˚C, and ideally below 1.5 ˚C above pre-industrial levels), to adapt to climate change impacts (those that are already emergent and those that are locked in because of greenhouse gas emissions to date and anticipated in future years) and to increase the resilience of human and biological systems. To date, no specific OSPAR measures to mitigate or adapt to climate change or to increase resilience are in place, although the NEAES 2030 has outlined an ambitious strategy by the OSPAR Contracting Parties intended to make significant progress on climate change and ocean acidification. Areas of opportunity for mitigation include offshore renewable energy, carbon capture and storage and protection and restoration of natural carbon stores. Through effective management of marine space and of human pressures on the marine ecosystem, the OSPAR Contracting Parties may be able to support adaptation to climate change and enhance the resilience of the marine ecosystem.

Climate change mitigation, adaptation and resilience in the OSPAR context

The ocean plays a pivotal role in climate regulation through its uptake of CO_2 and heat from the atmosphere. The ocean currents transport considerable energy around the globe. Ocean currents work like conveyor belts that transport vast quantities of heat around our planet, maintaining many of the Earth's climate zones. The uptake of heat by the oceans has significantly slowed down climate change and mitigated global warming. Through the processes of the marine carbon pump, atmospheric CO_2 is stored in plants, animals and marine sediments in the form of organic carbon. Absorbing more than a quarter of global anthropogenic CO_2 emissions, the ocean is one of the biggest natural carbon sinks on our planet.

However, the ocean is also vulnerable to the impacts of anthropogenic pressures and the effects of climate change. Mitigation (the reduction of greenhouse gas emissions or the enhancement of their sinks) and adaptation (the adjustment to actual or anticipated climate) are required in order to maintain and build the resilience of the ocean and its ecosystems against these threats. Resilience is the capacity of a system to absorb disturbance without losing its essential function. Mitigation and adaptation are processes which can either maintain or build resilience. OSPAR still needs to adopt further specific measures to mitigate or adapt to climate change or to increase resilience. The NEAES 2030 has outlined OSPAR's ambitions to support climate action across its Contracting Parties. The Ocean Acidification Other Assessment has highlighted a number of mitigation and adaptation responses that are effective for ocean acidification. Below, a broader overview is provided.



Climate change mitigation

Mitigation is defined as "*A human intervention to reduce emissions or enhance the sinks of greenhouse gases*" (IPCC, 2022). Each year, the global ocean absorbs approximately one quarter (Friedlingstein *et al.,* 2021) or possibly more (Watson *et al.*, 2020) of the carbon dioxide released to the atmosphere from human activities (Friedlinstein *et al.*, 2021). On a global scale, 12% of the mitigation required by 2030 to ensure that warming does not surpass 1.5˚C could be provided by ocean-based initiatives (Hoegh-Guldberg *et al.*, 2019). The growing role of all actors in the global effort to address climate change was recognised in the recent IPCC report on Mitigation of Climate Change (IPCC, 2022). This clearly also applies to marine initiatives, and can encompass national, regional and global climate policies that are boosted by the mitigation actions of citizens, businesses, cities, and local initiatives. Regional level initiatives that can reduce carbon emissions or increase carbon sinks are considered below. The same IPCC report also discusses wider policy considerations and their potential outcomes and implications.

Changing energy strategies (wind)

Electricity and heat account for 23% of total global greenhouse gas emissions (IPCC, 2022), and many countries are changing their energy strategies to reduce these. Renewable energy generation in the marine environment has grown substantially, mainly through the development of offshore wind farms, although wave and tidal energy are also being considered by some nations where conditions are suitable (high wave exposure, large tidal range or strong tidal streams).

Within the OSPAR Maritime Area, growth in offshore wind energy generation has been substantial, and a further significant increase is expected in the next decade, especially in Regions II and III.

The substantial current and anticipated growth of the offshore renewable energy sector also requires suitable consideration of the ecological impacts so as to ensure sustainable development. OSPAR will progress this under Strategic Objective S12.O4: “By 2023 OSPAR will develop common principles and by 2024 develop guidance to promote and facilitate sustainable development and scaling up of offshore renewable energy in such a way that cumulative environmental impacts are minimised”. Knowledge gaps remain, particularly around cumulative effects, although a number of major evidence programmes are in progress to address this aspect. OSPAR’s Intersessional Correspondence Group on Offshore Renewable Energy Development (ICG-ORED) was convened for the first time in 2022 and aims to contribute to this objective by producing a regional sea approach to the assessment of the cumulative effects associated with the development of offshore renewable energy. This approach could then guide future measures and actions across the OSPAR Contracting Parties.

Carbon capture and storage (CCS)

Carbon capture and storage (CCS) (see: glossary) is the capture of carbon dioxide from anthropogenic source emissions and its subsequent transport to and storage in underground geological storage sites. This is a human activity intended to reduce atmospheric carbon dioxide emissions. In 2007, the OSPAR Commission endorsed CCS in subsea geological formations, provided that carbon dioxide streams stored in geological formations are retained in those formations permanently (OSPAR Decision 2007/02). Under this Decision, storage of carbon dioxide should be authorised only if it does not lead to negative consequences for the marine environment, human health and other uses of the maritime area.

The storage of CO_2 in geological formations, including depleted oil and gas reservoirs and saline aquifers, is an emerging offshore activity. There are two large-scale CO_2 storage projects currently operating in the OSPAR Maritime Area (see: Offshore Industry Thematic Assessment). There is the risk of CO_2 leakage from a storage site, and should it occur it may have negative effects on the receptors in the marine environment. Other negative effects may include an increase in underwater noise from activities to monitor the integrity of sub-seabed storage (see: Underwater Noise Thematic Assessment).

Work by the IPCC has recognised that pathways to limit global warming to 2°C or below may require the deployment of a certain amount of carbon dioxide removal technology, such as CCS, particularly in the short-term. However, it is widely recognised that these should not be considered the sole method for reducing greenhouse gas emissions. For OSPAR Contracting Parties that are also Parties to the London Protocol (1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972), Resolution LP.5(14) recognises that CCS should be considered part of a portfolio of options and should not be considered as a substitute for other measures to reduce carbon dioxide emissions. The Decision also stresses that the disposal of carbon dioxide streams into sub-seabed geological formations does not remove the obligation to reduce the need for such disposal or the commitments undertaken in the framework of the UNFCCC to reduce greenhouse gas emissions.

As part of NEAES 2030, under Strategic Objective S12.O3, OSPAR will review and assess the adequacy of monitoring techniques and the effectiveness of measures to ensure that carbon dioxide streams are retained permanently in the storage complex and will not lead to any significant adverse consequences (as above).

De-carbonisation of fleets

Maritime transport plays a key role in the facilitation of international trade, accounting for almost 80% of worldwide goods transportation (European Commission, 2021). While shipping is the most carbon-efficient mode of transport per tonne/kilometre, it produced 2.9% of annual global greenhouse gas emissions in 2018, representing 1 076 million tonnes of CO_2. Approximately 85% of the total CO_2 emissions from international shipping comes from ships of 5,000 gross tonnage or above (IMO, 2018; IMO 2020). High densities of shipping occur in the OSPAR Maritime Area, with the highest occurring in the English Channel, southern and eastern North Sea and the entrance to the Mediterranean (see: Shipping and Ports Feeder Report).

Additionally, ships produce black carbon particles when burning heavy fuel oil, which are emitted into the environment via their exhaust fumes. These particles contribute to the warming of the Earth's atmosphere. When they fall on snow, glacier ice or sea ice, their warming impact is 7 to 10 times greater than on land, as their reflectivity (albedo) is reduced and consequently their absorption of heat increases. According to the International Council on Clean Transportation, approximately 7 to21% of global shipping's climate warming impacts can be attributed to black carbon over a 20-year Global Warming Potential time frame – the remainder being mostly CO_2, followed by methane (CH_4). Black carbon emissions from shipping increased by 85% between 2015 and 2019.

The IMO is responsible for the global regulation of international shipping and has a key role in ensuring that lives at sea are not put at risk, including by ensuring security of shipping, and that the environment is not polluted by ships' operations. Since 2011 (IMO, 2011), the IMO has developed mandatory regulations to address greenhouse gas emissions from ships through a number of resolutions focusing on mandatory technical and operational measures to improve energy efficiency. A revised strategy with strengthened objectives is to be adopted by the IMO in July 2023, while the initial IMO Strategy on reduction of greenhouse gas emissions from ships agreed in 2018 has the overall objective of full decarbonisation and the ambition to reduce the emissions from international shipping by at least 50% by 2050, compared with 2008 (IMO, 2018).

To date, the maritime sector is not on track to achieve the emissions reductions needed to achieve its commitments under the Paris Agreement. In the context of the IMO strategy, new measures are being developed and their prospects considered. Potential measures include support for the uptake of alternative low-carbon and zero-carbon fuels, in the form of guidelines on the lifecycle greenhouse gas intensity of marine fuels, low-carbon fuel standards and carbon pricing, as well as further energy efficiency measures such as fleet improvement and efficient new ship design, speed optimization and reduction, addressing emissions of methane and Volatile Organic Compounds, and others.

In the European context, the 2020 EU Communication on a Sustainable and Smart Mobility Strategy aims to achieve zero pollution of air and water from shipping in emission control areas and to bring the first zero-emission ocean-going vessels to market by 2030 (European Commission, 2020). Under the European Green Deal, a series of legislative proposals have been formulated with a view to reducing net greenhouse emissions, several of which address the maritime transport sector, such as the inclusion of shipping in the EU Emissions Trading System (ETS), the FuelEU Maritime (a carbon fuel standard for marine fuels), the Alternative Fuels Infrastructure Directive, the revision of the renewable energy directive (RED) and the revision of the Energy Tax Directive.

Ports

Ports are crucial to providing the infrastructure for maritime transport and play an essential role in the development of many maritime sectors. In 2018, the gross weight of goods handled in OSPAR ports was around 2,4 billion tonnes, with the number of containers involved slightly higher than 10 years previously (see: Shipping and Ports Feeder Report).

The future of ports lies in their key role as '*…energy hubs (for integrated electricity, hydrogen and other renewable and low-carbon fuels systems), for the circular economy (for collecting, transhipping and disposing of waste from ships and other port industries, and for decommissioning ships), for communication (for submarine cables), and for industry (as industrial clusters)'* (European Commission, 2021).

The greening of maritime transport and ports can contribute to the efforts to mitigate carbon emissions. The creation of zero-emission ports, for example, is one of the flagship initiatives of the European Commission's sustainable and smart mobility strategy, promoting measures to encourage the deployment of renewable and low-carbon fuels and onshore power supply together with renewable energy and the greening of port services and operations. Another element helping decarbonisation is the use of smart digital solutions and autonomous systems, as they can optimise traffic flows and cargo handling in and around ports.

The gross tonnage of ships entering OSPAR ports has increased in the last ten years. The trend towards larger ships, while resulting in lower average transport costs, also necessitates ongoing dredging, new port infrastructure and the possible relocation of ports, and increases the potential for greater environmental impacts if a serious accident were to occur (see: Shipping and Ports Feeder Report).

Blue carbon and marine sedimentary carbon stores

Some coastal and marine habitats can take up and store large quantities of carbon derived from atmospheric carbon dioxide through natural processes. Coastal blue carbon habitats include mangroves, salt marshes and seagrasses, which have high carbon burial rates on a per unit area basis and accumulate carbon in their soils and sediments (IPCC 2022, AR6). These ecosystems are recognised in the official international methodologies for inclusion in national greenhouse gas inventories. Seagrass meadows, mangrove forests and salt marshes are, per unit area, more effective stores of carbon than tropical forests. Despite their much smaller overall area, total global sequestration by these habitats is comparable to total global annual organic carbon storage by terrestrial forests (Mcleod *et al.*, 2011).

Other habitats that have not yet been incorporated in the international standard methodology owing to lack of knowledge include coastal and non-coastal processes and ecosystems such as macro-algae (kelp) and carbon-rich coastal and shelf sea sediments. There is a need to improve the evidence on these habitats so as to make future greenhouse gas reporting and accounting more robust.

Marine sediments are important areas of natural carbon sequestration and storage and constitute the largest permanent sink for carbon on our planet (Berner and Berner, 2012). In the North Sea area, carbon stocks in muddy sediments ("mud carbon") are two orders of magnitude higher than those in blue carbon ecosystems (Legge *et al.*, 2020). Activities that result in disturbances to the seabed, such as dredging or trawling, can cause carbon dioxide to be released from sediments, but the processes are complex and the overall impact of carbon dioxide release and its destiny (sediment, water or atmosphere) remains uncertain. Several scientific projects in OSPAR Contracting Parties continue to build the evidence for potential blue and mud carbon habitats, including marine sediments, and threats from human activities and climate change.

Within NEAES 2030, the role of natural carbon storage in marine habitats, such as blue carbon, in helping mitigate climate change and resilience is recognised under the following strategic objectives:

- Strategic Objective 6: Restore degraded benthic habitats in the North-East Atlantic when practicable to safeguard their ecosystem function and resilience to climate change and ocean acidification.
- Strategic Objective S12.O1: By 2025 OSPAR will develop a regional approach to applying nature-based solutions for carbon storage and implement specific measures to protect and restore relevant carbon sequestration and storage habitats, such as seagrass beds, kelp forests and saltmarshes.
- Strategic Objective S12.O2: By 2025 OSPAR will take nature-based carbon storage into account when reviewing the criteria for the designation of marine protected areas, and reviewing the OSPAR List of threatened and / or declining species and habitats.

Many of these carbon-storing habitats provide additional benefits (beyond carbon sequestration or storage), including their roles as a habitat for species of conservation and commercial interest and in coastal flood protection. They thus also provide climate change adaptation responses in terms of income and subsistence from harvesting, and coastal infrastructure.

Adaptation

Adaptation is defined as "*In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects."* (IPCC 2022, AR6). It requires persistent evaluation of climate-related risks and the implementation of proactive policies and measures, over time, to build resilience into our ecosystems and societies against the impacts of climate change. Adaptive actions should be risk-based, underpinned by an understanding of projected climate change, and informed by the existing vulnerabilities in our ecosystems and the human activities that take place in the marine environment.

Climate-smart marine management

Climate change is modifying the oceanographic conditions that underpin the structure and functioning of marine ecosystems. These evolving conditions will alter the spatial and temporal range of species and habitats and, in turn, the provision and distribution of vital goods and services they underpin. In combination with this, projected wind extremes, storm surges and increased wave energy may affect the distribution and sustainability of human activities such as fishing and aquaculture, maritime traffic, tourism, coastal infrastructure and maritime structures relating to offshore wind energy. The magnitude of the impacts will be regionally specific and will vary across different maritime sectors, requiring varying response and management options.

Adaptive management policies which integrate climate change into marine spatial planning ("Climate Smart MSP") could enable maritime sectors, and marine protection efforts, to respond to future scenarios (Frazao-Santos *et al*., 2020). This could reduce the vulnerability of marine systems to changing ocean conditions by ensuring that the cumulative impacts of climate change and anthropogenic maritime uses such as development, pollution and resource extraction, are taken into consideration (Santos *et al*., 2020). To inform this process, it would be essential to improve knowledge and data on the possible impacts of climate change. This could include the identification of vulnerable species and ecosystems and possible future shifts in their geographical and temporal distribution. The identification of climate change refugia (areas with natural resilience, where the ecosystem remains within the boundaries of its present state), hotspots (where climate drives the ecosystem towards a new state, inconsistent with present usage), and bright spots (areas where oceanographic processes drive range expansion opportunities that may support sustainable growth in the medium-term) would also help support adaptation (Queirós *et al.*, 2021).

The goals of the Paris Agreement include limiting the rise of global average temperatures to well below 2 ˚C, and ideally below 1,5 ˚C above pre-industrial levels. The expansion of renewable energy is one of the critical ways in which countries can help meet these obligations, the EU's energy and climate targets and the ambitions of the EU Green Deal. Considering the level of growth in this sector, it may be important to balance the distribution of renewable energy installations in accordance with the likely climate-related changes in ecosystem functioning. Moreover, there may be need to adapt maritime structures to changes in wave frequency and intensity, during construction and then during ongoing management periods. Balancing renewable energy needs, the possible impacts of climate change and the cumulative impacts of anthropogenic pressures on the marine environment will require foresight in all marine spatial planning scenarios.

Food Security and sustainability

Fisheries and aquaculture provide food and nutrition globally while also contributing to the income and livelihoods of millions of people (FAO, 2018). Observed climate change is already affecting global food security through increasing temperatures, changing precipitation patterns and greater frequency of extreme events (Mbow *et al.*, 2019). Impacts on marine systems, species redistribution and productivity are projected to challenge the provision of marine food by the mid-twenty-first century (IPCC, 2014).

Engaging in adaptation strategies that address climate change effects while concurrently considering other anthropogenic pressures will be essential to ensure the security and long-term sustainability of fisheries and aquaculture. Such strategies may include diversification within and across sectors, effective governance, improved management and conservation, and the continued development of low-input and low-impact aquaculture (FAO, 2018). Successful adaptation may depend strongly on the adaptive capacity of the industry, consideration of the correct options for localised pressures and the underlying environment, policy support and stakeholder involvement in the decision-making process.

Fisheries

The availability of fish stocks is strongly influenced by past and present fishing activities. Regional variations in the impacts of temperature and net primary production (an indication of the production at the base of the food web and ecosystem) have indicated that these two factors may also affect range shifts, growth, reproduction, the survival of fish stocks and species composition (Bahri, 2021; Bindoff *et al.*, 2019; State section).

Pursuing sustainable fishery practices and eliminating overfishing could reduce the risk caused by climate change and support the adaptation of fishery governance responses (Bindoff *et al.*, 2019). Management frameworks that allow decisions to be tested, evaluated, reviewed and adjusted, on the basis of the observations of real time changes in climatic, environmental and fish stock conditions, could also greatly assist adaptation (Bahri, 2021).

To support such robust fisheries management, reliable knowledge provision will be essential (Bindoff *et al.*, 2019). This includes data, modelling and projections of species shifts under forecasted climate scenarios. Such shifts in the range and distribution of fish stocks may require strong transboundary fisheries management together with adaptive allocation arrangements. Improved fishing gear and technology could also be considered in fisheries' adaptation strategies.

Aquaculture

The impacts of climate change on aquaculture can include short and long-term losses of production or infrastructure due to extreme weather events, increased risk of disease, toxic algae and parasites, decreased productivity due to suboptimal conditions, limited access to feeds, reduced feed production (e.g.

soy), scarcity of wild seed and increased perturbations such as eutrophication (Barange *et al.*, 2018). Ocean acidification may also affect aquaculture, in particular shellfish, in the North-East Atlantic, and threaten larval development, wild seed recruitment, the bio-availability of contaminants and the resilience of adult populations.

As with fisheries management, strategies that are adaptive and include considerations of the negative effects of climate change while also considering the possible positive gains could limit overall impacts (Maulu *et al.*, 2021). The adaptation options for aquaculture can include livelihood diversification, a shift to less vulnerable or more resilient species / techniques / areas, utilisation of local knowledge, and the introduction of insurance schemes among small-scale producers (see review in Maulu *et al.*, 2021).

Climate adaptation for coastal protection

Sea-level rise and changes in prevailing weather (storminess, wave climate) will increase the occurrence of coastal flooding events and coastal erosion. Future projections show that compound flooding (a co-occurrence between storm surge and heavy precipitation and run-off) will also increase around the coasts of the OSPAR Maritime Area, with the largest increases along the North Sea coast (Bevacqua *et al.*, 2019).

Coastal erosion, in particular, is a highly local and often episodic process, owing to the interplay between local coastal morphology, prevailing ocean conditions and meteorology. Adaptive actions for coastal protection will therefore require a site-specific approach taking into account local or sub-regional predictions of coastline response.

The range of measures for controlling flooding events includes hard engineering interventions (e.g. dikes, sea walls) and nature-based solutions (e.g. coastal vegetated ecosystems, biogenic reefs). Increasingly, preference is being given to “work with nature”, owing to the many associated co-benefits, whether environmental, social or economic. Examples of nature-based solutions in the coastal environment include the managed realignment of salt marsh, the restoration of oyster reefs, and protection and maintenance of natural dune systems. The implementation of nature-based solutions also calls for consideration of biosecurity in order to avoid the introduction of non-native invasive species.

Inland flood risk is also likely to increase due to climate change, and such events may cause acute pollution downstream in connected coastal and marine ecosystems. They could also have implications for nutrient loading (land run-off from agriculture and waste water treatment capacity), contaminants and litter (State section).

The adaptation-maladaptation continuum – a cautionary note

In “Climate Change 2022: Impacts, Adaptation and Vulnerability”, the IPCC documents increased evidence of maladaptation across many sectors and regions since the previous assessment cycle (IPCC, 2022). Maladaptive actions have been defined by the IPCC as “*actions that may lead to an increased risk of adverse climate-related outcome, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future*.” In its latest report, the IPCC recognises that successful adaptation is not a “black and white” outcome, but instead involves a continuum of risk management in which successful adaptation and maladaptation can be considered the two extremes (New *et al.*, 2022). Actions can score high or low against a range of outcomes, such as number of beneficiaries, ecosystem service benefits, equity outcomes, transformation and greenhouse gas emissions reduction. Examples of maladaptive actions in the context of OSPAR include lock-in caused by hard-engineered coastal defences or increased fossil fuel use in fisheries due to distributional shifts in target species. An adequate knowledge base, awareness of the long-term impacts and planning, and cross-sectoral and inclusive governance can help reduce maladaptation.

Resilience

Resilience is defined as "*The capacity of interconnected [...] systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function [...]*" (IPCC, 2022). A resilient ocean is thus one that is healthy and stable enough to withstand disturbances without losing its ecosystem functions. Such events could be due to climate change or other anthropogenic pressures that are threatening and changing marine ecosystems. OSPAR will support efforts to maintain and increase the resilience of marine ecosystems through a range of instruments. The following section discusses some of these measures.

Managing non-climate anthropogenic pressures to increase resilience

The combined effects of multiple pressures, including those from human activities, reduce the resilience of the marine ecosystem, habitats and species, including their ability to withstand and adapt to the impacts of climate change. It follows that the management of non-climatic pressures is also a critical tool for OSPAR to use in supporting climate change resilience. Examples of such management are control of nutrient inputs, addressing eutrophication effects, reducing the release of contaminants and radioactive substances, reducing marine and other litter and implementing an ecosystem-based management approach.

Area-based management tools as instruments for building resilience to climate change

Area-based management tools (ABMTs) enable the application of management measures to a specific area to achieve a desired policy outcome. ABMTs can focus on specific activities (e.g. fishery closures, pollution management) or on the coordination and management of several activities within an area (e.g. integrated coastal zone management, marine spatial planning). A wide variety of area-based management tools exists, each with their own purpose, mandate and authority (UN Environment, 2018). These include:

a. Sectoral ABMTs, including the IMO's Particularly Sensitive Sea Areas (PSSAs), traffic routeing systems, MARPOL Special Areas, RFMO temporal or spatial closed areas such as "Vulnerable Marine Ecosystems" (VMEs) or "other effective area-based conservation measures" (OECMs).
b. Cross-sectoral ABMTs, including Marine Protected Areas (MPAs), Highly Protected Marine Areas (HPMAs) or marine spatial planning, requiring consultation, cooperation and coordination across multiple organizations and bodies to manage clearly defined geographical areas.

While the management objectives and approaches may differ, the development of a well-managed, representative and connected network of protected areas will support and build resilience to climate change. The OSPAR MPA network comprises 572 MPAs covering 490 552 km^2 or 11% of the OSPAR Maritime Area. While all 12 Contracting Parties bordering the North-East Atlantic have designated MPAs, distribution is uneven across the five OSPAR Regions and the network cannot, as yet, be considered ecologically coherent (OSPAR, 2018).

Appropriate management is in place for some OSPAR MPAs, but many still await implementation. As a result, only 17% of OSPAR MPAs are known to be moving towards or have achieved their conservation objectives. A number of OSPAR countries also have area-based Other Effective Conservation Measures (OECMs) and non-OSPAR MPAs designated for specific features. These are protected, for the most part, through fisheries management measures (ICG-MPA 21/3/1.Add3).

A well-managed OSPAR MPA network will be crucial for maintaining protection of species and habitats and their resilience to the effects of climate change. There are two main areas where the MPA network may contribute to resilience. First, the protection of habitats and species across the MPA network at large spatial scales can contribute to ensuring that particular species or habitats survive within the network, even if they are lost in some locations due to changing ecological conditions or extreme events (such as increased frequency of storms or elevated sea surface temperature). Second, the MPA network can promote resilience to climate change by ensuring the maintenance and restoration of specific habitats that play vital roles in terms of climate regulation and regulation of ecosystem services. Such "blue carbon" habitats include kelp forests, seagrass beds, salt marshes or other habitats that represent effective carbon sinks or carbon. Other habitats such as reefs may provide valuable coastal ecosystem protection services. Such nature-based solutions also include providing protection from storm surges and regulating the effects of extreme weather events on coastal ecosystems and the communities they support.

The management of MPAs can be either active or passive. In active restoration, intervention is required so as to help restore ecosystems or increase the presence of species and features. Passive restoration allows ecosystems to recover via natural processes through the removal of pressures caused by human activities.

Three operational Objectives under OSPAR's North-East Atlantic Environmental Strategy will assist Contracting Parties in developing area-based management tools and improving the resilience of ecosystems in the OSPAR Maritime Area. These are:

- S5.O1: By 2030, OSPAR will further develop its network of marine protected areas (MPAs) and other effective area-based conservation measures (OECMs) to cover at least 30% of the OSPAR Maritime Area to ensure it is representative, ecologically coherent and effectively managed to achieve its conservation objectives
- S5.O4: By 2025 at the latest, OSPAR will take appropriate actions to prevent or reduce pressures to enable the recovery of marine species and benthic and pelagic habitats in order to reach and maintain good environmental status as reflected in relevant OSPAR status assessments, with action by 2023 to halt the decline of marine birds
- S11.02: By 2023 and every six years thereafter, OSPAR will assess at a regional scale the OSPAR network of MPAs in respect of the resilience of marine biodiversity to climate change, with the aim of ensuring that the network provides a good representation of species and habitats and that its spatial design and management regime remains relevant

Ecosystem restoration and Resilience

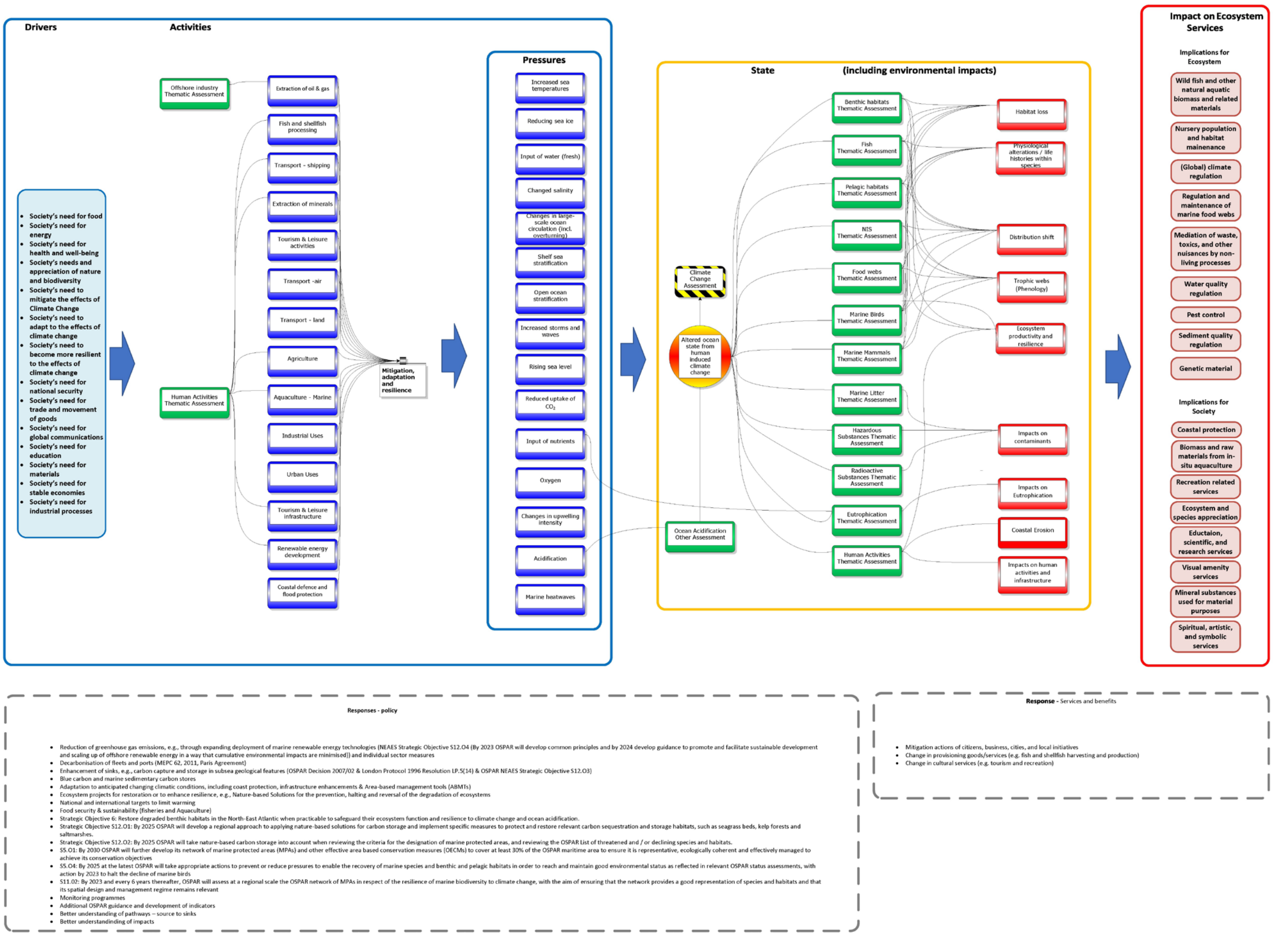
Ecosystem restoration – the prevention, halting and reversal of the degradation of ecosystems – is one example of a nature-based solution. More and more, ecosystem restoration is also recognised for its role in increasing resilience to climate change, and thus in indirectly benefiting human wellbeing. On average, the benefits of ecosystem restoration are ten times higher than the costs, with benefits including: employment, business spending, gender equality, and local investment in education and livelihoods (Montanarella *et al.*, 2018). The additional value to be obtained, through indirect benefits such as the climate resilience resulting from regulation services provided by the ocean, has still to be taken into account. Currently, the UN Decade on Ecosystem Restoration 2021-2030 is consolidating ecosystem restoration efforts globally in support of the UN's sustainable development goals (SDGs).

Coastal marine restoration is still a relatively young field, although it has gained in popularity recently (Saunders *et al.*, 2020). Marine restoration is still relatively less common practice than in terrestrial and freshwater systems. This may be due to the challenging environment (Saunders *et al.*, 2020), limited information on baselines and longer time scales (Danovaro *et al.*, 2021), or other technical, social and economic barriers (see for example Stewart-Sinclair *et al.*, 2020).

The natural regeneration of over-exploited ecosystems through passive restoration can be a low-cost and effective tool when it comes to offshore waters and carbon-rich sediments supporting the ocean's regulation function. Both passive and active restoration of marine ecosystems will contribute to higher ocean resilience to climate-induced changes and thus benefit nature and human society.

Natural capital approaches, where economic value is assigned to ecosystems and their components that provide valuable goods and services to society, are increasingly being recognised as a key tool to support ecosystem restoration (Farrell *et al.*, 2021). Under NEAES 2030, OSPAR will "start accounting for ecosystem services and natural capital by making maximum use of existing frameworks in order to recognise, assess and consistently account for human activities and their consequences in the implementation of ecosystem-based management".

Cumulative Effects



The bow-tie analysis of climate-change impacts on the marine ecosystem and human activities within it shows the relationships across the DAPSIR framework. Drivers of increased atmospheric greenhouse gases are linked through the global climate to changes in the marine environment that exert pressure on a range of state indicators and ecosystem services. The connectivity and implications of climate change as a factor of cumulative effects are described in the Pressure , State and Impacts sections of this thematic assessment.

Thematic metadata

Field	Explanation
Relevant OSPAR Documentation	OSPAR Publication 2018-730 Status Report on the OSPAR Network of Marine Protected Areas OSPAR 2021. Medium-level and detailed-level review of progress in the North-East Atlantic Environment Strategy 2010 2020

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Our vision is a clean, healthy and biologically diverse North-East Atlantic Ocean, which is productive, used sustainably and resilient to climate change and ocean acidification.

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