European Academies
easac
Science Advisory Council

A sea of change:
Europe's future in the Atlantic realm

EASAC policy report 42

June 2021

ISBN: 978-3-8047-4262-8

This report can be found at
www.easac.eu

Science Advice for the Benefit of Europe

EASAC

EASAC – the European Academies' Science Advisory Council – is formed by the national science academies of the EU Member States to enable them to collaborate with each other in giving advice to European policy-makers. It thus provides a means for the collective voice of European science to be heard. EASAC was founded in 2001 at the Royal Swedish Academy of Sciences.

Its mission reflects the view of academies that science is central to many aspects of modern life and that an appreciation of the scientific dimension is a pre-requisite to wise policy-making. This view already underpins the work of many academies at national level. With the growing importance of the European Union as an arena for policy, academies recognise that the scope of their advisory functions needs to extend beyond the national to cover also the European level. Here it is often the case that a trans-European grouping can be more effective than a body from a single country. The academies of Europe have therefore formed EASAC so that they can speak with a common voice with the goal of building science into policy at EU level.

Through EASAC, the academies work together to provide independent, expert, evidence-based advice about the scientific aspects of public policy to those who make or influence policy within the European institutions. Drawing on the memberships and networks of the academies, EASAC accesses the best of European science in carrying out its work. Its views are vigorously independent of commercial or political bias, and it is open and transparent in its processes. EASAC aims to deliver advice that is comprehensible, relevant and timely.

EASAC covers all scientific and technical disciplines, and its experts are drawn from all the countries of the European Union. It is funded by the member academies and by contracts with interested bodies. The expert members of EASAC's working groups give their time free of charge. EASAC has no commercial or business sponsors.

EASAC's activities include substantive studies of the scientific aspects of policy issues, reviews and advice about specific policy documents, workshops aimed at identifying current scientific thinking about major policy issues or at briefing policy-makers, and short, timely statements on topical subjects.

The EASAC Council has 29 individual members – highly experienced scientists nominated one each by the national science academies of EU Member States, by the Academia Europaea and by ALLEA. The national science academies of Norway, Switzerland and the United Kingdom are also represented. The Council is supported by a professional Secretariat based at the Leopoldina, the German National Academy of Sciences, in Halle (Saale) and by a Brussels Office at the Royal Academies for Science and the Arts of Belgium. The Council agrees the initiation of projects, appoints members of working groups, reviews drafts and approves reports for publication.

To find out more about EASAC, visit the website – www.easac.eu – or contact the EASAC Secretariat at secretariat@easac.eu

European Academies

easac

Science Advisory Council

A sea of change:
Europe’s future in the Atlantic realm

ISBN 978-3-8047-4262-8

EASAC Secretariat
Deutsche Akademie der Naturforscher Leopoldina
German National Academy of Sciences
Jägerberg 1
D-06108 Halle (Saale)
Germany

Telephone: +49 345 4723 9833
Fax: +49 345 4723 9839
Email: secretariat@easac.eu
Web: www.easac.eu
Twitter: @EASACnews
Facebook: www.facebook.com/EASACnews/

Cover image: Phytoplankton and sediment produced a vivid display in this relatively shallow sea between Great Britain and northern Europe, 25 March 2020. NASA Earth Observatory.

Copy-edited and typeset in Frutiger by The Clyvedon Press Ltd, Cardiff, United Kingdom

Printed by Schaefer Druck und Verlag GmbH, Teutschenthal, Germany. Printed on FSC-certified paper.

Contents

Foreword

However cold it may seem to some of us in a Scandinavian winter, northern Europe enjoys a relatively mild regional climate for our latitude, thanks to the massive amounts of heat brought up from the subtropics by circulation patterns in the North Atlantic Ocean. So it is no surprise that suggestions that this heat transport may weaken or 'switch off' attracts much media attention, with headlines that may refer to 'tipping points' or 'collapse' of the overturning circulation that brings warm surface waters all the way to the Arctic Circle. Studies of the ocean climate on long timescales have found these processes to have stopped or seriously reduced, generally following large freshwater discharges caused by rapid melting of glacial or multi-year ice in the Arctic. Were this to happen, there could be the paradox that global warming can lead to a colder climate for some of us!

With Greenland and Arctic ice melting at a rapid rate owing to the current rates of global warming, and the evidence from past climates, the future of the Atlantic conveyer has become an important topic for research programmes, and scientific papers are step-by-step improving our understanding of the underlying processes and current trends. The overturning circulation that includes the influx of waters from the subtropics to as far as the Arctic is reported to be weakening, but there is not yet a consensus on trends. At the same time, sea levels are rising and seawater acidification continues, placing additional stresses and uncertainties in safeguarding Europe's seas and coasts and the resources and ecosystem services that they provide. Europe is also looking to the seas to provide new resources, particularly renewable energy but also a range of activities under the general label of the Blue Economy.

Although previous EASAC reports have briefly looked at the evidence for changes in the fundamental circulation patterns in the Atlantic, we have not considered this in detail or examined the other anthropogenic changes that are occurring. In view of the ocean's critical importance to Europe's economy and environment, EASAC's council decided to extend its previous studies and examine in greater detail the vulnerability of Europe to changes in ocean circulation in the Atlantic, and how the ever-varying and interlinked states of the seas, weather and climate may impact the wide range of uses and benefits we gain from our coastal and marine environments. EASAC's council thus welcomed the leadership of Norwegian oceanographers to lead an expert group from other academies to examine the scientific evidence in more detail and consider the implications for the many strands of European Union policy that are potentially affected. A group comprising 17 experts from 12 countries worked with EASAC's Environment Programme Director to compile this report which has been peer reviewed and endorsed by EASAC's member academies.

In this report, we describe the underlying processes and trends in the Atlantic, and the ways in which the state of the ocean – currents, winds, waves and ocean mixing – impact Europe's climate, marine environment and resources. The report looks at the implications for a wide range of European policy issues, from the future of our regional climate, through marine resource and energy, to fisheries management. As found in many environmental issues, there are important interactions between different areas of policy, and we hope this analysis will help to ensure synergy between economic and environmental approaches to marine policy.

I express our gratitude to the members of our Expert Group for all the time and hard work they spent working with our Programme Director on assembling this comprehensive report.

Christina Moberg
EASAC President

Summary

Globally, the importance of managing the oceans in a more sustainable manner has been widely recognised in the United Nations Sustainable Development Goals (UN SDGs), the UN Decade of Ocean Science for Sustainable Development and elsewhere. In Europe the increased recognition of the importance of our oceans and seas is seen in the Blue Economy and in the Green Deal initiatives. However, such policies have to be set against the background that the historical state of flux in our oceans and seas is changing owing to global warming. This report focuses on the Europe's future in the Atlantic realm and thus the Atlantic Ocean and the seas along Europe's western coasts (excluding the Mediterranean and Black Seas).

The report describes the underlying processes and trends in the Atlantic, and the ways in which the state of the ocean – currents, winds, waves and ocean mixing – impact Europe's climate, marine environment and resources. A dominant influence is the global thermohaline circulation which includes the Atlantic Ocean currents that transport heat and salt into northern latitudes via the Gulf Stream and North Atlantic Drift, with colder and denser waters returning south at depth; this is the Atlantic Meridional Overturning Circulation (AMOC). Superimposed on this are patterns of variability in both the atmosphere (the North Atlantic Oscillation) and the ocean (the Atlantic Multidecadal Variability). Palaeoclimatic records show that changes in these basic processes may have substantial local and global effects on climate and on marine and coastal ecosystems.

Against the background of natural variability, direct impacts of global climate change can be seen in the **sea surface temperature** which has increased by nearly 1 °C since the 1890s, in **sea level** which has risen by 11–16 cm during the 20th century; and in **seawater pH** which has decreased by about 0.1 pH units since the start of the Industrial Revolution. Climate change may also be affecting the complex oceanic processes underpinning the goods and benefits we receive from marine ecosystems.

In this report, these processes and their importance for European Union (EU) marine policies are reviewed in detail together with the results of recent research. One policy example is the 'Blue Economy' which aims to increase the economic contribution from the oceans as part of an integrated marine policy. The Marine Strategy Framework Directive, adopted in 2008, addresses the environmental aspects. Most recently, protecting our seas and oceans is an integral objective of the European Green Deal and part of the Biodiversity Strategy for 2030. Key issues identified in this report are as follows.

The AMOC and the Gulf Stream. The transfer of heat from the subtropics to the Arctic Ocean is critical for Europe's climate. While several studies suggest that the AMOC has weakened in recent decades (upper estimates are 15–30%), this is not yet confirmed as a trend by several indicators described in detail in the report; nor has a similar weakening been observed in the Gulf Stream *per se*. Neither is it yet clear how to distinguish any trends from underlying interannual to decadal variability. Nevertheless, a weakening of around 20% in the AMOC is expected by the end of this century, and collapse remains a possibility in the longer term beyond 2100. Uncertainties remain in how the accelerated melting of the Greenland ice cap influences the AMOC as well as surface water salinity, and recent research has also emphasised the extent to which the AMOC affects climate as far as Asia and Africa while buffering the surface warming for the planet as a whole. The trends in the AMOC are thus not just a European issue, and monitoring and research to improve our understanding is important with the ultimate objective of providing an early warning for trends towards weakening or even collapse.

Of more immediate practical and societal impact are the effects of short-term fluctuations in European climate-related conditions that are the result of variations in ocean circulation (including variability of the Gulf Stream and its branches towards Europe), and their interaction with the atmosphere. There is evidence that the relatively slow changes in ocean circulation that affect the atmosphere and Europe downwind allow a degree of predictability with a forecast horizon of seasons to years into the future. Substantiating this predictability offers potential benefits for societal and commercial planning purposes and preparedness, and should be developed to allow application in a range of fields including tourism, renewable energy production, agriculture, aquaculture and fisheries.

Sea level rise. Rising sea levels increase the risk of future high-impact storm surges, waves and high tides. Under high emission pathways, the 5 million Europeans currently at risk of seawater flooding once every 100 years may be flooded almost annually by 2100. Planning for future sea level rise (SLR) along the European coast has to recognise two major sources of uncertainty. The first is the average global SLR derived mainly from the melting of the Antarctic and Greenland ice sheets. A second source of uncertainty arises from the local variations in geography and susceptibility to Atlantic circulation and associated weather patterns.

Substantial assets and populations will be at risk if insufficient SLR is factored into erosion control planning and adaptation for population centres along coasts and estuaries. Integrating both global and local factors in the prediction of local SLRs along European coasts is essential to improve the understanding of their magnitude and timing, which is critical in planning for local adaptation. On current evidence and taking into account the further 10–15 cm variability depending on Atlantic conditions, national and EU adaptation planning should be based on at least a SLR of 1 m by 2100, as well as adaptive planning to increase flexibility to respond to new estimates of Antarctic and Greenland melting.

The **acidification** of Europe's oceans and seas is increasing as atmospheric and therefore seawater concentrations of carbon dioxide (CO_2) rise. However, changes in circulation, especially those that promote upwelling of deeper waters, can exacerbate these trends through increasing microbial decay of organic matter. The variation in pH in some European waters may approach 1 between seasons and the resilience of commercially important species (particularly in their early life stages) to such variations remains poorly understood. While observations of carbon cycle and ocean acidification are ramping up within the Integrated Carbon Observation System, observations from key regions are missing and, combined with limited data on the impacts on marine ecosystems and commercial fisheries, information to assess the associated risks of acidification is lacking.

Renewable energy supply. Changes in ocean circulation and associated weather can affect the strength and direction of winds that directly impact power generation from **offshore wind**. Studies in the North Sea show that changes in future wind patterns may lead to an overall decline of 3% in generated energy. At the same time, processes over the North Atlantic influence the strength and northerly tilt of the winds and associated rain and snowfall affecting the supply of freshwater supplying **hydropower** reservoirs. Norwegian hydropower production varies with the state of the North Atlantic Oscillation, and research to improve understanding of the relationships between the North Atlantic circulation, European weather systems and the frequency of extreme events can offer improved predictability that can be factored into energy planning.

The degree of **eutrophication** is one of the criteria for determining 'good environmental status' in the Marine Strategic Framework Directive. The **Baltic Sea** is the largest marine area within Northwest Europe affected by eutrophication, and is described in detail in this report. Areas affected by hypoxia have increased more than 10-fold during the past century and the Baltic Sea relies on occasional 'Major Baltic Inflows' to allow oxygen to penetrate to its deeper parts. Global change driving towards increased eutrophication (higher water temperatures, stronger stratification, and increased inflows of freshwater and nutrients from land to coastal waters) make the frequency and intensity of future inflows a critical issue. Stronger or more frequent storm activity and rising sea levels at the entrance to the Baltic Sea will reduce the risks of increased eutrophication.

Effects on marine biodiversity and fisheries. Changes in ocean temperatures, circulation, upwelling and associated effects on water properties affect marine ecosystems. Globally, warming water seems to have reduced maximum sustainable yields, with North Sea fish populations and those off the Iberian coast among the highest declines globally. At the same time, combinations of human pressures and ecosystem changes may render some fisheries' management tools (e.g. the Large Fish Index) ineffective as stocks respond. Ecosystem-based fisheries management as required under the Marine Sustainability Framework Directive is still under development and increasingly important to the Common Fisheries Policy, Marine Strategy Framework Directive, Marine Protected Areas and Maritime Spatial Planning Directives. There is thus an urgent need to integrate a common ecosystems approach across all components of marine policy, and to ensure that initiatives under the Blue Growth agenda are compatible with protecting biodiversity and marine and coastal ecosystems.

Marine Protected Areas are vulnerable to climate change and ocean acidification, and selection and management of Marine Protected Areas need to consider how species may redistribute to new, suitable and productive habitats. The inherent uncertainties in modelling such complex systems need to be taken into account as well as the need for adequate protection and adherence to rules.

This report also discusses the ocean dimension of the **UN SDGs** and their relevance to the EU Blue Growth and Green Deal policies. Indicators for the targets assigned for SDG 14 (Conserve and sustainably use the oceans, seas and marine resources for sustainable development) suggest that EU policies are generally aligned with SDG 14, but that the targets related to sustainable fishing (14.4 and 14.6) and ocean science (14.A) are not being met. This emphasises the importance of assessing the implications for the marine ecosystem and its sustainability when promoting the Blue Growth agenda. The evidence presented in this report on the potential effects of changes in ocean circulation also needs to be taken into account when developing policies to meet SDG 14 – also interlinking with, for example, SDG 7 (Ensure access to affordable, reliable, sustainable and modern energy for all), SDG 11 (Sustainable cities and communities) and SDG 13 (Take urgent action to combat climate change and its impacts) – in line with the overarching SDG 17 (Strengthen the means of implementation and revitalise the global partnership for sustainable development).

Finally, regarding **research**, the ocean and its circulation are the subject of many academic projects funded on national or international levels. International coordination is available through the World Climate Research Program, the International Council for the Exploration of the Sea (ICES), Scientific Committee on Oceanic Research (SCOR) and multilateral programmes such as the Rapid Climate Change-Meridional Overturning Circulation and Heatflux Array (RAPID–MOCHA) and Overturning in the Subpolar North Atlantic Program (OSNAP) arrays and the Integrated Carbon Observation System. The EU supports a range of research programmes with an ocean component, including the 'Blue-Cloud' together with the Marine Knowledge 2020 initiative. The UN Decade of Ocean Science for Sustainable Development includes a challenge to 'enhance understanding of the ocean-climate nexus'. Key knowledge gaps that emerge from this analysis include the following:

- continued uncertainty over current and future trends in the AMOC and related ocean circulation;
- the ability to assess local magnitude and timing for SLR;
- the regional trends in ocean acidification and its effects on local ecosystems;
- further developing the links between oceanic changes and European weather, where the potential predictability offered by the long lag time between changes in the Atlantic and their impact on European weather is still to be fully tapped.

This report provides the scientific basis to support the future development of EU policies, both within the Commission and the European Parliament. Increased understanding of the science underlying the changes underway can contribute to better policies and foresight in the adaptation to and mitigation of climate change.

1 Introduction

1.1 Purpose of this report

Globally, the importance of managing the oceans in a more sustainable manner has been widely recognised—as in United Nations Sustainable Development Goal 14 (UN SDG 14) (Life below water), the current UN Decade of Ocean Science for Sustainable Development (www.oceandecade.org) and in the work of the High-Level Panel For A Sustainable Ocean Economy (2020a) towards a sustainable ocean economy[1]. In Europe (Figure 1.1), there are several island countries (such as Ireland, Iceland, Great Britain), while the continent faces the Atlantic in the west and adjoins the Nordic, Baltic, Mediterranean and other seas. The North Atlantic Ocean and its adjoining seas have greatly influenced the history, economy and culture of European nations, and Europe's climate is strongly influenced by the Atlantic

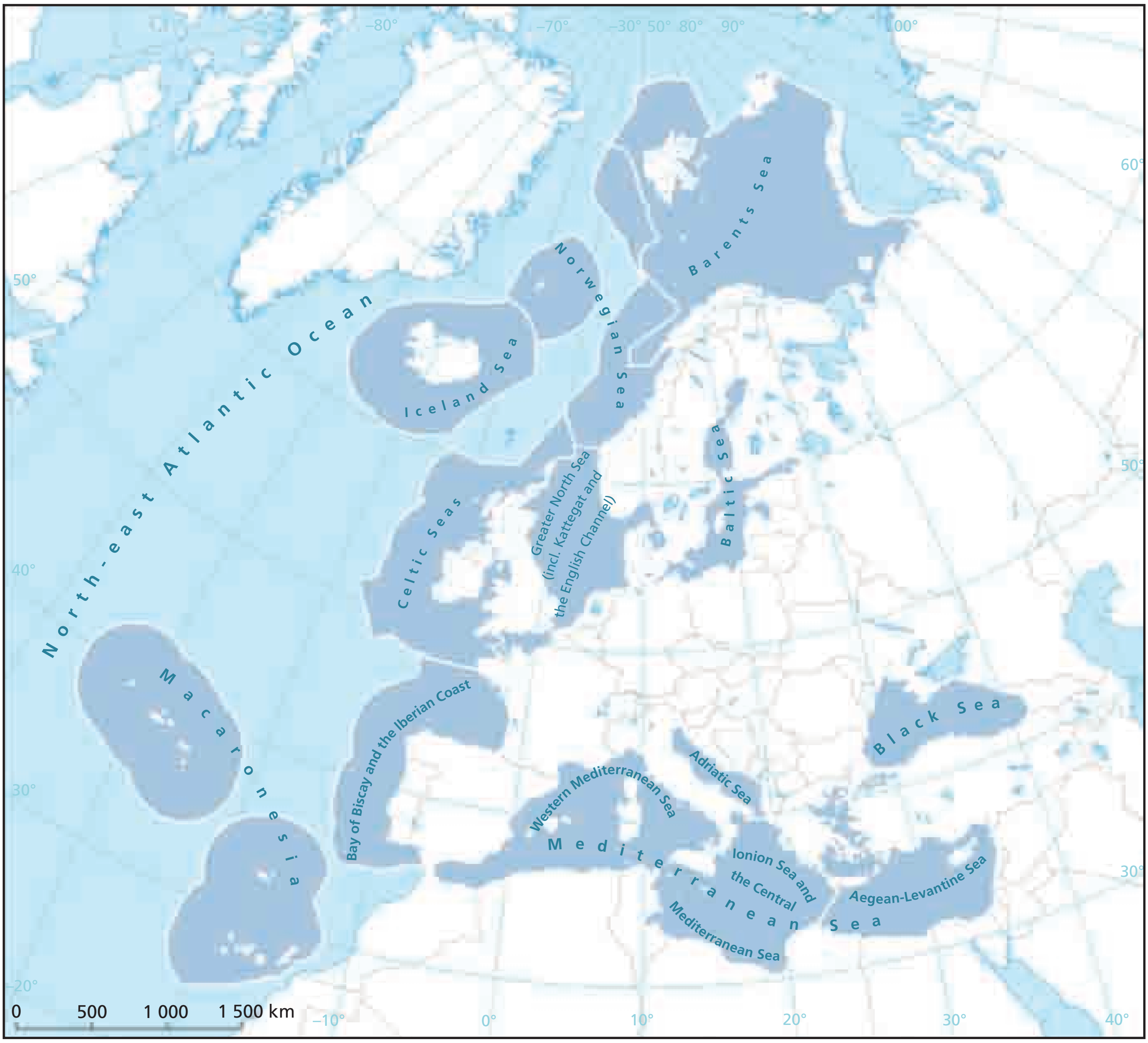


Figure 1.1 Regional seas surrounding Europe (https://www.eea.europa.eu/data-and-maps/figures/regional-ses-surrounding-europe-1).

---

[1] The 14 members of the High-Level Panel for a Sustainable Ocean Economy (the Ocean Panel) are heads of state and government representing people from across all ocean basins, nearly 40% of the world's coastlines and 30% of exclusive economic zones. European members are Norway and Portugal.

Ocean circulation bringing heat from the subtropics up to the Arctic Ocean.

Europe's oceans and seas have been the scene of exploration, migration and even conflict throughout history. Global shipping follows trade routes similar to those of the early European maritime explorers and constitutes the backbone of international trade. From key harbours such as Rotterdam, Bilbao and Felixstowe, goods are distributed inland, and vice versa. The European Commission's Directorate-General for Marine Affairs and Fisheries (DG MARE) recognised the importance of this 'Blue Economy' in its 2019 review (EC, 2019a), and the latest analyses (EC, 2020a) are that the Blue Economy generated around €750 billion in turnover, €218 billion in gross value added (GVA) and directly employed approximately 5 million people in 2018, in the primary sectors shown in Table 1.1.

Table 1.1 includes established sectors such as marine living resources and coastal tourism, while newer sectors such as renewable energy are expanding rapidly. Just the offshore wind sector in Europe now has an installed capacity of 22,072 megawatts from 5,047 grid-connected wind turbines across 12 countries (WindEurope, 2020), providing nearly 250,000 jobs and a GVA of €1.1 billion in 2018, a 14-fold increase on the €79 million in 2009. Other emerging sectors include ocean energy, marine biotechnology, marine minerals, desalination and maritime defence.

In addition to the economic assets, the ocean is a vital component of the climate system and acts as a means of exchanging with the atmosphere vast quantities of heat and water that generate clouds and weather systems, of gases such as carbon dioxide (CO_2), while redistributing heat from the tropics to polar regions keeping our planet habitable (Bigg *et al.*, 2003; Mechoso, 2020). As pointed out in the Blue Economy analyses, marine activities will be sensitive to the impacts of climate change on the oceans directly (e.g. through changes in the dynamics of fish stocks) or indirectly (e.g. through an increase in floods due to sea level rise (SLR) and increases in extreme weather). Moreover, the atmospheric processes that interact with and partly originate in the Atlantic Ocean affect the whole of Europe's weather systems, and thus impact on sectors much beyond those in Table 1.1, from agriculture to housing and infrastructure. Most recently, the European Green Deal (EC, 2019b) reinforces the importance of a sustainable 'Blue Economy' by recognising the role of oceans in mitigating and adapting to climate change (including offshore renewable energy), producing new sources of protein that can relieve pressure on agricultural land, and ensuring healthy and resilient seas and oceans. Global warming and circulation changes in the surrounding oceans thus impact on several of Europe's current policy priorities straddling the economy and environment.

Table 1.1 GVA (millions of euros) in sectors of the European Union's 'Blue Economy' (EC, 2020a)

GVA	2017	2018
Coastal tourism	76,152	88,575
Marine living resources	21,100	20,996
Marine non-living resources	19,435	19,565
Port activities	34,440	35,205
Shipbuilding and repair	17,135	17,276
Maritime transport	35,599	35,599
Marine renewable energy	1,015	1,089

The European Academies' Science Advisory Council (EASAC) looked at the impacts of global warming and other aspects of climate change on extreme weather (EASAC, 2013) and examined issues related to the sustainability of marine ecosystems (EASAC, 2016). EASAC also explored some of the underlying drivers of future extremes in weather (including potential changes in ocean circulation) in an update on extreme weather (EASAC, 2018). Since then, scientific research has continued to improve our understanding of the interactions between climate change and oceanic processes in the Atlantic, and their effects on our coastal seas and weather patterns. In view of the ocean's critical importance to Europe's economy and environment, EASAC's council decided to extend its previous studies and examine in greater detail the vulnerability of Europe to changes in ocean circulation in the Atlantic, and how the ever-varying and interlinked states of the seas, weather and climate may impact the wide range of uses and benefits we gain from our coastal and marine environments. The effects of increasing emissions of CO_2 on sea water acidity, and of warming on global SLR, are also considered. Member academies nominated an Expert Group to guide and inform this process (Annex 1).

In terms of geographical scope, the most direct impacts of changes in the Atlantic occur along the western coasts of Spain, Portugal, Ireland, the UK, France, Scandinavia (with Iceland and the Faroes mid-ocean) and the nations that border the North Sea, the Baltic and up to the Arctic Ocean. This region is under direct and often dominant Atlantic influence and will be the main focus in this report. The Mediterranean and Black Seas are not considered here, as there are strong constraints on oceanic exchanges through the Strait of Gibraltar, so that these seas are much more influenced by terrestrial runoff, requiring a scope beyond the Atlantic. Moreover, the countries bordering the Mediterranean and Black Seas include many academies outside those in EASAC and any study would thus require a separate and expanded expert group. This remains an option for future consideration.

In this report, we first describe the underlying oceanic processes that drive our regional climate and weather. Effects are felt locally, but arise through currents, winds, waves and ocean mixing in the adjoining oceans which in turn are linked to current systems encompassing the whole globe. We then consider how current systems determine critical features of the marine environment, and the resources it supports. We also discuss how future conditions can change and how such knowledge should be taken into account when formulating European marine policy.

This report provides the scientific basis to support the future development of European Union (EU) policies, both within the European Commission (DGs MARE (Marine Affairs and Fisheries), ENER (Energy), ENV (Environment) and GROW (Internal Market, Industry, Entrepreneurship and SMEs) are among the Directorates-General with potential interest in the contents of this report) and the European Parliament. Increased understanding of the science underlying the changes underway can contribute to better policies and foresight, and adaptation to and mitigation of the changes anticipated. We thank the Expert Group members (Annex 1) for dedicating their time and expertise to this report and, in line with EASAC's practice, the report has been peer reviewed and endorsed by EASAC's member academies.

1.2 Background and scope of the study

We first introduce the complex interactions between the open ocean and Europe's seas (Figure 1.1). A dominant influence is the global circulation driven by temperature and salinity (the thermohaline circulation) which includes the regional currents that transport heat through the upper layers of the Atlantic into northern latitudes (Figure 1.2). The North Atlantic is subject to its own natural variability. In the atmosphere, the North Atlantic Oscillation (NAO) can switch on an irregular basis between two dominant states: a 'positive' state characterised by strong southwesterlies and more storms (subtropical high pressure over the Azores and a strong low-pressure system over Iceland), and a 'negative' state that has much weaker, more zonal winds and fewer storms (Hurrell, 1995). In the ocean itself, there are interannual to multidecadal patterns reflected in anomalies in sea surface temperature (SST), including the Atlantic Multidecadal Variability (AMV; to which the largest contribution is the Atlantic Multidecadal Oscillation (AMO) (Wang *et al.*, 2017)). Superimposed on the AMV, the NAO can affect winter weather in Europe extending to North Africa and North America and as far as East Asia (Yan *et al.*, 2020). Palaeoclimatic records show that these fundamental circulation patterns may change, with substantial local

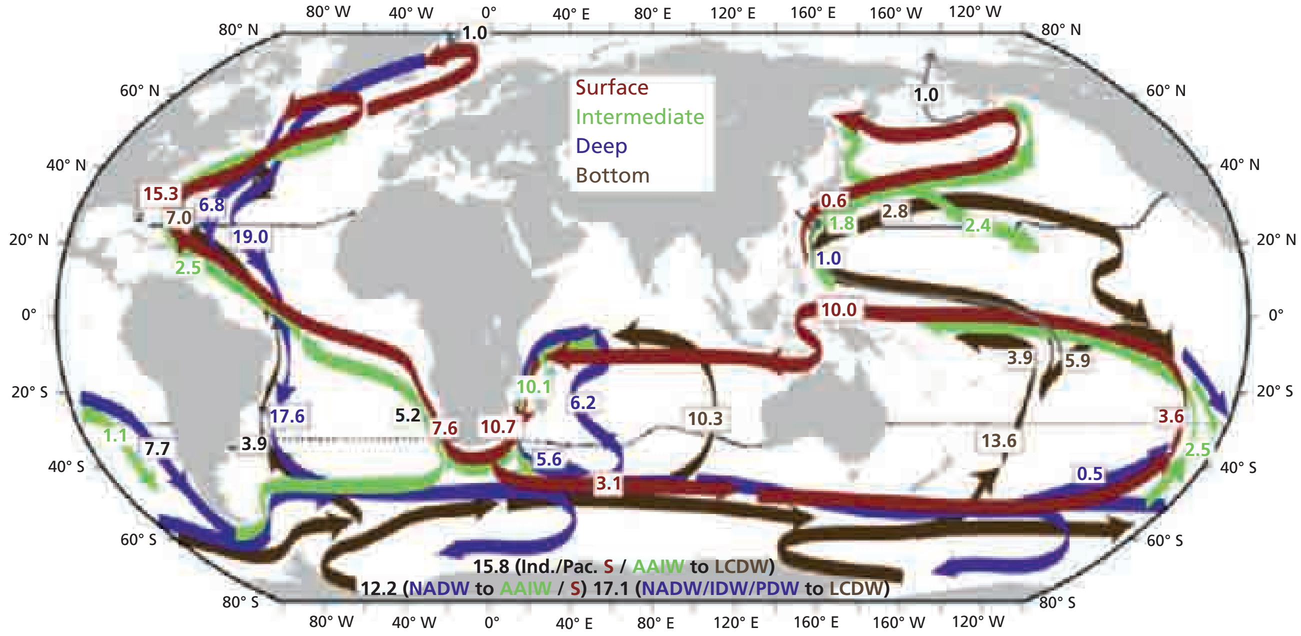


Figure 1.2 Global thermohaline circulation: volume transport in major overturning currents. Units are sverdrups (Sv)[2]. Source: Talley (2008).

---

[2] One Sverdrup (Sv) is equal to a flow of 1 million cubic metres per second (Eldevik and Haugan, 2020).

and global effects on climate and on marine and coastal ecosystems. For example, the rapid reversal of warming in the Younger Dryas cold spell (around 12,900–11,700 years ago) is attributed in part to the influx of freshwater from deglaciation reducing or shutting down the North Atlantic circulation transporting heat from the Gulf of Mexico to northern latitudes (see, for example, Bradley and England, 2008; Condron and Winsor, 2012).

Superimposed on these natural processes are the changes driven by anthropogenic emissions of greenhouse gases. A primary indicator of climate change is the **sea surface temperature** (**SST**) which has been increasing at a rate of about 0.11 °C per decade from 1970 onwards (Bulgin *et al.*, 2020). Recent measurements show the continued upward trend, as well as the high year-to-year variability (Figure 1.3a) with an average trend since 1900 of 0.84 °C per century. These trends are also seen in the ocean heat content since the oceans take up over 90% of the excess heat captured by greenhouse gases (Cheng *et al.*, 2020; see also Figure 1.3b). An increment in the SST of up to 4 °C in certain coastal zones by the end of the 21st century is projected (Lowe *et al.*, 2009; IPCC, 2013).

Warming leads to **sea level rise (SLR)** through thermal expansion of the oceans and from melting glaciers. During the 20th century, sea level has risen by 11–16 cm (Dangendorf *et al.*, 2017). Projections of average global SLR to 2100 range from as low as 0.5 m to as high as 2 m (Bamber *et al.*, 2019), with recent studies showing acceleration of ice sheet and glacial melting that may not be included in the lower projections (Siegert *et al.*, 2020). Changes in seawater **salinity** result from inputs of freshwater from glacier and sea-ice melting and

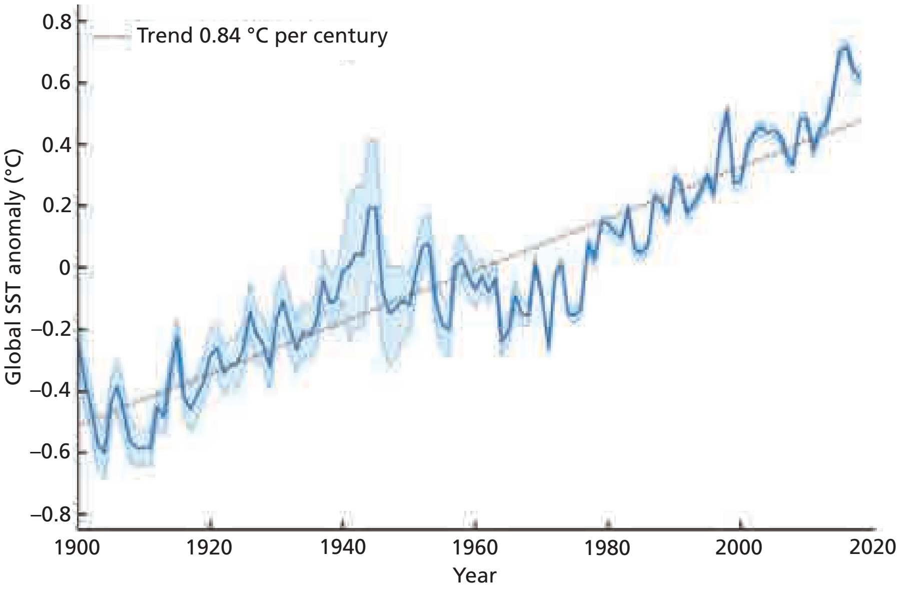


Figure 1.3a Annual global average SST. Anomalies are relative to the 1961–1990 mean. (Source: H. Asbjørnsen, based on HadSST4-data https://www.metoffice.gov.uk/hadobs/hadsst4.)

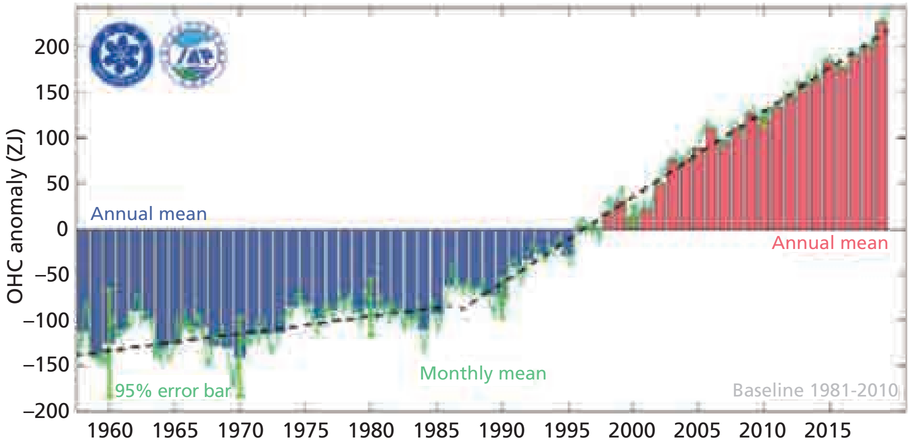


Figure 1.3b Change in global ocean heat content (OHC) in the upper 2000 m (Cheng et al., 2020).

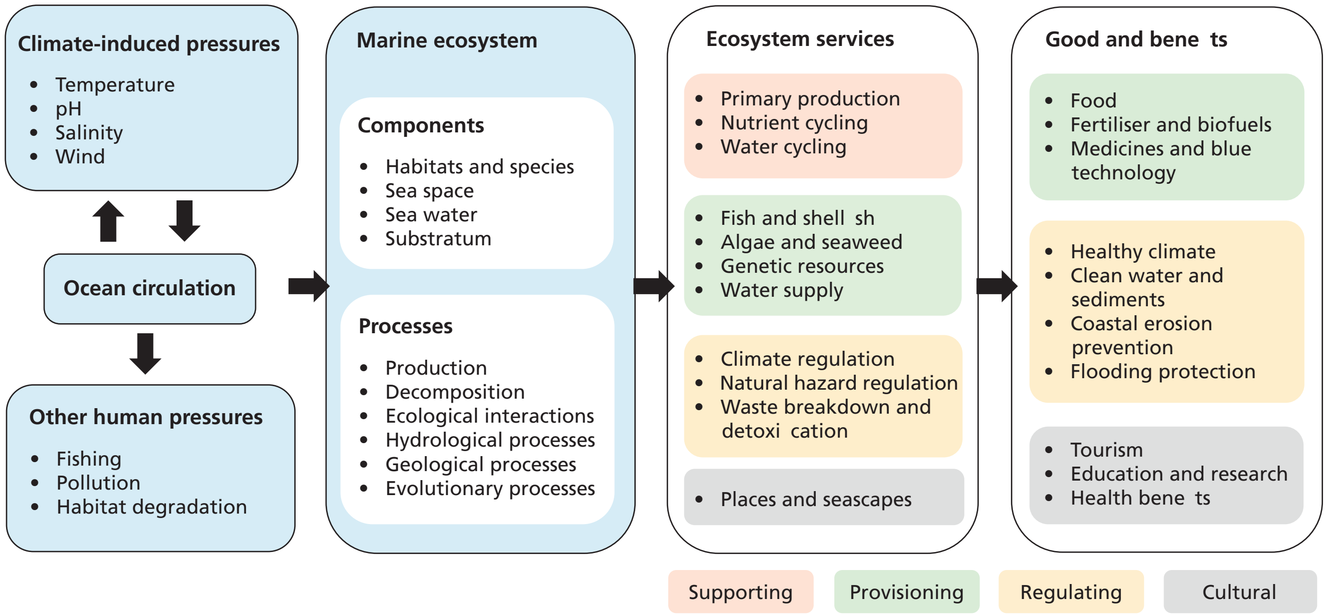


Figure 1.4 Climate-induced and other human pressures affecting marine ecosystem components, processes and their services. (Adapted from Potts et al., 2014.)

changes in the hydrological cycle (Durack *et al.*, 2012), while climate change also leads to increased frequency of extreme events, especially storm surges, as well as changes in water cycle dynamics depending on the geographical location (Robins *et al.*, 2016).

The oceans absorb between 20% and 30% of anthropogenic CO_2 emissions (IPCC, 2019), but dissolved CO_2 reacts with water to form carbonic acid, increasing **seawater acidity** and reducing its pH. The ocean has a pH of around 8 (slightly basic) and since the start of the Industrial Revolution it has decreased by about 0.1 units (the pH scale is logarithmic, so reducing by 1 pH unit represents a 10-fold acidification). As CO_2 concentrations continue to rise in the atmosphere, acidification will lead to further decreases in pH, with a further reduction of up to 0.3 pH units by 2100 (IPCC, 2019). Increased acidity in turn reduces the availability of carbonate ions that are needed by many marine organisms (especially corals, marine plankton, and shellfish) to build their calcium carbonate shells and skeletons. The combination of these climate-induced changes and other human pressures (e.g. pollution, habitat alteration, fisheries) affect the intermediate ecosystem services (right-middle column of Figure 1.4) of 'supporting services' such as primary production and nutrient cycling, and 'regulating services' such as carbon sequestration. In the right-hand column of Figure 1.4 are the final ecosystem services and the goods and benefits provided, such as fish and shellfish provision, tourism, coastal protection and a healthy climate.

As can be seen from Figure 1.4, the services we receive from marine ecosystems are numerous, and many can be influenced by the circulation of the Atlantic. Indeed, several changes have already been documented or are foreseen in marine ecosystem components, processes and services owing to climate change as summarised in Table 1.2.

In this report we focus on the interactions with climate, sea level, fisheries, acidification and eutrophication. Direct impacts of changing weather patterns on renewable energy are considered, but limited time and resources led us to exclude other aspects including shipping lanes, trade routes, aquaculture, search and rescue, seafloor mining, oil and gas exploitation, and tourism. In addition, the important issue of pollution (ranging from plastics to heavy metals and persistent organic pollutants) has been excluded and is covered by the comprehensive analyses under the Oslo and Paris Convention (OSPAR) and the Helsinki Convention, and by the work of the Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP).

1.3 Current EU policies

The EU's vision of the 'Blue Economy' is part of an Integrated Marine Policy within which the Marine Strategy Framework Directive (MSFD) covers the environmental component. The overall objective of the MSFD is to achieve 'good environmental status' for all marine waters by 2020[3] (EC, 2008). One of its aims is

---

[3] Good Environmental Status comprises 11 descriptors: biodiversity; non-indigenous species; commercially exploited fish; food-webs; eutrophication; sea-floor integrity; hydrographical conditions; contaminants in the environment; contaminants in seafood; marine litter; and energy.

Table 1.2 Some examples of climate-induced changes and their consequences to marine ecosystems (adapted from Brierley and Kingsford (2009) and Polunin (2008))

Climate-induced changes	Consequences
SLR	Habitat loss; altered productivity and biological zonation in coastal ecosystems.
Rising temperature	Changing species range and distribution patterns; changing growth rates, timing and duration of reproduction, metabolic stress; changing biological production and biogeochemical cycles.
Increasing storm frequency	Increasing physical damage in coastal habitats; changing abiotic characteristics of coastal waters; changing nutrient and sediment uploads to coastal areas.
Decreasing oxygen concentration	Expanding anoxic zones.
Increasing acidity	Reducing calcification and skeletal structure compromised for several organisms.
Altered circulation and connectivity	Larval transport disrupted and nutrient and planktonic food availability altered; changing SST, salinity, turbidity patterns, among other abiotic variables.

to apply an ecosystem-based management approach and overcome traditional sectoral management schemes. Progress made has been described in the European Environment Agency's review of the state of Europe's seas (EEA, 2015) and more recently by the European Commission's (EC, 2020b) own review of the implementation of the MSFD (Box 1.1). Most recently, protecting our seas and oceans is an integral part of the European Green Deal (EC, 2019b) and part of the Biodiversity Strategy for 2030 (EC, 2020c).

The role of the oceans and changes in the seas around Europe are thus critical factors in a wide range of European policy issues. We return to this in Chapter 4.

Box 1.1 Evaluating the achievements of the MSFD

(a) EEA Review (EEA, 2015)

The MSFD sets three main goals for the state of Europe's seas: (1) 'healthy', (2) 'clean' and (3) 'productive', with 'ecosystem-based management' encouraged to ensure that human activities are compatible with the full functioning of marine ecosystems. The review concluded that although Europe's seas can be considered 'productive', they cannot be considered 'healthy' or 'clean'. A closer coupling between plans for 'Blue Growth' and 'productive' seas on the one hand and aims for 'healthy' and 'clean' seas on the other is needed. Applying the ecosystem-based approach requires changes to traditional policy and management.

(b) The European Commission's own review (EC, 2020b)

This review stressed the increased recognition of the oceans as part of the European Green Deal and its aim to protect and restore biodiversity and make Europe the world's first climate-neutral continent. The MSFD is thus instrumental for the EU to reach its overarching objectives. The MSFD interacts with many international agreements (e.g. the Convention on Biological Diversity and regional seas conventions) and with many other EU Directives. The review identified the main challenges and scope for improvement as including the following.

- A need for more coherent and ambitious determinations of 'good environmental status'.
- Ensuring the effectiveness of measures taken by Member States.
- Further work to implement effectively the network of protected areas to halt biodiversity loss and to increase the resilience of the marine environment to climate change.
- Measures to improve and streamline implementation involving greater integration of activities that affect marine ecosystems (e.g. fisheries, shipping, offshore oil and gas extraction, renewable energies); for example, in avoiding conflict between the Blue Growth strategy and the MSFD's aim of good environmental status.
- Linking MSFD and climate policy since the oceans store anthropogenic CO_2 and a much greater quantity of heat than the atmosphere. Therefore, the oceans can have dramatic effects on the global climate, and vice versa. Since 1993 the rate of ocean warming has more than doubled and already affects the entire water column (IPCC, 2019), ocean acidification is increasing, the ocean is losing oxygen and oxygen-depleted zones have expanded, and marine heatwaves have doubled in frequency since 1982.
- Regional cooperation should be improved to attain full regional coherence of the marine strategies, and data availability and comparability ensured.

2 Oceanic processes, and climate, environmental and coastal change

Europe's weather and climate are influenced by the circulation in the North Atlantic Ocean and Nordic Seas. Changes in the Atlantic circulation ranging from seasonal to centennial timescales have significant implications for climate, weather systems and flood risk. This is particularly the case for Ireland, Scotland, the Faroes, Iceland and Norway where weather is driven largely by westerly airflow and coastlines are directly exposed to Atlantic storms, but effects extend to wider regions of Europe where variability in air temperatures across seasons is derived from both dynamic (large-scale atmospheric circulation) and thermodynamic (ocean temperatures in the North Atlantic) sources (Årthun *et al.*, 2018a). We describe here the main ocean currents, the modes of natural climate variability and their connections with weather regimes, before reviewing the recent science about the future state of the Atlantic Meridional Overturning Circulation (AMOC) and its associated currents including the Gulf Stream, trends in sea level and other factors.

2.1 Large-scale circulation in the Atlantic, the Gulf Stream and the Atlantic Meridional Overturning Circulation

Circulation in the upper North Atlantic Ocean (typically down to 500–1000 m) primarily consists of large-scale gyres that are anticyclonic (clockwise) at mid-latitudes and cyclonic (anti-clockwise) at higher latitudes, driven by prevailing wind patterns. These gyres are asymmetric with widespread and relatively weak currents in the east, and rather narrow and strong return currents in the west (Figure 2.1). This is particularly visible in the North Atlantic subtropical gyre with the Gulf Stream that transports northwards roughly 30 sverdrups (Sv) of subtropical water masses within 100 km of the coast of Florida at speeds of up to 150 cm/s, while

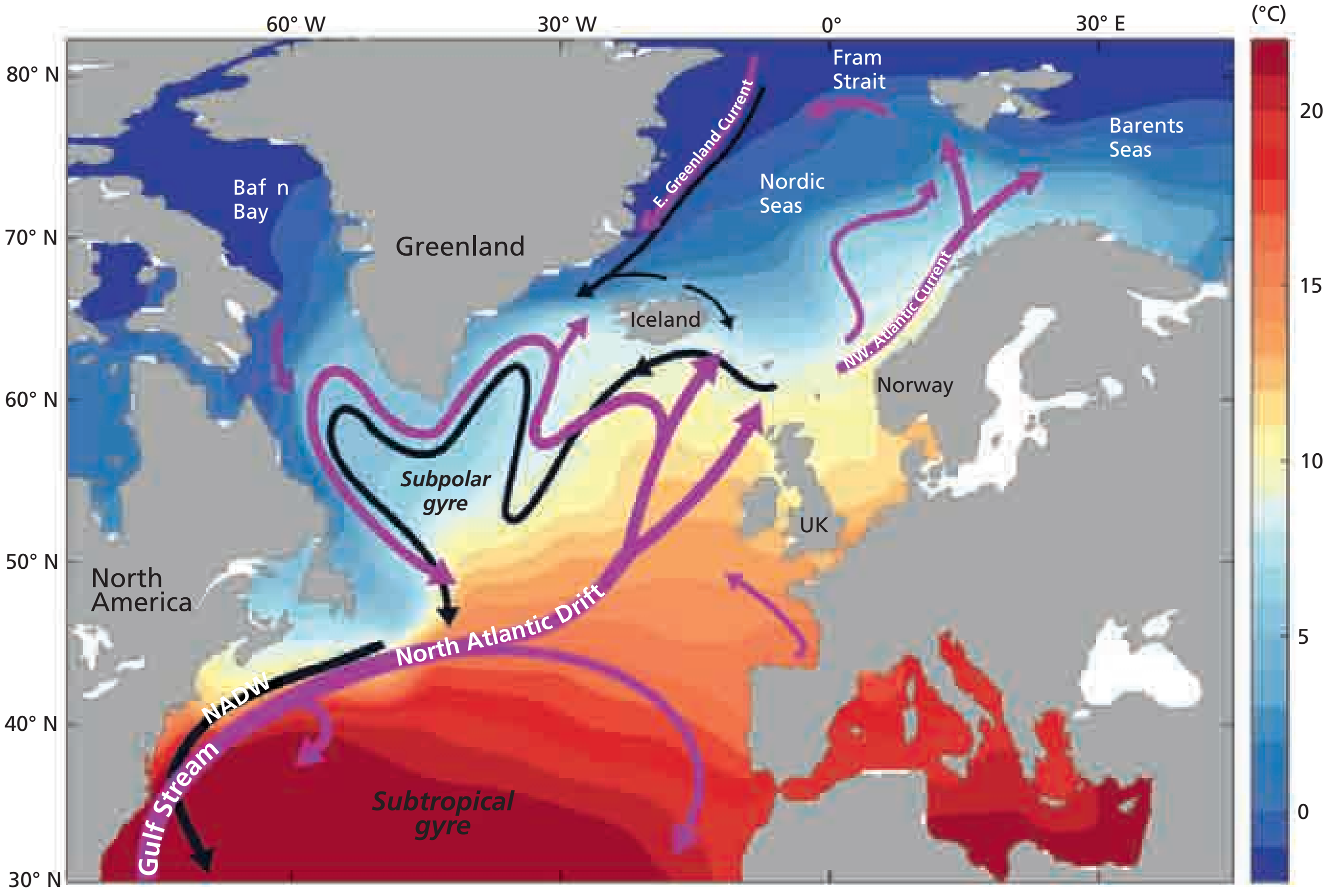


Figure 2.1 North Atlantic mean SST and branches of circulation. Purple and black arrows indicate surface and deep ocean branches of circulation, respectively. (Source: H. Asbjørnsen, SST-data from the ECCOv4-r3 'ocean state estimate'; https://ecco-group.org/products.htm.)

the corresponding southward currents further east are spread over a wide area with speeds of just a few centimetres per second.

As the Gulf Stream travels north, it entrains adjacent waters from lateral and large-scale turbulent eddy mixing, so that transport to the south of Nova Scotia reaches up to 150 Sv. Because this current transports relatively warm water from the subtropics, substantial transfers of heat and energy from the ocean to the atmosphere occur, driving local weather systems and those further afield through atmospheric teleconnections. The northeastward extension of the Gulf Stream, the North Atlantic Drift (or Current), can be tracked from Nova Scotia to Iceland and into the Nordic Seas, interacting with the atmosphere all along. It both separates and is part of the subpolar gyre to the north and the subtropical gyre to the south, the former transporting colder and less saline water from the cool freshwater inputs at higher latitudes (also in Figure 2.1).

Although they lose heat and gain freshwater as they cross the Atlantic, the waters of the North Atlantic Drift are still fairly warm and saline when they reach the submarine ridge that extends from Greenland to Scotland via Iceland and the Faroes. A small part of this water crosses the Greenland–Scotland Ridge into the Nordic Seas west of Iceland (Jónsson and Valdimarsson, 2012) while most traverses between Iceland and Scotland (where it is joined by the Slope Current (White and Bowyer, 1997)). Together, some 8 Sv of warm water are estimated to enter the Nordic Seas with a similar amount of cold water leaving (Østerhus *et al.*, 2019).

Most of the warm inflow continues northwards as the Norwegian Atlantic Current, which sends branches into the Barents Sea and the Arctic Ocean. On the way, it is cooled by the atmosphere and receives freshwater from river runoff, precipitation and ice melt, as well as outflows of brackish water from the Baltic. As a consequence, approximately 30% of the warm inflow becomes very cold but is still sufficiently fresh that it remains close to the surface, where it combines with water from the Pacific and flows southwards on both sides of Greenland to enter the subpolar gyre. The remaining approximately 70% retains sufficient salinity to reach high densities when cooled, sinks and fills up the deep parts of the Nordic Seas and Arctic Ocean (Mauritzen, 1996; Eldevik and Nilsen, 2013).

These denser waters leave the Nordic Seas through the deep passages across the Greenland–Scotland Ridge, flowing mainly through the Denmark Strait (Jochumsen *et al.*, 2017) and the Faroe Bank Channel (Hansen B. *et al.*, 2016). The total volume transport of these flows (termed overflows) is estimated to be approximately 6 Sv (Østerhus *et al.*, 2019), but shortly after crossing the ridge the overflows entrain adjoining ambient water masses (Fogelqvist *et al.*, 2003), which warms the overflow water and decreases its density, but also increases volume transport by a factor of up to 2 (Dickson and Brown, 1994; Sarafanov *et al.*, 2012; Lozier *et al.*, 2019).

The modified overflow water is supplemented by dense water that has sunk to great depths (termed 'deep ventilation') in the Labrador Sea and Irminger Basin. The resulting water mass is the North Atlantic Deep Water, which continues southwards at depth through both the western and the eastern basins of the North Atlantic, constituting the main part of the lower limb of the AMOC.

The AMOC refers to the combination of all these currents, and can be summarised as the net northward transport of waters from the surface down to around 1,000 m depth, compensated for by an equivalent return current at greater depths (plus a net 1 Sv influx across the Bering Strait). As the Gulf Stream and its poleward branches transport warm water of subtropical origin north with colder water masses formed at higher latitudes returning mostly at depth (section 3.1), it provides the northward meridional heat transport that (together with flows of warm maritime air from dominant southwesterlies; Seager *et al.*, 2002) is responsible for the warmer climate in Europe compared with similar latitudes in North America. Whereas the subpolar and subtropical gyres are mainly wind-driven, the dense-water formation is driven by differences in seawater density, caused by temperature and salinity and the associated thermohaline forcing. We discuss potential weakening of the AMOC in a warming world and effects in Europe (Laurian *et al.*, 2010) and beyond (Jackson *et al.*, 2015) in section 2.4.

There may sometimes by an association between the AMOC and the Gulf Stream in the media that is oversimplified. It can thus be useful to keep in mind that the AMOC and its thermohaline circulation overturn from surface-to-deep flow have a maximum strength of about 20 Sv. In contrast, the wind-driven near-surface flows of the Gulf Stream are much greater and peak at more than 100 Sv. Accordingly, substantial return flows are also near the surface. The timing and changes between the two, although related, are accordingly not identical, nor is the degree of correlation constant in time (Johnson *et al.*, 2019).

2.2 Multidecadal modes of climate variability in the Atlantic

When linear trends due to climate warming are removed using statistical filters from historical patterns of SST in the North Atlantic, a multidecadal variability emerges (Figure 2.2). This AMV features in climate models where its cycle ranges from 50 to 100 years depending on the model used. Model results are consistent with the instrumental data in Figure 2.2, but records are too short to allow an exact timescale to be inferred. AMV

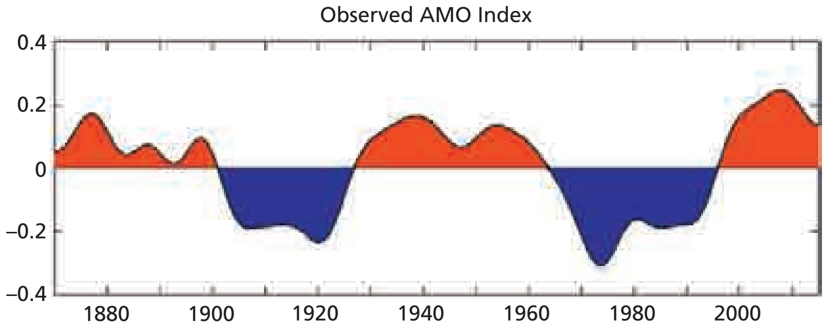


Figure 2.2 Atlantic Multidecadal Variability (Oscillation; AMO) index 1870–2015.
(Source: https://climatedataguide.ucar.edu/climate-data/atlantic-multi-decadal-oscillation-amo.)

anomalies considerably affect the NAO, the jet stream variability and the frequency of atmospheric blocking[1] over the Euro-Atlantic sector (see, for example, Davini *et al.*, 2015). The AMV can affect multiple features of the Northern Hemisphere climate, including Sahelian and Indian monsoons, Atlantic hurricanes, and both North American and European summer climates. While the sources of the AMV are still under debate (Mann *et al.*, 2021), climate models demonstrate a causal link with changes in the AMOC-related ocean circulation, whereby variations in the amounts of heat transported northwards affect SST which in turn triggers an atmospheric response that impacts the above-mentioned features (Yeager and Robson, 2017; Moat *et al.*, 2019). As one example, the temperature in central England in summer is in phase with the AMV (Knight *et al.* 2006). Uncertainty remains, however, over separating the AMV and global warming contributions to SST levels, while variations in aerosol loading could also play a role (Mann *et al.*, 2014).

2.3 Shorter-term variability: weather regimes and ocean circulation

On interannual timescales, the dominant climate signal for Europe is the above-mentioned NAO (Hurrell, 1995), related to the varying strength and structure of the westerlies. In addition, two other patterns of ocean/atmosphere interaction can be identified: the East-Atlantic Pattern (Wallace and Gutzler, 1981) and the Scandinavian Pattern (Barnston and Livezey, 1987). In addition, various weather regimes can be identified that occur repeatedly and persist for days to weeks (i.e. are quasi-stationary). In the North Atlantic–European domain, there are four principal winter weather regimes: Atlantic Ridge (anticyclonic anomalies off Europe), Scandinavian Blocking (anticyclonic anomalies in northern Europe and cyclonic anomalies centred in Southern Greenland), the positive state of the NAO (sometimes called the zonal regime) and the negative state of the NAO (known as the Greenland anticyclone regime; Vautard, 1990).

These regimes reflect different interactions with North Atlantic Ocean dynamics. Using a regional ocean model, Barrier *et al.* (2014) found that Atlantic Ridge causes a large, wind-driven reduction in the strengths of the subtropical and subpolar gyres, while positive NAO causes a strengthening of both gyres. A negative NAO induces a wind-driven southward shift of the gyres, while a Scandinavian Blocking regime is found to strengthen the subpolar gyre via anomalous heat fluxes. The overturning circulation is shown to strengthen following a persistent Scandinavian Blocking regime and positive NAO and to weaken following persistent Atlantic Ridge and negative NAO conditions. These responses are mainly driven by changes in deep water formation in the Labrador Sea.

In the reverse (ocean effects on atmosphere) direction, Joyce *et al.* (2019) found that between 1979 and 2012, the wintertime atmospheric blocking events near Greenland and storm tracks were associated with changes that had occurred 1–3 months earlier in the latitude of the Gulf Stream in the western North Atlantic Ocean. This suggests that shifts in the Gulf Stream path can significantly alter wintertime atmospheric conditions regionally, especially over the Labrador Sea and Greenland. Sutton and Allen (1997) find decadal phases of cold and warm anomalies to travel the North Atlantic Drift with a predictable influence on continental winter temperatures downwind and Arctic sea-ice extent downstream (Årthun *et al.*, 2017, 2018a). Whether this connection also pertains to the NAO is unknown, but an oceanic influence on the NAO is commonly understood. The extent and mechanisms of this influence remain unresolved (Sutton *et al.*, 2000; Cobb and Czaja, 2019).

2.4 Changes in the Gulf Stream and Atlantic Meridional Overturning Circulation

Northern Europe's relatively mild climate (for its latitude) is due, in part, to the heat transported from the subtropics into the Arctic via the Gulf Stream and its poleward extensions (section 2.1). In the past, the

---

[1] Long-lasting and slow-moving high-pressure systems that 'block' westerly winds.

AMOC has undergone total or partial collapses which allow the implications of weakening/collapse to be inferred: for instance, Schenk *et al.* (2018) found that the partial collapse during the Younger Dryas was associated with a shift to a continental climate with extreme winter to spring cooling and short growing seasons.

Weakening of the AMOC is expected to be a consequence of warming and increased precipitation in high latitudes, since that increases the stability of the water column and inhibits the formation of the deep, cold branch of the AMOC. In addition, increasing freshwater from accelerating Greenland ice melt could also inhibit the formation of the deep, cold branch of the AMOC and increase the rate of weakening (Rahmstorf *et al.*, 2015; Frajka-Williams *et al.*, 2016; Hansen J. *et al*., 2016). The fate of the AMOC is thus a critical issue for Europe and has been studied extensively (e.g. Seager *et al.*, 2002; Laurian *et al.*, 2010; Drijfhout *et al.,* 2012; Drinkwater *et al.,* 2013; Jackson *et al.,* 2015; O'Reilly *et al.*, 2017; Wang *et al.*, 2017; Chen and Tung, 2018; Josey *et al.*, 2018).

Earlier studies had suggested a decline of around 30% in the strength of the AMOC over 50 years (Bryden *et al.*, 2005), but this was based on limited data. More recently, Caesar *et al.* (2018) suggested a weakening of the AMOC by about 3 ± 1 Sv (around 15%) since the mid-20th century on the basis of modelling of observed SST. To provide reliable direct data on flows, the 'RAPID–MOCHA' programme was launched, which has been providing detailed flow data since April 2004. This array is located along the 26° N latitude and has been supplemented since 2014 by a second set of measurements further north in the Overturning in the Subpolar North Atlantic Program (OSNAP).

Initial results from the RAPID array showed a weakening from 2007 to 2011 (Smeed *et al.*, 2014), followed by a more stable flow. Overall, the AMOC decreased from 18.8 Sv during 2004–2008 to 16.3 Sv during 2012–2017 (Smeed *et al.*, 2018). A recent review (Moat *et al.*, 2020) suggests some recovery or fluctuating behaviour (Figure 2.3) while Worthington *et al.* (2021) infer no decline over the past 30 years based on historical hydrographic data. Also, winds seem to play an important role in AMOC variability on timescales of days to a decade (Johnson *et al*., 2019), in addition to the circulation driven by sinking cold and saline waters further north. Caesar *et al.* (2021) used a set of proxy indicators to reconstruct the strength of the AMOC since 400 AD and place recent measurements in a longer historical context. They found that, after a long period of relative stability, some decline could be detected during the 19th century, but a more rapid decline occurred around the 1960s, followed by a short-lived recovery in the 1990s and a return to decline in the 2000s.

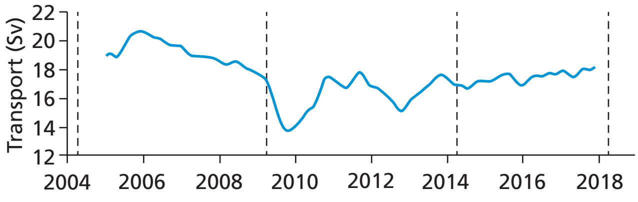


Figure 2.3 Annual variations in AMOC flows at 26° N (Moat et al., 2020).

Other approaches do not show any clear trends in recent decades. Trenberth and Fasullo (2017) quantified the meridional heat transport on the basis of energy budgets and found no trend in heat transport between 2000 and 2013; they suggested that the RAPID array may overestimate the heat transport. Another approach by Fu *et al.* (2020), based on hydrographic data and satellite altimetry over the past three decades, showed that the AMOC state in the past decade is not distinctly different from that in the 1990s. Direct surveys of the Gulf Stream generally imply no clear trend over recent decades. Piecuch (2020) report a slight weakening of the Gulf Stream off the Florida coast (the Florida Current) over the past century but Rossby *et al.* (2014) showed no decrease in the 1993–2011 period, while Meinen *et al*. (2010) found no trends separable from year-to-year variability over a 40-year period.

From the data available so far, it remains unclear whether periods of AMOC weakening are part of a trend or just reflect a variable circulation. In this context, it is still unclear whether there is any underlying interannual to decadal variability in the AMOC. In some climate models, such variability exists with a link with dense-water formation in the subpolar gyre and/or Nordic Seas (Ortega *et al.*, 2015), but this is not confirmed by higher-resolution models that represent overflow and entrainment processes (Deshayes *et al.*, 2007; Talandier *et al.*, 2014).

The RAPID array is not the only source of flow data; these can also be obtained from research and monitoring of overflow water, water entrained by the overflow, and water generated by deep convection in the Labrador Sea and Irminger Basin (Box 2.1). These figures do not suggest significant weakening in overflow or entrainment flows, and thus little evidence for weakening in the northeastern components of the AMOC, extending towards and into the Nordic Seas.

A stable volume transport does not guarantee a stable heat (or salt) transport, since the temperature (and salinity) of the North Atlantic Drift as well as inflow to the Nordic Seas vary. The longest temperature series from open ocean and coastal sites in the Northeast Atlantic may indicate a long-term warming trend, but are dominated by decadal-scale variations (González-Pola *et al.*, 2019), linked to variable subpolar gyre

Box 2.1 Flow data other than the RAPID array relevant to the AMOC

Additional data on individual components of the AMOC include the following.

- The generation of Labrador Sea Water by deep convection is highly variable from year to year and export of water varies by a factor of more than 2 (Yashayaev and Loder, 2016). Similarly, high variability for deep convection in the Irminger Basin (de Jong and de Steur, 2016) makes trend estimates difficult. The first results from OSNAP indicate only a weak overturning (approximately 2 Sv) in the Labrador Sea from 2014 to 2016.
- Overflow water across the Greenland–Scotland Ridge is dominated by two main branches: the Denmark Strait overflow and the Faroe Bank Channel overflow, both of which have been monitored by direct current measurements since the mid-1990s. These observations show no sign of weakening (Østerhus *et al.*, 2019).
- Rossby *et al.* (2020) found no long-term trend in the poleward surface flow of Atlantic water across the Greenland-Scotland Ridge since the early 1900s, based on historical hydrographic observations and recent ship mounted acoustic current meter data.
- The volume transport of overflow is strongly enhanced by entrainment and estimates of a combination of overflow and entrained water have been reported by Sarafanov *et al.* (2012) for 2002–2008 as 13.3 Sv. This is the same as Dickson and Brown (1994) estimated for a period before 1994 (with an uncertainty of 1.3 Sv). A direct comparison with the results from the OSNAP measurements reported by Lozier *et al.* (2019) for a 21-month period in 2014–2016 is not straightforward; however, at 15.6 ± 0.8 Sv between the southern tip of Greenland and Scotland, it is consistent with the 16.5 ± 2.2 Sv reported by Sarafanov *et al.* (2012).

circulation (Häkkinen and Rhines, 2004; Hátún *et al.*, 2005) as well as to AMOC variations (e.g. Robson *et al.*, 2016). Generally, temperature variations have been associated with parallel salinity variations (González-Pola *et al.*, 2019), but recently there are indications of a decoupling between temperature and salinity, most notably demonstrated by extreme freshening in the eastern subpolar North Atlantic after 2012 (Holliday *et al.*, 2020).

One particular feature of the debate on the state of the AMOC has been the existence of an abnormally cold area south of Greenland, commonly known as the ‘North Atlantic warming hole’ or ‘cold blob’. Some authors have assigned this to a weakening of the AMOC associated with increased melting from the Greenland ice cap (Drijfhout *et al.*, 2012; Rahmstorf *et al.*, 2015), and models developed by Liu *et al.* (2020) suggest a weakened AMOC can explain ocean cooling south of Greenland that resembles this phenomenon. However, other factors including increased reflection of solar radiation from the low clouds generated by the cold water and changes in the subpolar gyre may also be involved (Keil *et al.*, 2020).

Regarding longer-term trends, Bakker *et al.* (2016) found in their model that, with the IPCC high-emissions scenario (Representative Concentration Pathway (RCP) 8.5) and taking into account Greenland meltwater, the Gulf Stream system weakens by 37% by 2100 and continues to fall by 74% by 2290–2300. A critical point of uncertainty is the net flow of freshwater across the Atlantic, since measuring precipitation and river flows for this vast area is difficult. Model results that rely on salinity data to infer freshwater flows also suggest that the AMOC breaks down (after 100–200 years) at warmings associated with a doubling of atmospheric CO_2 levels (Liu *et al.*, 2017). The IPCC (2019) concluded that a collapse was very unlikely under lower emission scenarios, but under high emission scenarios a collapse could be about as likely as not by 2300.

Overall data thus do not give rise to short-term (years to 1–2 decades) concerns over substantial AMOC declines; however, even if there are uncertainties considering the longer periods, the ‘*very likely*’ (IPCC 2019) climate change projection of substantial weakening in the AMOC by 2100 and the high-impact/low-probability issue of ‘collapse’ remains. We return to this in Chapter 4.

2.5 Predictability and future projections: weather, climate

Climatic conditions affect all aspects of our lives, from farming and fisheries, through tourism to renewable energy generation. Weather systems vary greatly from year to year and from season to season, with the strength and path of the westerlies blowing in from the Atlantic Ocean a major influence. The extent to which such seasonal-to-decadal climate fluctuations can be predicted is of great practical and economic importance, and realising the potential for long-term forecasting is one of the ‘Grand Challenges’ for the World Climate Research Programme, and for future IPCC assessments through its Coupled Model Intercomparison Project. There is currently a large European effort on seasonal-to decadal-scale predictions: for instance, the European Centre for Medium-Range Weather Forecasts monitors the Earth system and produces forecasts over time frames ranging from monthly and seasonal, and up to a year ahead. Steady progress is being recorded in forecast performance, increasing the potential for the results to be applied commercially and in society.

The large-scale ocean and atmospheric circulation of the North Atlantic has a fundamental influence on the European climate (Drange *et al.*, 2005). Some general aspects of ocean-based predictability were described as long as 100 years ago (Helland-Hansen and Nansen, 1909), but the natural climate variability of the ocean currents and winds continues to provide a potential mechanism for predictability (Årthun *et al.*, 2018a). As described earlier, the AMOC, AMV and NAO lead to the surface air temperature varying on interannual to multidecadal timescales depending on the region

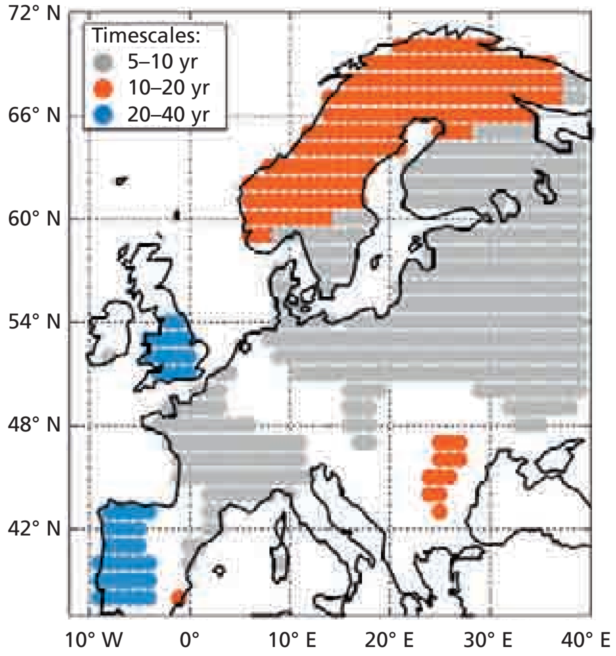


Figure 2.4 Timescales of European wintertime surface temperature variability (in years), all related to the relative warmth of Atlantic Ocean circulation and the westerly winds connecting ocean and land (Århthun et al., 2018a).

and timescale (Årthun *et al.*, 2017, 2018a). As shown in Figure 2.4, the ocean-induced variance over land is inter-decadal in northern Europe and Scandinavia (red), with a dominant timescale of 14 years, and dominated by SST in the Norwegian Sea. The multidecadal timescale that dominates variability in surface air temperature over the Iberian Peninsula and Great Britain (blue) is associated with North Atlantic SST variability and the AMV (O'Reilly *et al.*, 2017). Over most of eastern and central Europe, sub-decadal (less than 10 years) NAO-like variability dominates (grey).

Changes in SST resulting from variations in the strength of the Atlantic Ocean circulation and its meridional heat transport are of critical importance since they affect the overlying air masses and the formation, development and dissipation of extra-tropical cyclones in the North Atlantic, which in turn affect the intensity of storms and their tracks. Climate models (Wang *et al.*, 2015; Gallagher *et al.*, 2016) suggest that the reduction in temperature gradient between the Arctic and Equator (because of Arctic amplification leading to more warming in northern latitudes) should result in a reduction in average wind speeds and wave height.

On the other hand, the North Atlantic storm track may be influenced by the state of the AMOC, with weakening of the AMOC leading to an increase in the meridional mid-latitude gradient in SST, leading to baroclinic instability from which the storm track draws its energy (Woollings *et al.*, 2012). Where this leads to intensification of storms, risks will increase of extreme wind and wave events with associated risks of storm surges leading to flooding and coastal erosion. The uncertainties in future ocean circulation changes cause uncertainties in estimating the storm track response. However, since the ocean flow is slow (around 2 cm/s; Årthun and Eldevik, 2016), ocean heat anomalies need about 5 years to travel the 3000 km between Newfoundland and Scotland, and thus fluctuations in flow and temperature of the oceanic heat reservoir can contribute to climate predictability over a range of timescales (Gulev *et al.*, 2013; Yeager and Robson, 2017).

On interannual to decadal timescales, the progression of temperature and salinity anomalies is found to propagate persistently and predictably from the North Atlantic, through the Norwegian Sea, and into the Arctic with the North Atlantic Drift and its poleward extension (Sutton and Allen, 1997; Årthun *et al.*, 2017), also implying predictable change in Arctic sea-ice extent and fish stock habitats (see, for example, Miesner and Payne, 2018; Årthun *et al.*, 2018b). These poleward travelling phases of warm and cold anomalies, upon reaching the Norwegian Sea, are furthermore reflected in winter temperatures over Scandinavia, with anomalous ocean heat being communicated over land with the mean westerlies (Årthun *et al.*, 2018a).

Currently the UK Met Office seasonal prediction system (GloSea) can predict a winter NAO 1–4 months ahead with a correlation of 0.6 (Scaife *et al.*, 2014) from such measurements. There is evidence that the NAO is predictable on much longer timescales, although the exact nature of ocean–atmosphere interactions has yet to be resolved (Smith *et al.*, 2020). Reducing the remaining uncertainties is thus a research priority (section 4.8).

In addition to oceanic influences, the European climate is also responding to changes in the Arctic, where rapid warming in the Arctic atmosphere weakens the equator-to-pole thermal gradient and mid-latitude circulation. Possible consequences are still being researched but weakened storm tracks are expected, as are shifted jet streams and amplified quasi-stationary waves associated with persistent floods/droughts (Screen, 2017a; Coumou *et al.*, 2018). In addition, Arctic ice loss has been estimated to increase the likelihood of cold continental air outbreaks over western Europe during winter (Jaiser *et al.*, 2012), although cooling brought about by more easterly winds will be offset by the overall warming of the Arctic (Screen, 2017b). The winter sea-ice extent will respond to the anomalous heat of the Atlantic water reaching the Fram Strait or the Barents Sea: more heat, less sea ice (and vice versa; see, for example, Yeager *et al.*, 2015; Årthun *et al.*, 2017).

2.6 Global and regional sea level rise

SLR is caused by the combination of thermal expansion of the oceans and the additional water from melting of the grounded cryosphere (Slangen *et al.*, 2017; Frederikse *et al.*, 2020), and has been dominated by anthropogenic forcing since 1970 (Slangen *et al.*, 2016). Currently ice melting contributes approximately 50% of the 3.6 mm annually of global SLR. The largest contributions in the future, as well as the largest sources of uncertainty will come from melting of the Antarctic and Greenland ice sheets (Edwards *et al*., 2021). Ice loss in Antarctica will have the greater impact on European SLR because of a change in the Earth's gravitational forces as a result of the reduction in the horizontal gravitational pull from Antarctica (Mitrovica *et al*., 2009). Glaciers worldwide outside Greenland and Antarctica, including the European high mountain areas, have recently (2006–2015) lost mass at an average rate of 220 Gt/yr (about 0.6 mm/yr SLR). The comparable mass loss from Greenland is higher, with an estimated 278 Gt/year (about 0.77 mm/yr SLR), while Antarctica has lost about 155 Gt/yr (about 0.43 mm/yr SLR), mostly because of rapid thinning and retreat of major outlet glaciers draining the West Antarctic Ice Sheet (IPCC, 2019).

With the accelerating SLR globally, direct impacts on coastal communities are already apparent, with population movements underway from submerged areas such as low-lying Pacific islands and coastal areas such as in Bangladesh. Kulp and Strauss (2019) recently used a neural network approach to improve the estimate of how many people currently live below annual flood levels and will do in the future. Under IPCC's high emission scenario (RCP 8.5), an estimated 630 million people globally currently reside in areas that will be flooded by high tide in 2100 with an average rise of 1.1 m, mostly in Asia. This would reduce to 190 million (average rise of 29 cm) under RCP 2.6.

In Europe, the areas around the North Sea that will be inundated with an SLR of 1 m are shown in Figure 2.5, where large areas along the Dutch, German and Danish coasts (Wadden Sea) and the UK coast (inland of The Wash) are particularly vulnerable. As noted in EC (2020a), with a projected rise of 1 m by 2100, annual damage from coastal flooding could increase sharply from the current €1 billion annually to almost €814 billion by 2100 if no mitigation or adaptation measures are taken, with over 3 million people affected by coastal flooding.

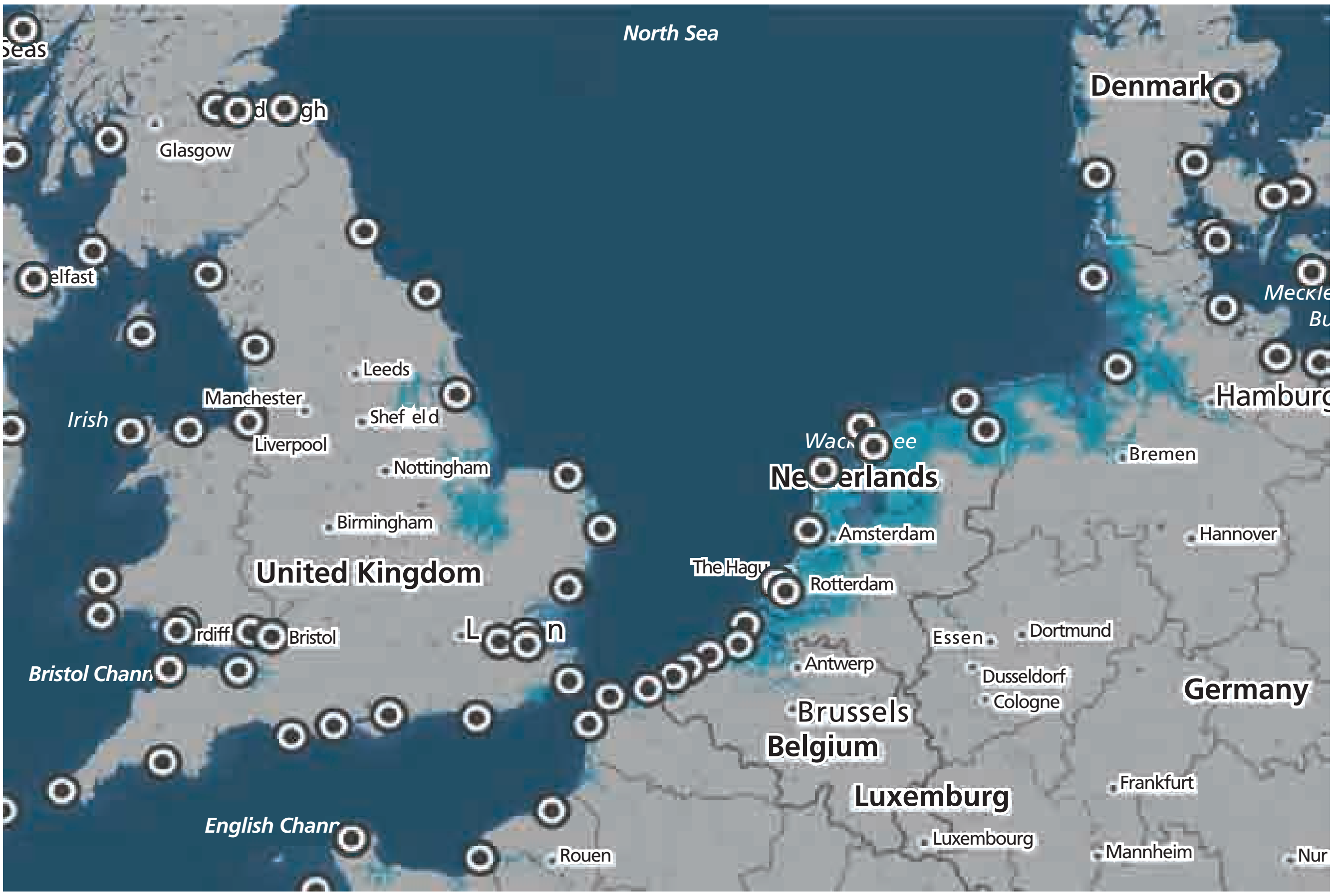
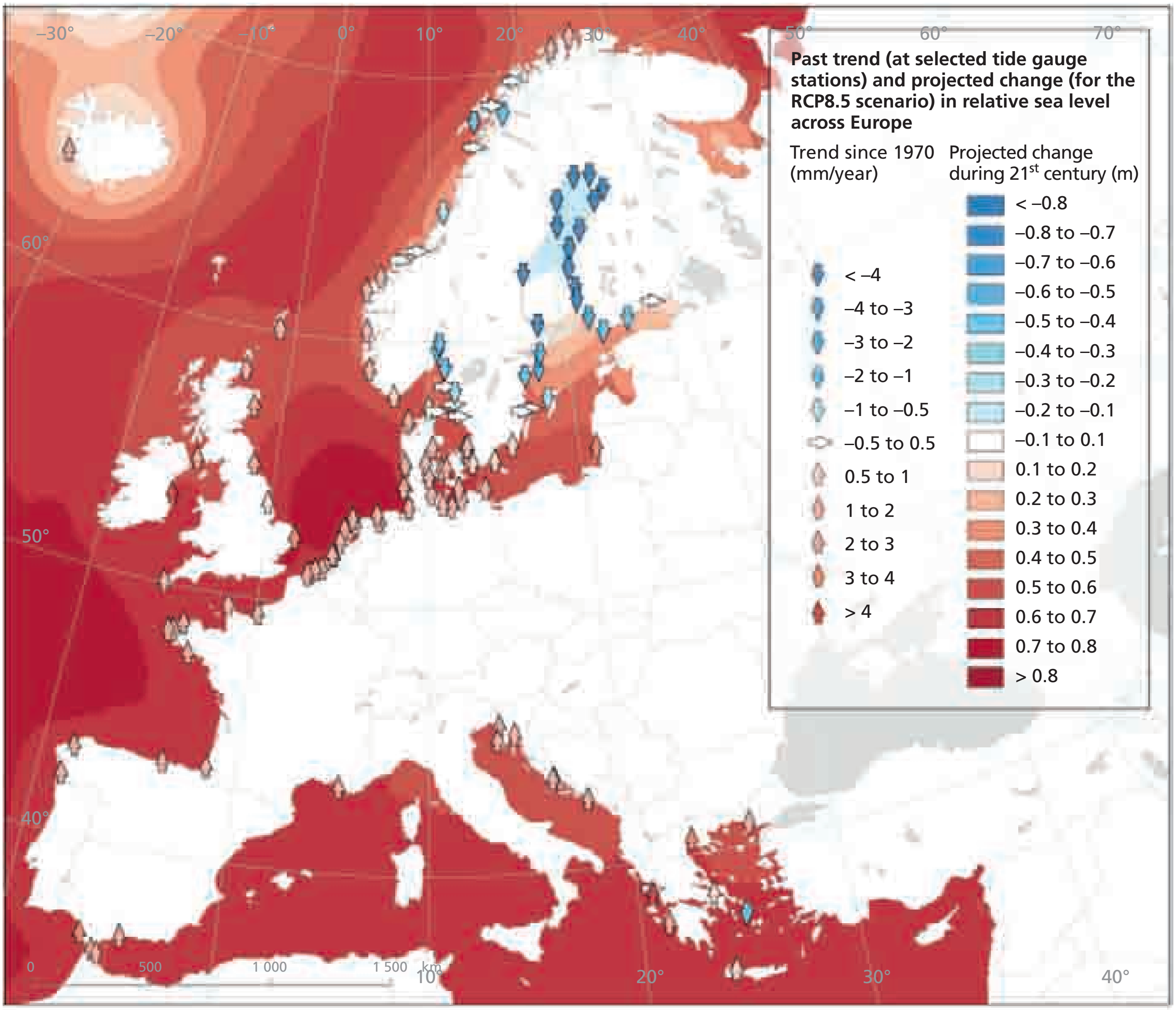


Figure 2.5 The North Sea coastline with +1 m of global SLR with the flooded areas in blue. Major population centres are marked in circles. (Source: https://sealevel.climatecentral.org/maps/.)



Reference data: ©ESRI

Figure 2.6 Past trends and projected changes for the IPCC RCP 8.5 scenario (EEA, 2020).

The dominant contribution to rising sea levels along the European coast will be the average global SLR. Indeed, Europe has experienced a rise close to +200 mm over the past century, which is close to the global mean (Church and White, 2011). However, European sea level may vary on interannual to multidecadal timescales, because of surface wind anomalies and heat fluxes associated with the NAO (Han *et al.*, 2017), and by ocean heat transport due to changes in the AMOC (McCarthy *et al.*, 2015). Regional differences from the global mean result from glacial isostatic adjustment, which offsets some of the SLR in much of northwestern Europe (Kopp *et al.*, 2014), and the Gulf of Bothnia is still rising faster than the mean global SLR (Johansson *et al.*, 2014)[2]. Such variations are already included in European SLR maps such as that in Figure 2.6 (EEA, 2020).

Local SLR can also vary with the state of the NAO and the associated wind patterns that may drive water towards coastlines. For instance, Chafik *et al.* (2017) found that the positive phase of the NAO led to anomalous high monthly sea levels in the North Sea and along the Norwegian coast (Figure 2.7), while levels along the French coast were higher in the negative phase of the NAO. There is also evidence that changes in the North Atlantic Ocean circulation can influence the sea level around the North and Baltic Seas through

---

[2] Recent analysis of the combined effect of coastal subsidence (e.g. through water or oil/gas extraction) and SLR (Nicholls *et al.*, 2021) show local effects up to four times the global average. Most of the areas affected with highest population densities are in Asia, and northern Europe is one of the few areas where land is uplifting.

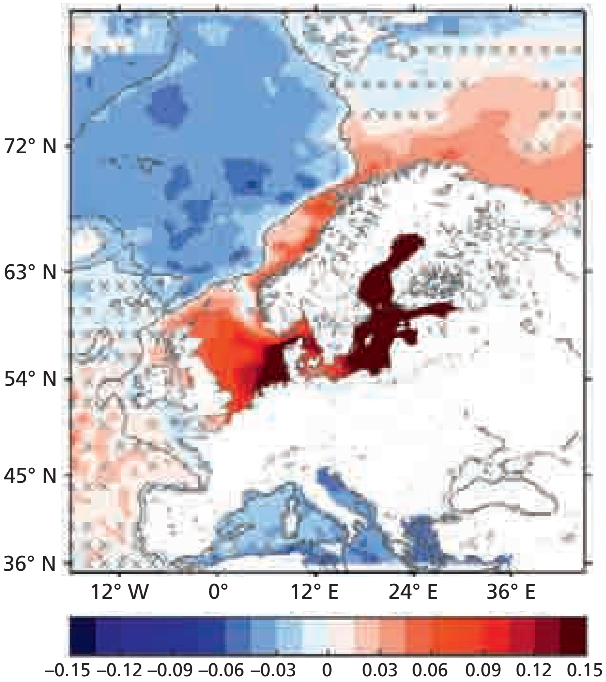


Figure 2.7 The SLR over both the Norwegian and North Seas with the NAO and its associated winds parallel to these coasts. The rise in sea level (in metres) for one standard deviation in NAO is shown (Chafik et al. 2017).

wave-induced processes (Bonaduce *et al.*, 2020). Integrating these factors to predict SLRs locally along European coasts and providing a better understanding of their magnitude and timing is important for local adaptation planning, and is discussed further in Chapter 4.

2.7 Marine ecosystems

Ocean circulation is a major factor (in combination with terrestrial discharges and deposition from the atmosphere) in determining the temperature, the chemical composition of the water (e.g. oxygen, CO_2 and nutrient content) and the environment for marine ecosystems in general. Important processes include the seasonal upwelling along the western coast of the Iberian Peninsula, the carbon cycle in the ocean and seas, and the gradual acidification of marine waters.

2.7.1 Supply of nutrients through upwelling and mixing

With a narrow continental shelf around the Iberian Peninsula (Figure 2.8) that receives limited river runoff (of the order of 2,000 m^3/s), colder nutrient-rich waters rising from depth (upwelling) is the key to ecosystem functioning. Large estuaries such as the Galician Rías in the northwestern corner of Iberia are fertilised by upwelled nutrient-rich water, enhancing primary production and contributing to productive fisheries including aquaculture (Tenore *et al.*, 1995). This exchange with deep Atlantic waters is responsible for the productivity of these coastal waters (see, for example, Pérez *et al.*, 1999; Borges and Frankignoulle, 2002; Bode *et al.*, 2011, 2019), and any weakening in upwelling and increased stratification could reduce primary production, fishery catches and storage of organic carbon by sedimentation. Kersting (2016) found no clear trends in productivity, but in recent decades a weakening of upwelling intensity in the northwestern Iberian coast (Galicia) and the Gulf of Biscay has been reported (Llope *et al.*, 2006; Pérez *et al.*, 2010; Bode *et al.*, 2011). Whether these observed changes relate to decadal variability or are long-term trends remains unclear. Results from climate models do not predict a significant decline in upwelling (Gomis *et al.*, 2016), but Bode *et al.* (2019) showed that variability at multidecadal scales could not be explained by upwelling winds and source water origin, pointing to the importance of nutrient inputs from continental waters and re-mineralisation, which in turn could be affected by variations in precipitation and temperature related to climate change.

From the northern side of the Bay of Biscay to the northern Atlantic coast of Scotland, direct exchange with the open ocean dominates nutrient supply. The northern side of the Bay of Biscay has a wide shelf but still with limited river runoff (about 1,000 m^3/s), while the Bay is bounded by the Azores current from the subtropical gyre and the North Atlantic Current from the subpolar gyre (Figure 2.9). The water masses are mainly of North Atlantic origin, and it is an area of deep winter mixing reflected in the nutrient and dissolved inorganic carbon concentrations being as high in winter surface waters as in deep water (see, for example, Jiang *et al.*, 2013). In the summer, these concentrations decrease when biological primary production sets in, also resulting in supersaturated surface oxygen concentrations.

Moving further north to the waters surrounding Ireland and the UK, the conditions change dramatically depending on which side of the islands is observed. West of Ireland and Scotland, the situation is similar to that described above: significant impact by the open Atlantic Ocean with little direct influence from land. Offshore from the continental shelf, multidecadal oscillations of warm and cold Atlantic surface temperatures impact the range and distribution of fishes, particularly pelagic fish (see Hátún *et al.*, 2009a; Alheit *et al.*, 2014). For example, blue whiting disperse widely in the Atlantic northwest of the Irish continental shelf when conditions are warm and saline, but cling to the shelf when conditions are cool and fresh (Hátún *et al.*, 2009a, b; Miesner and Payne, 2018). Direct impact on the livelihoods of local fishing communities can be seen in Ireland's second largest fishing port (Killybegs), where blue whiting landings doubled between 2017 and 2018 as the Atlantic re-entered a cool phase (BIM, 2018, 2019).

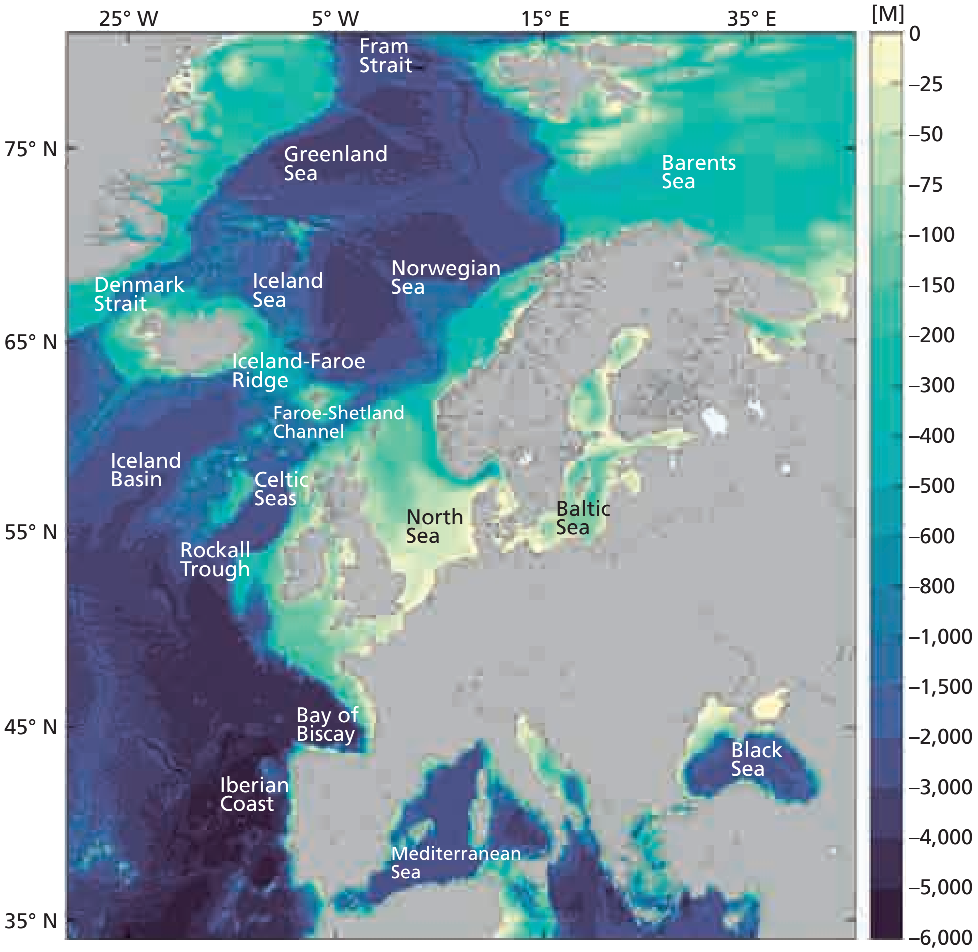


Figure 2.8 Ocean bathymetry and the continental shelf along the European Atlantic coasts. (Source: H. Asbjørnsen, bathymetry from ETOPO1-data https://www.ngdc.noaa.gov/mgg/global/.)

The Bay of Biscay and the northern Atlantic coast of Scotland are linked via the European Slope Current. This current has its origins in Iberia and can be traced intermittently along the continental margin as far as the Shetland Islands (Xu *et al.*, 2015). Owing to increasing seawater density offshore, the current gathers strength to the north (Simpson and Sharples, 2012; Marsh *et al.*, 2017) so that from the southwest of Ireland northwards, where it is fed by inflowing Atlantic currents, it can be traced. The Slope Current can act as a barrier to the mixing processes between the shelf and deep ocean described previously, but can also act as a highway for biological material. Thus, although the North Sea is similarly isolated from the deep ocean as the Irish Sea and the English Channel, its northern entrance and the Fair Isle gap between Shetland and Orkney contain sessile species of subtropical origin that have been transported along the Slope Current.

The more enclosed waters of the Irish Sea, English Channel and North Sea show much more variable conditions, being isolated from the deep ocean. Nutrient contents vary greatly both spatially and temporally with an area's ecology and hydrodynamics, influenced by local features in near shore waters. As one example, the North Sea was observed during the UK Shelf Sea Biogeochemistry Programme (www.uk-ssb.org) between January 2014 and August 2015, and showed how the seafloor can at times remove carbon, oxygen, nitrogen and iron from the water column and return these elements, making them biologically available at other times.

2.7.2 The carbon cycle in the seas around Europe

As mentioned earlier, oceans are a critical part of the natural carbon cycle and reduce the climate impacts of anthropogenic emissions of CO_2 by absorbing 20–30% of them. Oceans remove CO_2 by both physico-chemical and biological processes. The former vary with temperature (lower temperatures increase the solubility of CO_2), the partial pressures of CO_2 in the air and surface waters, and the degree of air–water mixing. The biological uptake through phytoplankton depends on the season and upwelling and mixing to provide the necessary nutrients. In winter, vertical mixing transfers waters already containing high concentrations of CO_2 to the surface layer, reducing

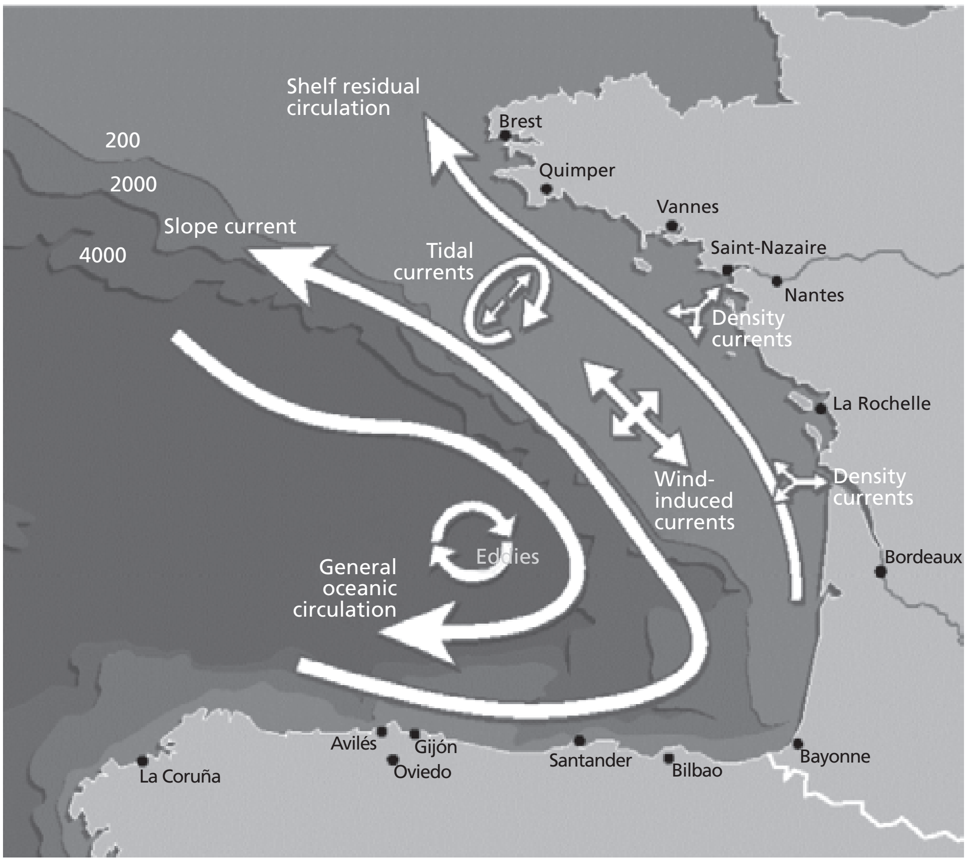


Figure 2.9 Flows in the Bay of Biscay (Lavin et al. 2006).

the difference between atmospheric and water CO_2 partial pressures and thereby offsetting some or all of the effect of increased solubility during winter. Typically, the mixing effect dominates, making the winter surface waters supersaturated with respect to CO_2, preventing additional uptake from the atmosphere. In the spring, primary production by phytoplankton removes CO_2, while the warming decreases solubility. Northern European seas are a net annual sink of atmospheric CO_2 (Becker *et al*., 2021).

Further complications may arise from the impact of local river runoff. For instance, substantial supersaturation by CO_2 has been observed around the south coast of the UK from July to December, owing to high river runoff containing organic carbon which biodegrades and increases CO_2 levels (Ostle *et al.*, 2016). Rivers also enhance the growth of phytoplankton through supplying nutrients; for instance, phosphate concentrations up to 3 μM and nitrate concentrations up to 50 μM were reported from the coast compared with less than 0.5 μM and less than 6 μM in the central North Sea, respectively (van Beusekom and Diel-Christiansenavenh, 2009).

The overall carbon budget of the North Sea is dominated by the inflow and outflow of Atlantic water, with small additions from the Baltic Sea, rivers and the atmosphere (Thomas *et al.*, 2005; Kitidis *et al.*, 2019). Overall, the surveys mentioned in section 2.7.1 found that there is a net removal of CO_2 from the atmosphere into the sediment in the North Sea, but this varies greatly spatially and temporally with the ecology and hydrodynamics. Most (over 90%) of the CO_2 taken up from the atmosphere in the North Sea is exported to the Atlantic Ocean. The European research infrastructure Integrated Carbon Observation System (https://www.icos-cp.eu) now monitors the carbon uptake in European seas.

The Baltic Sea is also a sink for atmospheric CO_2, with net uptake of CO_2 in spring and summer when primary production is most active, combined with little exchange during the rest of the year (Kuliński and Pempkowiak, 2011). The lack of autumn/winter out-gassing implies that the deeper waters that contain high levels of CO_2 as a result of the decay of organic matter are prevented from mixing with surface waters by the density gradient, before flowing into the North Sea, and potentially the Atlantic Ocean. The signature of Baltic Sea water (high alkalinity) can be traced in surface waters off the Norwegian coast (Anderson and Dyrssen, 1981), and contributes to the properties of the Norwegian Coastal Current.

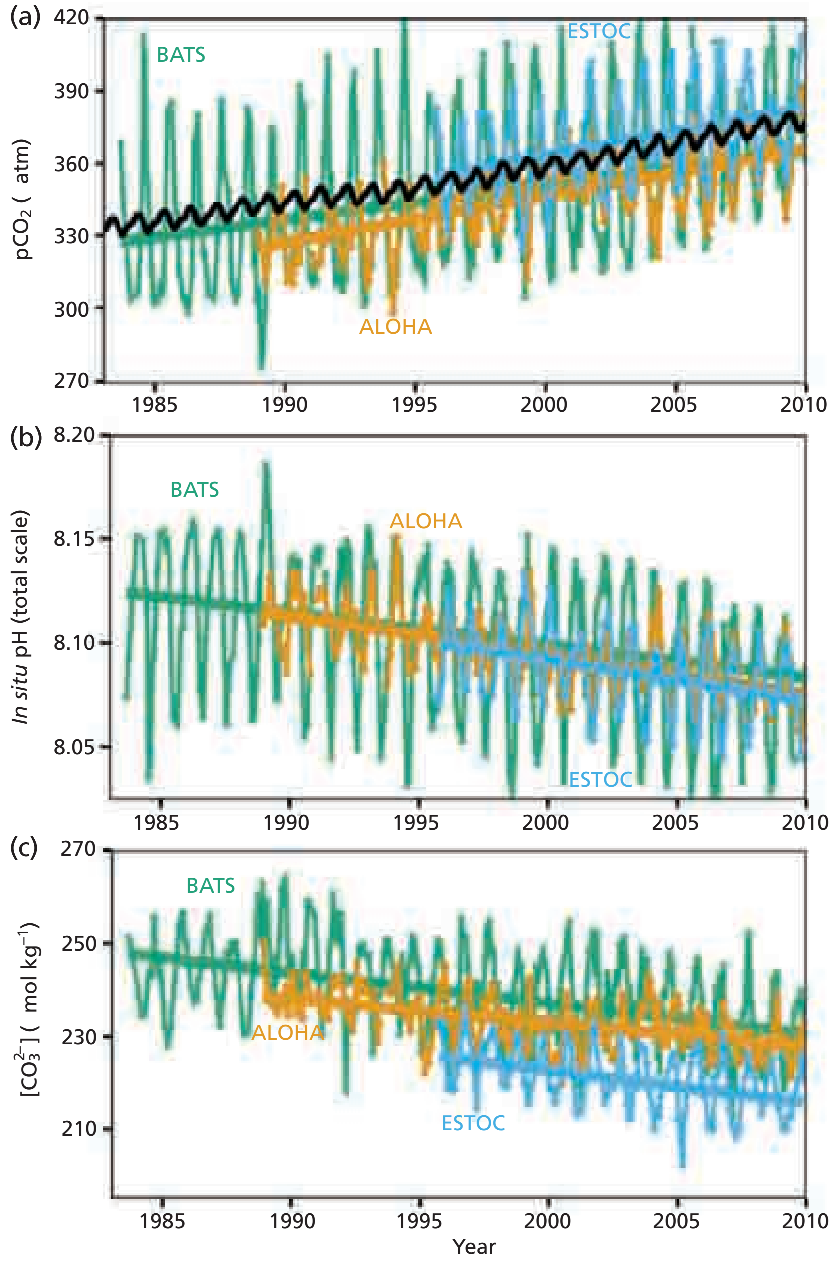


Figure 2.10 Trends of (a) surface seawater pCO_2, (b) pH and (c) carbonate ion concentration at two stations in the Atlantic Ocean (BATS, green line; ESTOC, blue line) and one in the Pacific Ocean (ALOHA, yellow line). The atmospheric pCO_2 record from the Mauna Loa Observatory is shown in black in (a). (Source: Rhein et al. 2013.)

2.7.3 Ocean acidification

When seawater absorbs CO_2, chemical reactions occur that increase acidity (a decrease in pH)[3]. As shown in Figure 2.10, there is a direct relationship between increasing atmospheric CO_2 concentrations, an increase in the partial pressure of CO_2 in the water, and a consequent decrease in pH and carbonate ion availability. In parallel with the unprecedented rate of increase in atmospheric CO_2, the present rate of ocean acidification is larger than at any other time during the past 65 million years (Zeebe *et al.*, 2016). Superimposed on the acidification trend in Figure 2.10 is the seasonal variability resulting from the consumption of CO_2 by primary production during the summer, and microbial decay of organic matter that produces CO_2 during the

---

[3] As studied by Hagens *et al.* (2014), atmospheric emissions of sulphur and nitrogen oxides can also reduce seawater pH. However, these have declined substantially since 1990 (reporting to the Long-range Transboundary Air Pollution Convention shows sulphur oxide emission declining by 70–80%; and nitrogen oxide emission by 40%) while CO_2 emissions continue to rise.

winter. Solubility varies with the seasonal temperature. While observations in the framework of the Integrated Carbon Observation System are suitable for monitoring ocean acidification, they are not yet of sufficient duration to be comparable with the subtropical monitoring stations in Figure 2.10. However, one study in Icelandic waters (Olafsson *et al.*, 2009) has shown a surface pH in winter decreasing at a rate of 0.0024 pH units per year, which is 50% faster than the average yearly rates at the BATS (Bermuda Atlantic Time-series Study) and ESTOC (European Station for Time-Series in the Ocean, Canary Islands) stations.

The decline of 0.04 in the pH of ocean waters during the past 25 years is against the backdrop of a seasonal variation of ±0.05 pH units. In coastal seas of higher productivity, the seasonal variation can be larger. In the Kattegat there is a variability is about ±0.2 pH units, and in the Baltic and Bothnian Bay as much as ±0.3 and ±0.4 pH units respectively (Havenhand *et al.*, 2019). Modelling beyond the short time series of detailed data available suggests (on the basis of the Eastern Gotland Basin) a decrease of about 0.4 pH units from 2000 to 2100 in a business-as-usual emissions scenario (Omstedt *et al.*, 2012). Summer pH remains almost constant; therefore it is the winter pH that decreases. In coastal areas with high seasonal variability, the present variation of ±0.3 is expected to increase to about ±0.4 pH units by the end of the century, expanding the range of pH units to which marine organisms have to adapt.

The manner in which organisms, from phytoplankton to fish, respond to ocean acidification has been studied (e.g. Wittmann and Pörtner, 2013; IPCC, 2014; AMAP, 2018). Field studies and experiments have shown that many organisms are adversely affected both directly and indirectly through ecological interactions, in an environment of lowered pH (IPCC, 2014; Crawfurd *et al.*, 2017), although some plankton species can benefit (see, for example, Bach *et al.*, 2017). Larvae are particularly sensitive. The associated reduction in the concentration of carbonate ions (Figure 2.11c) reduces the ability of many marine organisms (including larval stages) to produce the calcium carbonate required to build shells and skeletons (see, for example, Riebesell *et al.*, 2017). Calcium carbonate exists in different forms; the most common ones in marine organisms are calcite and aragonite, the latter being more soluble. Adverse effects on corals that build up their structures from aragonite crystals have been studied (e.g. Mollica *et al.*, 2018) but effects in the cold waters of the Atlantic and Arctic Oceans are also anticipated. For example, the pteropod *Limacina helicina* (an important food source both for fish and for whales) has shells of aragonite that are negatively impacted (e.g. Comeau *et al.*, 2012), with shells in waters of high local acidity showing clear signs of dissolution (e.g. Bednaršek *et al.*, 2014).

As ocean acidification is a direct response to global atmospheric concentrations of CO_2, the emphasis on forest biomass (without carbon capture and storage) as a primary source of 'renewable' energy within the EU will exacerbate acidification since this technology leads to a net increase of CO_2 levels in the atmosphere for some decades (Norton *et al.*, 2019). While the general trend towards more acidity is occurring independently of changes in the ocean circulation, local effects can arise when microbial decay of organic matter decreases pH. This process is most common in deeper waters and at the sediment surface; it is therefore usually of little consequence for surface waters. However, in shallow coastal waters with high organic matter load, or coastal regions susceptible to ocean upwelling, this effect can be significant. Organisms living in such areas are exposed both to low pH and to low oxygen conditions that can be fatal. As one example, along the west coast of the USA (Feely *et al.*, 2008, 2018), the loss of larvae in the oyster industry caused losses worth millions of US dollars. Similar conditions can arise in several locations along the European Atlantic coast.

3 Atlantic connections with the Baltic and Arctic

3.1. Estuarine gateways

Europe's western coastline bordering the Atlantic is affected directly by its large-scale ocean circulation. Other areas are shielded from the Atlantic proper by the extensive continental shelf (Figure 2.8) and the restrictions on the influx of Atlantic water caused by key 'gateways': the English Channel to the North Sea, the Gibraltar Strait to the Mediterranean Sea, the Kattegat to the Baltic Sea and the Fram Strait/Barents Opening connecting the Atlantic with the Arctic Ocean.

The cooling that leads to overturning in the AMOC was described in section 2.1, but different processes govern the Atlantic flow beyond the northern gateways. In the Arctic Ocean and Baltic Sea (see section 3.2), a so-called estuarine circulation is sustained by freshwater input and consequent buoyancy gain. The freshwater subsequently circulates within the 'estuary' entraining saline Atlantic water from below. The result at the gateways is a relatively fresh surface-layer outflow balanced by denser Atlantic inflow at depth (Stigebrandt, 1981, 1983)[1]. The two interconnected circulation loops that jointly feed from the Norwegian Atlantic Current – the completion of the AMOC turning inflow into dense overflow, and the Arctic estuarine circulation – are illustrated in Figure 3.1.

Climate change and variability in Atlantic circulation may affect the flows across these gateways. The Barents Sea (beyond the gateway of the Barents Opening) has little direct river runoff, and its hydrography reflects a balance between the temperate Atlantic inflow and the presence of sea ice. As the sea ice retreats, the Barents Sea has increasingly become part of the Atlantic domain (so-called 'Atlantification'; Årthun *et al.*, 2012; Barton *et al.*, 2018) leading to a poleward shift of the Northeast Arctic cod fishery (see section 4.6). Atlantification has recently been observed further downstream along the Arctic shelves (Polyakov *et al*., 2017). There is in addition a large interannual to decadal variability that is linked with the Atlantic Ocean. The wintertime sea-ice extent fluctuates from year to year with the anomalous state of the North Atlantic Drift and the Norwegian Atlantic Current upstream – less heat, more sea ice – with a predictability of up to 10 years (Onarheim *et al.*, 2015; Årthun *et al.*, 2017).

The processes driving the inflow of Atlantic water into the Arctic Ocean have been studied (e.g. Timmermans and Marshall, 2020) and may include wind-driven mixing interior to the Arctic that draws water in, and winds exterior to the Arctic that drive water in along bathymetric contours. The relatively warm and salty northward flows are along the eastern side of Fram Strait, while the outflowing cooler and fresher upper Arctic Ocean waters flow along the western side. As indicated in Figure 3.1, the increase in freshwater input from the melting of Greenland glaciers is mostly

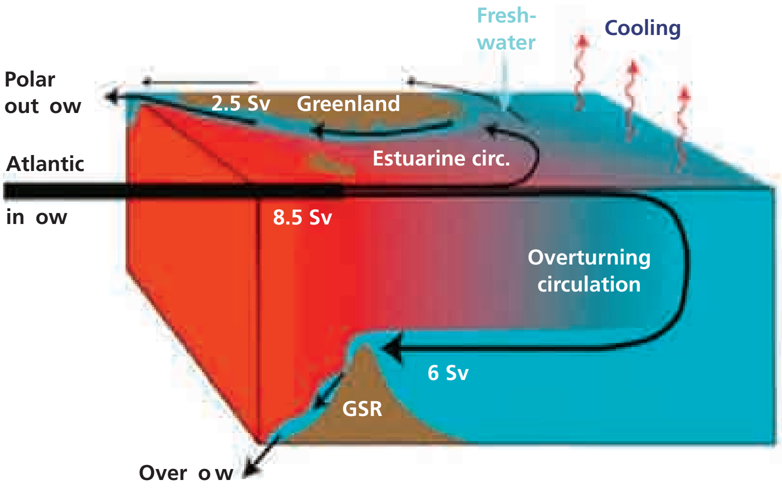


Figure 3.1 The estuarine and overturning circulations constituting the Arctic–Atlantic thermohaline circulation (Eldevik and Nilsen, 2013; adaptation of original figure in Hansen et al. (2008); courtesy of B. Hansen). GSR, Greenland–Scotland Ridge.

---

[1] Although not the subject of this report, it is worth noting that for the Gibraltar Strait and the Mediterranean Sea, the opposite is the case. Owing to evaporation, the Mediterranean Sea is more saline and denser than its Atlantic source-water. A 'negative' estuarine circulation is the result with Atlantic surface inflow through the Gibraltar Strait and Mediterranean Sea water exported below (Bryden and Kinder, 1991).

accommodated within the existing surface flows southwards along the Greenland coast, without reducing the compensating northward flows of Atlantic water along the Norwegian coast in the Norwegian Atlantic Current. Indeed, additional freshwater input on the Greenland side can provide additional 'pull' polewards for surface waters in the Norwegian Atlantic Current (Lambert *et al.*, 2016), and climate model projections do indicate that the current will increase slightly through the 21st century (Årthun *et al.*, 2019).

3.2 The Baltic Sea

The Baltic Sea catchment covers an area of 2.13 million km^2 with a population of 85 million people in 14 countries. It is separated from the Atlantic by one of the gateways mentioned above. Changing North Atlantic circulation can impact the sea either directly by changing the water inflow and outflow through the Kattegat and Danish Straits, or indirectly through atmospheric processes such as changes in wind patterns, precipitation and freshwater inputs from rivers.

Impacts via the atmosphere

Weather in the Baltic is influenced by the state of the Atlantic Ocean, with decadal SST trends reflecting a combination of global warming and the AMV (Lehmann *et al.*, 2011; Rutgersson *et al.*, 2014; Kniebusch *et al.*, 2019). As discussed in sections 2.1–2.4, analogously to other European regions, the Atlantic variability by the AMOC and the subpolar gyre can influence agriculture, water and energy resources, via changing storm tracks and regional temperatures in the Baltic Sea region (Buchan *et al.* 2014; Sgubin *et al.*, 2017). As with the AMOC and the Arctic sea-ice cover (see section 2.5), there seems to be a similar causal relationship with Baltic Sea ice through perturbations of the North Atlantic and Arctic Oscillations[2]; Figure 3.2 shows a significant negative correlation of the maximum ice extent in the Baltic Sea with both Arctic Oscillation and NAO indexes (Uotila *et al.*, 2015).

In summer, weather patterns that lead to persistent high pressure over the British Isles and a negative NAO (Haarsma *et al.*, 2015) result in an increase of precipitation over the Baltic Sea region and a decrease over the Mediterranean (Jackson *et al.*, 2015). Cold anomalies in the subpolar gyre, such as in 2013–2016 (Josey *et al.*, 2018), can increase the probability of heatwaves over central Europe, while over the Baltic Sea a slightly cooler-than-normal weather pattern might prevail (Duchez *et al.*, 2016).

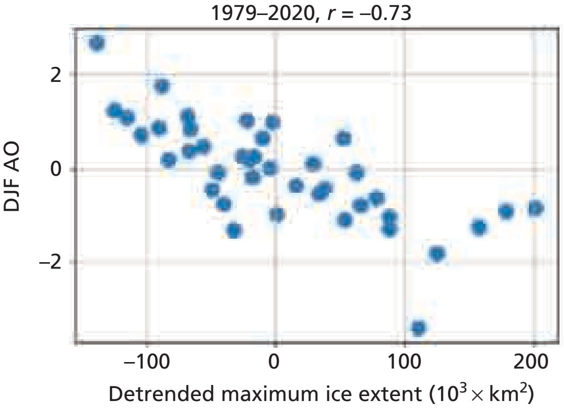


Figure 3.2 The relationship between detrended maximum ice extent of the Baltic Sea and the Arctic Oscillation index in winter (DJF AO) for 1979–2020. The correlation between these variables is strongly negative, indicating that winters of positive Arctic Oscillation (or NAO) coincide with winter lows in ice in the Baltic Sea. (Source: P. Uotila.)

Impacts via the Danish Straits

The deep water in the Baltic Sea originates from the North Sea (Leppäranta and Myrberg, 2009). Inflows from the North Sea renew water below the strong halocline of the Baltic Sea and increase oxygen levels, so are important for the Baltic ecosystem. Inflows of moderate volumes occur continuously, but only large flows (termed Major Baltic Inflows (MBIs)) are capable of renewing the deepest water.

MBIs follow large-scale weather conditions, such as strong and persistent westerlies across the North Sea for several weeks after a period of high pressure over the Baltic Sea region (BACC II Author Team, 2015). The high pressure first suppresses the water volume of the Baltic Sea and then the westerlies bring back high-salinity ocean water from the North Sea. Accordingly, MBIs are correlated with sea-level variability in the North and Baltic Seas (Hordoir *et al.*, 2015). The nature of the inflow water will vary with the season: summer inflows would be warm and of low oxygen content, while in winter and spring the water would be cold and oxygen-rich. MBIs may take up to a year to reach the deeper parts of the central Baltic Sea basin.

Time series of frequency and intensity of MBIs since the late 19th century do not contain significant trends, although there seems to be some variability over a 25- to 30-year period (Mohrholz, 2018). Climate models point to MBIs increasing slightly in all climate scenarios

---

[2] The Arctic Oscillation is a climate pattern characterized by winds circulating anti-clockwise around the Arctic at around 55° N latitude. When the Arctic Oscillation is in its positive phase, strong winds circulating around the North Pole confine colder air in polar regions. When weaker in the negative phase, this allows southward penetration of colder, Arctic air (Rudels *et al.*, 2012).

(Schimanke *et al.*, 2014), and Hordoir *et al.* (2015) predict saltwater inflows becoming stronger, longer and more frequent owing to rising sea levels that increase the water depth at the entrance to the Baltic. However, such changes have not yet been detected against the background of natural variability. The influence of changes in Atlantic circulation processes such as the AMOC and subpolar gyre is difficult to determine as the Atlantic inflow into the North Sea is highly variable (Marsh *et al.*, 2017), and small compared with the effects of wind forcing (Lehmann *et al.*, 2017).

Hypoxic, anoxic and euxinic zones[3]

Owing to the strong and permanent halocline, deep layers devoid of oxygen are not refreshed by mixing vertically; rather, they rely on lateral dispersion triggered by MBIs, which are thus critical in determining the extent of anoxic zones. Nine countries adjoin the Baltic, making it vulnerable to discharges from effluents and agricultural runoff, combined with aerial deposition from traffic, household and industrial emissions. As a result of excess inputs of nitrogen and phosphorus, algal blooms are common in summer (Hong *et al.*, 2017) in most parts of the Gulf of Finland, the Gulf of Riga, the Baltic proper and in the southwestern parts of the Baltic Sea. The microbial respiration that results, depletes oxygen (Conley *et al.*, 2009). In addition, overfishing of the highest trophic level species (cod) increases the abundance of forage fish (sprats) that feed on zooplankton, thus reducing grazing intensity on the algae. The result is that the part of the Baltic Sea affected by hypoxia has increased from 5,000 to more than 60,000 km^2 over the past century (Carstensen *et al.*, 2014). This has adverse impacts on the dominant commercial fished species owing to a reduction in areas suitable for spawning, loss of benthic food supply and a decline in physical condition (Limburg and Cassini, 2018). Hypoxia may also favour the growth of the potentially toxic cyanobacteria that also produce decaying mats that become stranded along the shores; this has increased in recent decades with adverse impacts on coastal recreation.

Owing to the restricted water exchange with the North Sea and the permanent haline stratification in the central Baltic Sea, restoring oxygen levels in the deeper waters depends on the infrequent MBIs and, between these, the Baltic contains large volumes of anoxic waters in its deeper basins, some of which become sufficiently anoxic to form hydrogen sulphide. One of the strongest inflows was observed in December 2014, substantially reducing anoxic zones the following year. The status of Baltic waters is routinely monitored and reported under the Helsinki Convention (see, for example, Feistel *et al.*, 2016). In parallel, measures to reduce nutrient inputs are implemented within the Helsinki Convention[4].

---

[3] Hypoxia, low oxygen content; anoxic, lack of oxygen; euxinic, anoxic conditions in the presence of hydrogen sulphide.

[4] https://helcom.fi/baltic-sea-action-plan/nutrient-reduction-scheme/.

4 Policy issues

In the previous sections we have described the processes that drive the highly complex circulation in the Atlantic Ocean and how they interact with European waters, the atmosphere and the climate, as well as trends in SLR and acidification. The state of the seas around Europe not only influences the economic sectors covered in the EC's Blue Growth policies, but also the quality and sustainability of fisheries within the scope of the MSFD, as well as the broader infrastructure and economic assets at potential risk through SLR and extreme weather. Incorporating scientific knowledge, with its inherent uncertainties, in such a broad range of EU policies is quite a challenge and we encourage the directorates and stakeholders involved to make full use of the information in this report. To stimulate what we hope is a continuing dialogue between science and policy-makers, the Expert Group offers some initial thoughts on the policy areas most affected by this scientific analysis.

4.1 The future of the Atlantic Meridional Overturning Circulation and Gulf Stream

The transport of heat and salt by ocean currents from the subtropics to as far as the Arctic Ocean is a critical component of Europe's climate, and therefore the stability of the underlying circulation is an important issue. The current state of the Atlantic Meridional Overturning Circulation (AMOC) was discussed in section 2.4, where scientific debate continues over the extent of natural variability and the degree to which the changes observed by the physical measurements of the RAPID and OSNAP arrays are attributable to anthropogenic warming. Overall, there are no recent data to change the IPCC view that a weakening (of the order of 11–34%) may be expected by the end of this century.

One of the narratives in the public discourse is the perception of a European 'little ice age' as a consequence of a weakening of the AMOC. However, this review finds that perception to be misleading for the degree of weakening expected this century for the following two reasons.

- The heat transport to northern latitudes in the warm surface waters is expected to be maintained (or even increase slightly) owing to the ocean circulation patterns connecting with the Arctic, even if the overturning circulation weakens (section 3.1).
- A reduction in heat transport to northern latitudes would be against the background of temperature rises from global warming and thus would merely slow regional warming and not reverse it.

Even though this may be reassuring in the near-term, effects of a more substantial weakening or collapse would be wide-ranging. High-resolution climate models (Jackson *et al.*, 2015) show the wider impacts in Europe to include weaker peak river flows and vegetation productivity, with implications for water availability and crop production. Analysing the economic impact of the changes in temperature and water availability on UK agriculture, Ritchie *et al.* (2020) concluded that there would be a widespread cessation of arable farming in the UK with associated loss of agricultural output. Beyond Europe, teleconnections may strongly diminish precipitation in the Sahelian region and weaken the Asian monsoon, extending impacts to hundreds of millions of people, increasing pressures for migration. As the IPCC (2019) points out, a substantial weakening of the AMOC would induce '*strong and large-scale climatic impacts with potential far-reaching impacts on natural and human systems*'. Furthermore, as observed by Chen and Tung (2018), the AMOC plays an important role in buffering surface warming for the planet as a whole, by transporting surface heat northwards and transferring heat into the deeper Atlantic. Weakening is thus associated with increased global surface warming.

The AMOC remains an issue not only of European but also global importance. As we already alluded to in section 2.4, the role and routing of freshwater fluxes both in nature and models remain a source of uncertainty about the risk of substantial weakening. Research (e.g. Alkhayuon *et al.*, 2019) suggests that trends in the salinities of the subtropical and subpolar Atlantic may provide an early indication of substantial AMOC weakening, and monitoring and research to improve our understanding and to provide an early warning of substantial change should continue to have a high priority. In addition to the possibility of eventual abrupt AMOC-change, there is the persistent if gradual change of ocean warming, acidification and deoxygenation, where there is concern that such incremental changes can accumulate to a '*quiet crossing of tipping points*' (Heinze *et al.*, 2021).

Focusing more directly on the fluctuating Gulf Stream and its branches of temperate waters, section 2.5 pointed to the potential for greater climate predictability based on the relatively slow-moving changes in ocean circulation and their interactions with the atmosphere. Harvesting this potential to allow predictability over forecast horizons of months to years would have large societal benefits for Europe. Examples include predicting probabilities of relatively dry, cold or windy seasons that could impact agriculture and renewable energy (section 4.3); how the preferable hydrographic conditions of key fish stocks may shift within and across national economic zones, and providing further guidance to sustainable management (section 4.6); as well as identifying regional variations on sea level (sections 2.6 and 4.2).

4.2 Effects on sea level rise

Current trends in global SLR were described in section 2.6, where the vulnerability of the coastal population to a 1 m rise was shown (Figure 2.5). Future rises will depend on emission pathways and the associated increased SST, and the rates of melting of the Greenland and Antarctic ice sheets. The simulated SLR for 2100 globally is +0.48 m for RCP 2.6 and +0.84 m (range 0.61–1.1 m) for RCP 8.5 (IPCC, 2019), although a wider range of 0.5–2 m can be found in the literature. A recent review of ice loss and its contribution to SLR (Slater *et al.*, 2021) estimates that 28 trillion tonnes of ice have been lost between 1994 and 2017, causing sea levels to rise by 34.6 ± 3.1 mm. Most glaciers are losing mass at accelerating rates larger than those of the Greenland and Antarctic ice sheets and account for 21% of the global SLR since 2000 (Hugonnet *et al.*, 2021). Moreover, Grinsted and Christensen (2021) found a nearly linear relationship between mean SLR and global mean surface temperature since 1850 that suggested recent predictions from IPCC models underestimate future sea level rise. Most recently, DeConto *et al.* (2021) found the rate of Antarctic ice melt to be very sensitive to the future rate of warming. Limiting global mean warming to 2 °C or less would continue Antarctic ice loss at rates similar to those of today, whereas the rate of warming associated with current polices would cause a sudden acceleration in losses after 2060 equivalent to a global SLR of 0.5 cm per year by 2100.

SLR will increase the risk of future extreme events caused by storm surges, waves and high tides, especially along the northern European coast. The frequency of such events is expected to increase under all emission scenarios, and the 5 million Europeans currently at risk of seawater flooding once every 100 years may be flooded almost annually by 2100 in the high emission (RCP 8.5) pathway (Vousdoukas *et al.*, 2017). Changes to the Baltic coastline as a result of SLR and wave climate are also expected (Weisse *et al.*, 2021). There are many factors that need to be integrated into coastal erosion control planning and adaptation for population centres along the coast and estuaries. Among these is how coastlines will respond to different levels and rates of SLR. For instance, Cooper *et al.* (2020) argue that the historical migration of beaches as a result of changes in postglacial SLR (which allowed beaches to retreat without being lost) may continue. On the other hand, many sandy beaches can no longer migrate owing to building and infrastructure; and Vousdoukas *et al.* (2020) conclude that global SLR poses a generic threat to sandy beaches that occupy more than one-third of the global coastline, along with their high socio-economic value.

As described in section 2.6, planning for future SLR along European coastlines has to recognise two major sources of uncertainty: first, in the average global SLR where the key variables are the rates of melting in Antarctica and Greenland; second is the local variations of the mean SLR caused by geography and susceptibility to Atlantic circulation and associated weather patterns. The uncertainties in planning are thus large and national risk assessments often offer a wide range of options for policy-makers. For instance, the UK Foresight (2017) analysis covers scenarios from ‘low’ (20 cm), through ‘medium’ (60 cm) to ‘extreme’ (250 cm) rises by 2100. National assumptions in planning for SLR in practice vary significantly (McEvoy *et al.*, 2021), with some EU Member States already factoring in such projections, while others assume lower levels.

Uncertainties remain in future SLR projections. However, the evidence for increasing glacier and ice sheet melt that is higher than recent IPCC estimates (Siegert *et al.*, 2020), together with the need to account for a further 10–15 cm variability depending on Atlantic conditions, suggests that national and EU adaptation planning should prepare for a minimum of a 1 m SLR by 2100. (This would be relative to a 2000 baseline and before local isostatic rebounds are taken into account.) In view of the uncertainties inherent in longer-term projections, adaptive planning is favoured by some to help resolve the trade-off between potentially investing too much too soon, or too little too late (e.g. Hall *et al.*, 2019). In addition, since inadequate preparation for SLR has major implications for sea defence and population movements, further coordinated research is important to reduce the current wide range of uncertainty in SLR estimates.

On a longer-term horizon, climate models show that even meeting Paris Agreement targets to hold the mean global surface temperature rise below 2 °C will still be associated with a likely further global SLR of between 50 and 450 cm by 2300 (Mengel *et al.*, 2018). Future rises are very sensitive to further delays in a global peak in CO_2 emissions. For instance, delaying the peak by 5 years adds a further 20 cm to the 2300 rise. Slowing the rate of increase in SLR is one of the most clearly visible benefits of rapid emissions reduction.

4.3 Effects on demand and supply of renewable energy

Energy demand

Energy demand during winter in northern Europe increases with cold temperature anomalies, while the demand in southern Europe increases with warm anomalies in the summer. Spinoni *et al.* (2015)

Table 4.1 Potential supply of offshore wind power to European countries by 2050 (WindEurope, 2019)

Country/area	Capacity (GW)	Country/area	Capacity (GW)	Country/area	Capacity (GW)
UK	80	Poland	28	Latvia	3
The Netherlands	60	Ireland	22	Estonia	1
France (excluding Mediterranean)	40	Sweden	20	Mediterranean; (Spain, Portugal and France)	70
Germany	36	Finland	15		
Denmark	35	Belgium	6		
Norway	30	Lithuania	4		

calculated the number of heating degree days[1] between 1951 and 2011, and found that the warming had led to lower energy demand in northern Europe, with large year-to-year variations. Given that prediction can be made for continental and Scandinavian temperatures on seasonal to 10-year timescales (Figure 2.4), future energy demand may be estimated on the basis of dynamic circulation predictions (Brands, 2013). Estimates of energy demand will probably become more important in the future with the transfer from fossil fuel to renewable energy sources that will be subject to changes in wind patterns and precipitation.

Offshore wind

As mentioned in the introduction, the offshore wind sector in Europe now has an installed capacity of 22 GW (WindEurope, 2020). Rapid growth is projected to continue as costs decline both for fixed and floating offshore installations (offshore wind offers very high values in tackling climate change, and Cranmer and Baker (2020) estimate such values to be up to US$30 trillion). Within Europe, projections indicate that capacity of up to 450 GW can be installed in a cost-efficient way by 2050; this would provide 30% of the forecasted demand for electricity (WindEurope, 2019) to the countries shown in Table 4.1.

These projections are based on current wind patterns. Changes in the strength and frequency of wind flows could affect the viability of reaching such targets. Climate change can affect wind power in several ways. Changes in the strength and direction of winds, variability between extremes in high speeds and turbulence, and prolonged quiet periods during quasi-stationary events directly impact power generation. Equally, waves, especially extreme events, may limit access for maintenance or have implications for design (Bisoi and Haldar, 2016). There are large fluctuations in atmospheric wind forcing over the North Atlantic region, with variability on many timescales (Woollings *et al.*, 2010). While globally there has been an increase in wind speed over the ocean (Young and Ribal, 2019), research on likely trends in the North Atlantic region is still underway.

In one study, Hdidouan and Staffell (2016) estimated the impact of climate change on the UK's wind resources to 2100. This showed capacity increase in some regions and decrease in others, with an increase in year-to-year variation. Meanwhile, a project under the EU Copernicus Climate Change Service has simulated the effects of climate projections on offshore wind farms at several locations (JBA, 2020). Overall, wind speeds and wave heights in the North Sea are expected to decline: this would provide greater turbine accessibility (0.2%), but a 3% decrease in generated energy. In a future scenario of Europe's offshore wind installed capacity reaching 190 GW, a 3% reduction would translate to 16 TWh per year less electricity (equivalent to €1 billion per year in missed revenue and 8 million tonnes of CO_2 per year if the lost power was replaced by fossil fuel). Such intermittency problems due to winds that are too low or too high can be moderated by using a larger array of connected sites (Solbrekke *et al.*, 2020) but knowledge of large-scale atmospheric variability is required.

Clearly the productivity of offshore wind and its ability to meet emission reduction targets is sensitive to changes in the climate, and more work is required to quantify and incorporate the results into adaptation strategies. This should include further work to improve understanding of the relationships between the North Atlantic circulation, European weather systems and the frequency of extreme events with increased wind speed or prolonged periods without wind.

Hydropower

Hydropower remains the largest source of renewable energy in Europe, generating over 341 TWh per year, equivalent to about 36% of the renewable electricity generated (VGB, 2018). Water availability affects

---

[1] The number of degrees that a day's average temperature is below 18 °C: assumed to be the temperature below which buildings need to be heated.

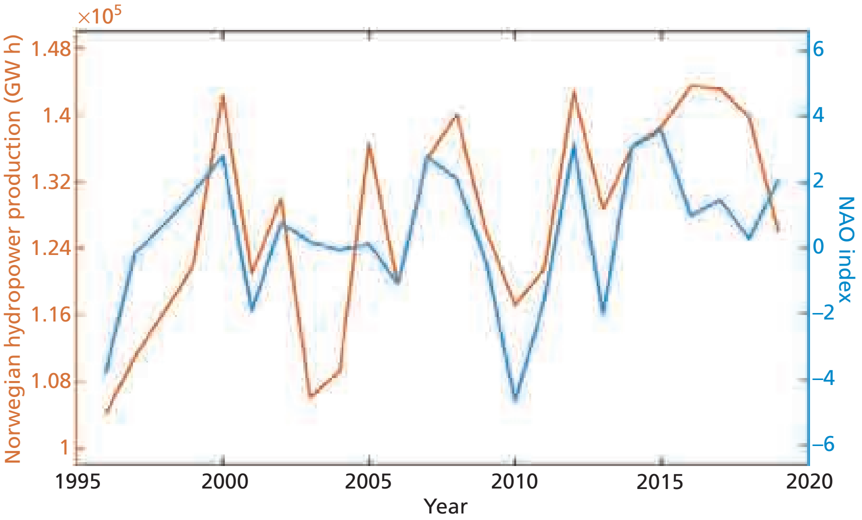


Figure 4.1 Norwegian hydropower production swings with the westerly winds (wintertime NAO; variance explained 40%). (Source: H. Asbjørnsen and N. Keenlyside, University of Bergen / Bjerknes Climate Prediction Unit; power production and NAO data from https://www.ssb.no/en/statbank/table/08307 and https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based, respectively.)

hydropower directly, with northern Europe having generally become wetter in recent decades while southern Europe has become drier. In Nordic countries (particularly Norway and Sweden), increased annual or seasonal water availability is due to increasing precipitation, and, to some extent, increase in glacier melt. While increased stream flow increases hydropower production, excessive water may exceed hydropower storage capacities. The EEA (2019) note that those facilities with substantial reservoir storage can be more resilient to short-term changes in river flow.

The processes over the North Atlantic described earlier influence the strength and direction of the winds over land and, with it, the rain and snowfall over much of Europe (Hurrell, 1995; Hurrell and van Loon, 1997). The state of the NAO (which can be expressed as an NAO index[2]) is a significant influencer on European climatic conditions and on Scandinavian hydropower production (Cherry *et al.*, 2005). This used to be considered unpredictable, but evidence is now emerging that interannual variability such as the NAO may be predicted from the guiding influence of the varying SST in the vicinity of the Gulf Stream extension. Such a relationship with Norwegian hydropower production is shown in Figure 4.1, where a strong correlation may be seen between production and the NAO index (stronger westerlies, more precipitation, more water into reservoirs). This may offer improved predictability that can be factored into short- and medium-term energy planning.

4.4 Eutrophication of coastal/enclosed seas

Eutrophication is a process of nutrient enrichment which can lead to harmful algal blooms, hypoxia and mortality of fish and other marine fauna; it is one of the criteria for ‘good environmental status’ in the MSFD. We described the eutrophication status of the Baltic in section 3.2 and that measures were in place under the Helsinki Convention to reduce nutrient inputs. Even though the Baltic remains the most sensitive region to eutrophication in European waters, other areas have also been affected (e.g. the Wadden Sea) and a range of policy instruments (Box 4.1) are in place to monitor trends and reduce nutrient loadings.

As in the Baltic, periodic renewal of deeper hypoxic waters is also observed in fjords along the Swedish and Norwegian coasts, with renewal taking place when the density of the coastal water at sill level outside the fjord exceeds that of the stagnant water within the basin. In the Gullmar fjord of Sweden, the renewal rate is linked to the NAO index, with long periods of positive NAO leading to fewer renewals and more hypoxic conditions that in turn affect the fjord ecosystem (Polovodova and Nordberg, 2013). Analysis of recent trends for Norwegian fjords (Darelius, 2020) suggests that the renewal frequency has probably decreased in many of the fjords since 1990. Initial studies (Gillebrand *et al.*, 2006) of Scottish sea lochs also suggested that 28 out of a total of 135 sea loch basins in Scotland may be at risk of developing hypoxic conditions, although research on trends has yet to be done.

---

[2] https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/history/method.shtml.

Box 4.1 Policy instruments relevant to eutrophication

These encompass both EU and international measures that include the following.

EC Directives. The Urban Wastewater Treatment Directive and the Nitrates Directive contain a requirement to assess eutrophication. Monitoring should identify eutrophic areas and measure nitrate loads, so that the state of surface waters, estuaries and coastal waters can be assessed every 4 years, and sensitive areas designated. These actions are supported by the Water Framework Directive which classifies the ecological status of waters, and by the relevance of eutrophication to the assessment of good environmental status in the MSFD.

International conventions. The two major conventions of the Helsinki Convention for the Baltic and the Oslo/Paris Convention for the Northeast Atlantic and North Sea include countries outside the EU and provide assessment criteria, the monitoring of selected parameters for nutrient enrichment, and quantification of nutrient inputs and their direct and indirect effects. In addition, coordinated action between the Netherlands, Germany and Denmark in the World Heritage Site of the Wadden Sea have reduced riverine nutrient loads and led to a decrease in phytoplankton biomass, contributing to an improved ecological status in the adjacent coastal zone (van Beusekom *et al.*, 2019).

In EEA's recent assessment (EEA, 2019b), some 563,000 km^2 (or 23% of the 2,400,000 km^2 of European seas that have been mapped for eutrophication) have a eutrophication problem. The situation is worst in the Baltic Sea, where 99% of the assessed areas are affected, followed by 53% of the Black Sea, 7% of the Northeast Atlantic and 12% of the Mediterranean Sea, mainly close to densely populated coasts or agricultural land. EEA's review also found that positive effects of nutrient management strategies under the policies in Box 4.1 can be seen in all EU regional seas[3].

Of particular interest for this report is whether changes in ocean circulation resulting from climate change may add an additional factor to those already considered within existing policy frameworks. In this context, the main mechanisms through which climate changes may increase eutrophication (Rabalais *et al.*, 2009) include higher water temperatures, stronger stratification, and increased inflows of freshwater and nutrients from land to coastal waters. On the other hand, stronger or more frequent storm activity would reduce the risks.

4.5 Effects on marine biodiversity and fisheries

As noted by the High-Level Panel For A Sustainable Ocean Economy (2020b), most fishing today is not economically or ecologically optimised, with too many fishing vessels, excessive waste and bycatch. As a result, catches fail to attain the maximum sustainable economic yield. By shifting to a system where this yield is achieved, catches could be increased by 40% (Costello *et al.*, 2020). Policies aimed at improving fisheries management will need to take into account how changes in the oceans may impact the ecosystems that in turn support potentially sustainable fisheries.

Changes in ocean temperatures, circulation, upwelling and associated effects on water properties affect ecosystems over wide areas in such a boundary-free environment. Direct impacts of nutrients on primary production by phytoplankton cascade up through the next trophic levels to the species that are harvested in fisheries, while shifts in currents affect dispersal of eggs and larvae. While this web of interactions is complex, there is sufficient understanding and data on which to make general observations of changes that have already occurred and estimate those that are likely to occur in the future.

Well-documented biological impacts from climate change include shifts in population range and distributions, reflecting the product of several interacting processes. The dispersal capacity of species from a regional species pool determines their ability to inhabit new sites, while the environmental conditions that are physiologically tolerable to a species define its potential niche, which may in turn be constrained because of biological interactions (Doney *et al.*, 2012). A general pattern emerging from documented changes related to climate is the shift in the distributions of marine fishes and invertebrates to higher latitudes and/or into deeper depths (see, for example, Perry *et al.*, 2005; Mueter and Litzow, 2008; Spencer, 2008; Nye *et al.*, 2009; Lucey and Nye, 2010).

Temperature is a critical factor and, at the global scale, Free *et al.* (2019) examined the impact of SST changes on the productivity of fish stocks over the past 80 years for 235 populations of 124 species in 38 eco-regions around the world. By using temperature-dependent population models, the effects of warming water were separated from overfishing and other factors; on average across the world, the maximum sustainable yield had decreased by 4.1% from 1930 to 2010. Five eco-regions experienced losses of 15 to 35% and, of particular significance to Europe, North Sea fish populations declined by 34.6% and those off the

---

[3] An EU project (https://cordis.europa.eu/project/id/226213) was set up under Framework 7 to monitor oxygen depletion and associated processes in aquatic systems that included semi-enclosed seas with permanent anoxia (Black Sea, Baltic Sea) and seasonally or locally anoxic land-locked systems (fjords, lagoons, lakes).

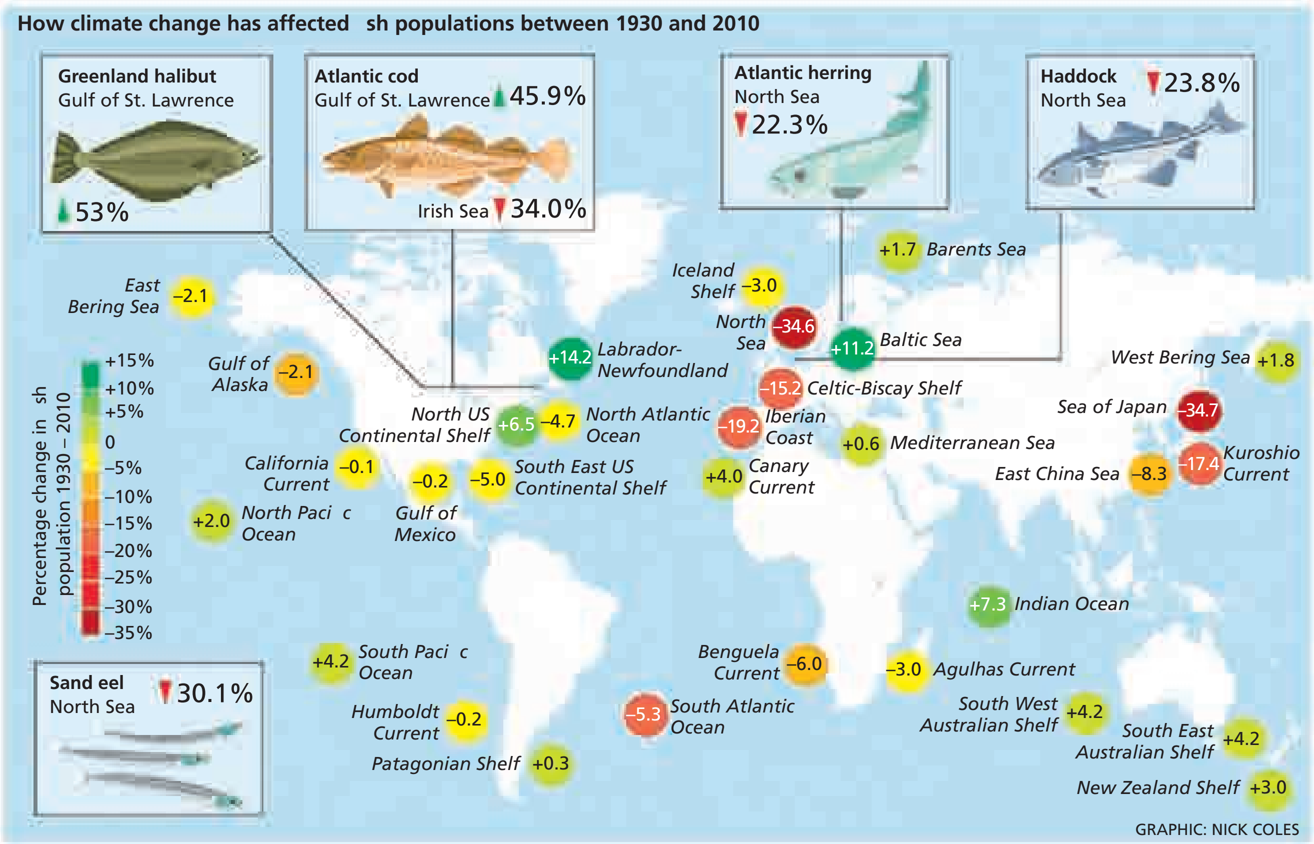


Figure 4.2 Summary of yield declines around the world from the work of Free et al. (2019). (Figure from https://inews.co.uk/news/environment/how-global-warming-is-decimating-some-fish-populations-and-helping-others-271343)

Iberian coast by 19.2%, among the highest declines globally (see Figure 4.2).

Declines in the North Sea and in the Celtic-Biscay Shelf eco-regions were attributed to warming that increased stratification, leading to shifts in primary productivity from warmer to cooler waters (Richardson and Schoeman, 2004), with cascading effects on higher tropic levels of zooplankton and forage fish (see Clausen *et al.*, 2017). Effects of the declines in food for commercially harvested fish also extend to seabirds[4]. On the other hand, in the Baltic Sea where cool waters delay and reduce spring zooplankton production, warming has had a positive effect[5].

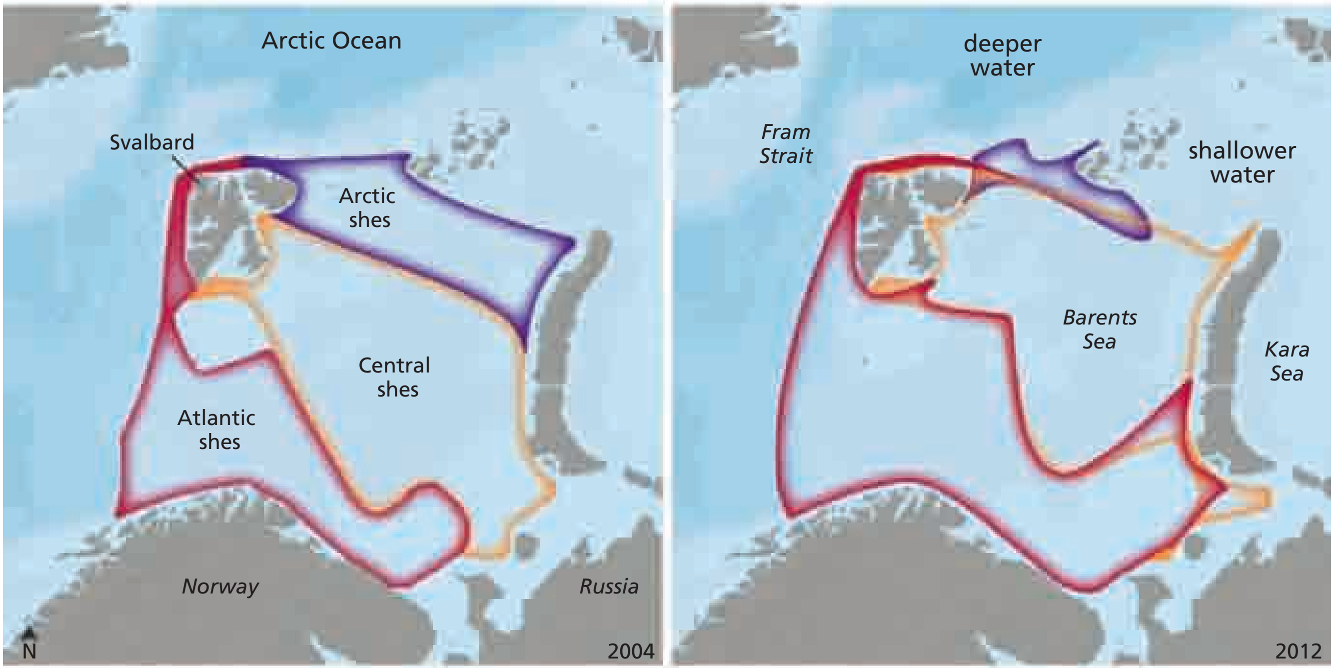
As noted by Maltby *et al.* (2020), there is a substantial literature where it is demonstrated that climate change has affected the abundance, dynamics and distribution of marine fish populations, with associated social and economic consequences (see Weatherdon *et al.*, 2016; Barange *et al.* (2018) for a synthesis of available data). Warming affects the phenology, behaviour, abundances and distributions of fish and of prey species; populations of warm water species may increase, while cooler water species shift polewards or to deeper waters. Such shifts are incorporated into a range of species distribution models available to fisheries management experts (see Robinson *et al.*, 2017). However, such models may not always take account of constraints from availability of habitat (e.g. at suitable depths for migrating demersal species (see Rutterford *et al.*, 2015)), and more detailed models may be required to estimate trends due to future warming. For example, Maltby *et al.* (2020) examined scenarios for eight fish species to estimate the changes up to 2090 under different warming scenarios, and how these increased the abundance of the warm-adapted species of red mullet, Dover sole, John Dory and lemon sole, and decreased abundance of the cold-adapted species of Atlantic cod, monkfish and megrim.

The substantial variability of the marine ecosystem in the North Atlantic region has been studied (Drinkwater *et al.*, 2014; Fossheim *et al.*, 2015). Periods with a stronger inflow of Atlantic water and/or warmer ocean temperatures cause fish stocks to migrate northwards.

---

[4] Declines include a 30% fall in North Sea sand eels, leading to the major declines in seabird populations such as kittiwakes and puffins.
[5] In addition, the Baltic Sea has brackish waters and therefore the distribution of salinity has a crucial role in separating freshwater, brackish and oceanic ecosystems and fish stocks (see Andersson *et al.*, 2015).

Arctic fishes almost pushed out of the Barents Sea between 2004 and 2012



NOAA Climate.gov

Figure 4.3 The poleward migration of fisheries. The 'Atlantification' and corresponding sea-ice retreat in the Barents Sea expands the domain of warmer water species ('Atlantic fishes'), including Atlantic cod, pushing the colder water species further polewards. Figure from NOAA climate.gov based on Fossheim et al. (2015).

This was the case during a period of warming in the 1930s when the catch of cod increased along the Greenland coast (Drinkwater *et al.*, 2014). As mentioned in section 2.7.1, the multidecadal variability of warm and cold Atlantic surface temperatures influences pelagic fisheries such as blue whiting. During recent decades, warming in the Barents Sea has led to a similar northward shift in the Barents Sea cod stock, as shown in Figure 4.3 (Fossheim *et al.*, 2015).

Predictions for the commercial Barents Sea cod stock are possible over the next 7 years (Årthun *et al.*, 2018b) on the basis of ocean temperature predictions, and on the behaviour of cod stocks and North Atlantic Ocean temperature between 1957 and 2017. On this basis, the Barents Sea cod stock is forecast to decline towards 2024 because of a less favourable marine environment as a result of a recent cooling phase of the Norwegian Sea and North Atlantic Ocean, leading to a slightly colder Barents Sea. The potential predictability of how fish stocks are affected by key Atlantic hydrographic conditions is a priority of the International Council for the Exploration of the Sea (ICES) with the establishment of its Working Group on Seasonal-to-Decadal Prediction of Marine Ecosystems.

The 2020 Blue Economy report (EC, 2020a) includes an economic assessment of the likely impact of climate change on European fish and shellfish resources and concludes that, at least up to 2050, fishing fleets such as the North Sea demersal fishery will be able to adapt to the movement of stocks, so that climate-related changes are unlikely to affect profitability. Nevertheless, changes in distribution and abundance have significant implications for the assessment of stocks, assignment of quotas and attempts to implement ecosystem-based modelling as required under the MSFD, which is discussed further in the next section.

4.6 Implementing the Marine Strategy Framework Directive, fisheries management and Marine Protected Areas

The MSFD encourages an ecosystems approach (ecosystem-based fisheries management (EBFM)) to address the cumulative impact of human activities (including fisheries but also maritime transport, coastal tourism, pollution, aquaculture, minerals exploitation and sea-based energy production). EBFM essentially reverses the order of management priorities so that management starts with the ecosystem rather than a target species, and aims to sustain healthy marine ecosystems and the fisheries they support, thus requiring an understanding of large-scale ecological change in the marine ecosystem (McQuatters-Gollop, 2012). The potential benefits of implementation of EBFM far outweigh the difficulties of making the transition from a management system based on maximising individual species (Pikitch *et al.*, 2004; Fogarty, 2013).

Box 4.2 Ecosystem-based Fisheries Management

EBFM is a management approach that addresses all environmental, ecological and anthropogenic (including fisheries) impacts on an ecosystem and takes into account the interconnectedness and interdependence of various components of an ecosystem (Curtin and Prellezo, 2010). EBFM is thus a complex interaction between the physical environment and the biological species and interactions it supports, the economic and social dimensions of the many stakeholders involved, and the economic incentives and regulatory constraints within which they operate.

Essentially the rationale is to preserve ecosystem structure and functioning so as to ensure the ongoing provision of products and services. For instance, the catch of forage species such as capelin or sand eels needs to be limited to ensure sufficient food for cod and other species further up the food chain. The impacts of human activities must focus on the entire ecological system and not its component parts. New forms of valuation and assessment are needed, and different sectors of society will view ecosystems from their own environmental, economic and societal needs (O'Hagan, 2020). An important component of EBFM is to create marine reserves with no fishing; the populations therein will recover to levels that are compatible with the abundance of their prey and predators.

Application of EBFM across regions and species varies greatly. Trochta *et al.* (2018) found a lack of consensus on the interpretation of EBFM between fisheries policy-makers and managers, stock assessment scientists, conservationists and ecologists, and drew up a checklist of the characteristics of EBFM perceived by stakeholders. This provides a comprehensive list from which the key considerations that are most relevant to fisheries management in a specific case can be selected. Several case studies on applying the EBFM approach are available (Townsend *et al.*, 2019) including the Atlantic herring management, the Alaska Bay cod harvest, and from Louisiana, Hawaii and California. In Norway, fisheries management for the Barents Sea provides another case study for the application of EBFM principles (e.g. Olsen *et al.* 2007, 2016). ICES has a working Group on Cumulative Effects Assessments Approaches in Management, which aims to develop a common framework for considering the various stresses and responses to the many human activities in the marine environment (e.g. fisheries, shipping, offshore wind, oil and gas), and how they impact the different ecosystem components (e.g. fish, marine mammals, birds or seabed habitats).

EBFM (see Box 4.2) is still under development, and its links to climate change are an important issue. Iceland, Australia, New Zealand and Norway are considered to be among those at the forefront of developing EBFM (Paul *et al.*, 2017). The EU's aim of adjusting its Common Fisheries Policy targets and regulations to achieve maximum sustainable yield based on scientific advice from ICES, combined with conservation measures on limiting discards, are helping improve the prospects for the future sustainability of its fisheries. Nevertheless, the current situation (Wakefield, 2018), where quotas established under the Common Fisheries Policy permit harvesting up to the estimated maximum sustainable economic yield and may still exceed scientific advice, is not compatible with the objectives in the MSFD to protect biodiversity and ecosystems. There is thus an urgent need to integrate a common ecosystems approach across all components of marine policy, from the MSFD, through the Common Fisheries Policy and Maritime Spatial Planning Directive, and ensuring that initiatives under the Blue Growth agenda are compatible with protecting biodiversity and marine and coastal ecosystems.

Regarding resilience, Holsman *et al.* (2020) evaluated the role of EBFM measures in ameliorating the effects of climate change on Bering Sea fisheries. They found that EBFM did reduce future declines more than non-EBFM approaches, but that benefits are species-specific and decrease markedly after 2050. Shifts in species location and size distribution mean that quotas need to be urgently revised/updated to take into account oceanographic impacts on marine ecosystems. In general, as summarised in section 4.5, fish stocks face the threat of further major declines in the future as the oceans continue to warm. Even if quotas were strict and successfully enforced, current fishery targets may become unachievable as the planet warms. For instance, Queirós *et al.* (2018) predict that the proportion of large fish in the North Sea is likely to continue to decline as SST rises—rendering the use of the Large Fish Index currently being developed to meet Ecological Quality Objectives for the North Sea unachievable. Fisheries management plans need to adjust to a warmer climate by recognising such inherent ecosystem changes, and allow social and economic consequences of the ecological impacts of warming on future fisheries catch to be modelled, contributing to adaptive and responsive management strategies (e.g. Fernandes *et al.*, 2017).

An important component of EBFM is the role of Marine Protected Areas (MPAs), which are intended to '*to protect vulnerable species and ecosystems, to conserve biodiversity and minimize extinction risk, to re-establish ecosystem integrity, to segregate uses to avoid user conflicts, and to enhance the productivity of fish and marine invertebrate populations*' (Hoyt, 2010). The EU has 10.8% of sea surface designated as MPAs, and thus achieves the Aichi Target 11 under the Convention on Biological Diversity to assign 10% of coastal and marine areas to '*effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area–based conservation measures*'.

MPAs are also vulnerable to climate change and ocean acidification, and their management will need to adapt. Queirós *et al.* (2016) identified a need for climate impact models to be used to improve the positioning of MPAs to limit impacts. The vulnerability of the marine ecosystems first needs to be mapped, and the areas co-mapped with human activities and the distribution of existing MPAs. Selection and management of MPAs needs to consider how species may redistribute to new, suitable and productive habitats, taking into account the inherent uncertainties in modelling of such complex systems (Payne *et al.*, 2015). Cashion *et al.* (2020) argue for MPAs to be dynamic and to change and evolve with the marine environment they are seeking to protect. Moreover, the effectiveness of MPAs in achieving their objectives depends very much on adequate protection and adherence to rules, posing challenges that may be difficult to solve. As noted by Humphreys and Clark (2020), enforcement cannot be successful without willing compliance, and persuading the majority to comply is a precondition for MPA effectiveness, so that visible enforcement can focus on an increasingly residual minority, marginalising and ultimately suppressing non-compliance.

As recommended in EASAC (2016), networks of MPAs need increased attention as tools within overall ecosystem-based management. This requires substantially increased commitment to understand water movements and ecological connections between ecologically important and vulnerable areas. This knowledge needs to be built into the development of networks of MPAs, which can play a strong role in securing good environmental status within the MSFD.

4.7 Implications for the Sustainable Development Goal targets

The SDGs are integrated into all European Commission proposals, policies and strategies, and all 17 SDGs feature in one or more of the six headline ambitions announced in President von der Leyen's Political Guidelines[6]. This reflects the need to rethink policies affecting all dimensions of the economy so that the value given to protecting and restoring natural ecosystems, using resources sustainably, and improving human health is properly considered (EC, 2020d). As reviewed in EASAC (2020a), transformational change is needed, as envisaged through the European Green Deal (EC, 2019a) whose growth strategy contributes directly to achieving at least 12 of the 17 SDGs. This report's focus on the potential effects of changes in ocean circulation is most relevant to SDG 14 (Life below water) but it also links with others including SDG 7 (Ensure access to affordable, reliable, sustainable and modern energy for all) and SDG 13 (Take urgent action to combat climate change and its impacts)—in line with the overarching SDG 17 (Strengthen the means of implementation and revitalize the global partnership for sustainable development).

Within the European Green Deal, the objective of a sustainable 'Blue Economy' is established to help alleviate demands on the EU's land resources and tackle climate change. For instance, new sources of protein can relieve pressure on agricultural land; mitigating climate change requires nature-based solutions that include healthy and resilient seas and oceans; while renewable energy is increasingly located offshore. Part of the challenge in realising this ambition is to resolve spatial conflicts and this is being achieved through the Maritime Spatial Planning Directive (EC, 2014), where Member States are required to develop plans (through public participation, the best available data and cooperation with bordering countries) that cover spatial and temporal distribution of existing and future activities in marine waters, take into account land–sea interactions and have an ecosystem-based approach.

The Blue Growth and Maritime Spatial Planning Directive strategies can be seen as the economic pillars of EU Maritime policy, while the MSFD represents the environmental pillar. Ensuring consistency and avoiding conflicts between the two thus represents a challenge, as recognised by both the Commission and the EEA (Box 1.1). In this context, it is helpful to be able to measure the extent to which performance within Blue Growth economic activities is consistent with the SDG for Oceans and Coast/Life below water Goal (SDG 14), which includes the specific targets and indicators shown in Table 4.2. To make such an assessment, Rickels *et al.* (2016; 2019) developed a set of 18 indicators to measure progress against SDG targets, and concluded that the EU's objective of ensuring that ocean development is sustainable '*is missed*'. The weakest performance was seen in the targets related to sustainable fishing and to ocean science (especially where setting total allowable catch does not follow scientific advice).

This emphasises the importance of properly assessing the implications for the marine ecosystem and its sustainability in promoting the Blue Growth agenda, as well as incorporating knowledge on the potential effects of the changes in ocean circulation considered in this report on the ability to meet SDG 14.

4.8 Research needs

The ocean and its circulation are the subject of many academic research projects funded by national and international agencies. The EU supports several research programmes with an ocean component such as the Joint Baltic Sea research and development programme (BONUS), the Baltic and North Sea Coordination and Support Action (BANOS), the Joint Programming Initiative Healthy and Productive Seas and Oceans (JPI Oceans), the European Multidisciplinary Seafloor and water column Observatory (EMSO-ERIC), and the

---

[6] https://ec.europa.eu/commission/sites/beta-political/files/political-guidelines-next-commission_en.pdf.

Table 4.2 Targets under SDG 14 (Life Below Water)

Target number	Examples of UN indicators
14.1 Reduce marine pollution[7]	Index of coastal eutrophication and floating plastic debris density.
14.2 Protect and restore ecosystems	Proportion of national Exclusive Economic Zones managed using ecosystem-based approaches.
14.3 Reduce ocean acidification	Average marine acidity (pH) measured at representative sampling stations.
14.4 Sustainable fishing	Proportion of fish stocks within biologically sustainable levels.
14.5 Conserve coastal and marine areas	Coverage of protected areas in relation to marine areas.
14.6 End subsidies contributing to overfishing	Instruments aiming to combat illegal, unreported and un-regulated fishing.
14.7 Increase the economic benefits from the sustainable us of marine resources	Sustainable fisheries as a percentage of GDP.
14.a Increase scientific knowledge, research and technology for ocean health	Research budget allocated to marine technology.
14.b Small scale fishing	Legal/regulatory/policy/institutional framework to recognise/protect access for small scale fisheries.
14.c Implement and enforce international law	Progress in ratifying, accepting and implementing ocean-related instruments of international law.

European Marine Observation and Data Network. The EU's Copernicus programme and its marine service (CMEMS) are also major service and research infrastructures providing satellite data on, *inter alia*, the marine environment. Horizon 2020 included the 'Blue-Cloud' programme to develop innovative services between marine research and the Blue Economy, and the successor Horizon Europe includes the mission of 'Healthy oceans, seas, coastal and inland waters'. In addition to EU-supported marine research, international coordination is available through the World Climate Research Program, ICES, Intergovernmental Oceanographic Commission (IOC), the Scientific Committee on Oceanic Research (SCOR), and multilateral programmes such as the RAPID and OSNAP arrays.

One of the key challenges in the UN Decade of Ocean Science for Sustainable Development is (Challenge 5) '*Enhance understanding of the ocean-climate nexus and generate knowledge and solutions to mitigate, adapt and build resilience to the effects of climate change across all geographies and at all scales, and to improve services including predictions for the ocean, climate and weather*'. As is evident in this report, the functioning of the oceans is based on interactions of many processes working together, so there is a need for a systems approach. Currently, much ocean circulation research is dependent on national projects of limited duration, making it difficult to develop a coordinated longer-term strategy to address changes on ocean circulation and climate in the region as a whole. This is recognised in the EU's Mission Starfish (EC, 2020e) which noted that '*relevant financing for the necessary research and innovation investment…is lagging behind. In general, the approach has been project-based and bottom-up, and not starting from a perspective that strategic and systemic investment in the natural capital is necessary to keep and to improve the public goods and services.*' A further issue is that some bathymetric and sea floor data are not readily accessible owing to their commercial or defence value, with implications for the 7th Challenge of the UN Decade of Ocean Science for Sustainable Development to '*Ensure a sustainable ocean observing system across all ocean basins that delivers accessible, timely and actionable data and information to all users*'.

As described in section 4.6, the application of ecosystem-based management presents a challenge across several EU Directives. Research priorities relevant to this were identified in EASAC's earlier study (EASAC, 2016) as including the following.

- Interactions between species, habitats and ecological processes, and the work towards a complete realisation of the concept of good environmental status under the MSFD.

---

[7] Marine pollution (target 14.1) is an important issue in itself as well as within the context of the SDGs. Pollution sources include chemical and toxic substances (including oil spills and acid deposition), plastics and nutrients, but also underwater noise and other inputs from energy. The current status of the EU's seas and pollution control measures are described in some detail in the Blue Economy report for 2020 (EC, 2020). The thermohaline circulation has been shown to transfer floating plastic debris from the North Atlantic to the Greenland and Barents seas, which would essentially be a dead end for this 'plastic conveyor belt' (Cózar *et al*., 2017), leading to the Arctic seafloor becoming a sink for plastic debris. Broader reviews of plastics pollution in the oceans can be found in EASAC (2020a).

- Quantifying marine species' interactions and how they adapt to changing conditions in marine environments, including benthic–pelagic coupling.

- Developing end-to-end integrated models that characterise socio-economic benefits from the sea, the supporting ecosystems and biodiversity, and the human and natural pressures that threaten them.

- Building scenarios that explore future responses of marine ecosystems under anthropogenic and natural forcings and that help to define the controls and limits of ecosystem resilience.

Research on these aspects continues under both national and international (e.g. ICES) programmes.

Knowledge gaps identified in this report that can inform research priorities include the following:

- Strengthening abilities to detect early warnings of potential high-impact tipping points in the ocean and understanding their dynamics (Heinze *et al.*, 2021), as mentioned in section 4.1.

- Improving the ability to assess the magnitude and timing for local SLR.

- Monitoring the regional evolution of ocean acidification and understanding the effects on local ecosystems and the resilience of commercially important species.

- Further developing the links between oceanic changes and European weather and climate fluctuations to improve predictability (section 2.5). In this context, the mechanisms of air–sea interaction, whereby anomalies in the ocean translate into anomalies in atmospheric circulation, remain poorly understood.

A final word

This report provides the scientific basis to support the future development of EU policies in many different fields affected by climate and ocean resources. We hope it may assist the European Commission (e.g. in the Directorates-General of MARE, ENER, ENV and GROW) and the European Parliament. Increased understanding of the science underlying the changes underway can contribute to better policies and foresight, adaptation to and mitigation of the changes anticipated.

Annex 1 Members of the Expert Group

The Royal Academies for Science and the Arts of Belgium
Jean-Marie Beckers, Université de Liège

The Royal Danish Academy of Sciences and Letters
Bogi Hansen, Havstovan - Faroe Marine Research Institute

The Council of Finnish Academies
Petteri Uotila, University of Helsinki

The Académie des sciences (France)
Jean-Claude Duplessy, Laboratoire des Sciences du Climat et de l'Environnement
Julie Deshayes, French National Centre for Scientific Research | CNRS Laboratoire de physique des océans (LPO)

The German National Academy of Sciences Leopoldina
Martin Visbeck, Kiel University, Helmholtz Centre for Ocean Research Kiel

The Royal Irish Academy
Frederic Dias, University College Dublin
Gerard McCarthy, Maynooth University

The Royal Netherlands Academy of Arts and Sciences
Erik van Sebille, Utrecht University

The Norwegian Academy of Sciences and Letters
Tor Eldevik, University of Bergen and Bjerknes Centre for Climate Research (Chair of the Expert Group)
Lars H. Smedsrud, University of Bergen and Bjerknes Centre for Climate Research
Beatriz Balino, University of Bergen and Bjerknes Centre for Climate Research
Helene Asbjørnsen, University of Bergen and Bjerknes Centre for Climate Research

The Academy of Sciences of Lisbon
Henrique Cabral, University of Lisbon

The Spanish Royal Academy of Sciences
Marta Estrada Miyare, Institute of Marine Sciences (CSIC)

The Royal Swedish Academy of Sciences
Leif G. Anderson, University of Gothenburg

The Royal Society (United Kingdom)
Tim Palmer, University of Oxford

Chair of the Environment Programme
Lars Walløe

Director of the Environment Programme
Michael Norton

Abbreviations

AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
AMV	Atlantic Multidecadal Variability
AO	Arctic Oscillation
CMEMS	Copernicus Marine Environment Monitoring Service
CO_2	Carbon dioxide
EBFM	Ecosystem-based fisheries management
EC	European Commission
EEA	European Environment Agency
EMODnet	European Marine Observation and Data Network
GVA	Gross Value Added
ICES	International Council for the Exploration of the Seas
ICOS	International Carbon Observation System
IPCC	Intergovernmental Panel on Climate Change
JPIOceans	Joint Programming Initiative Healthy and Productive Seas and Oceans
MBI	Major Baltic Inflows
MPA	Marine Protected Areas
MSFD	Marine Strategy Framework Directive
NAO	North Atlantic Oscillation
OSNAP	Overturning in the Subpolar North Atlantic Program
RAPID–MOCHA	Rapid Climate Change-Meridional Overturning Circulation and Heatflux Array
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
SLR	Sea level rise
SPG	Subpolar gyre
SST	Sea surface temperature

References

Alheit J. *et al.* (2014). Reprint of 'Atlantic Multidecadal Oscillation (AMO) modulates dynamics of small pelagic fishes and ecosystem regime shifts in the eastern North and Central Atlantic'. *Journal of Marine Systems* **133**, 88–102.

Alkhayuon H *et al.* (2019). Basin bifurcations, oscillatory instability and rate-induced thresholds for Atlantic meridional overturning circulation in a global oceanic box model. *Proceedings of the Royal Society A* **475**, 20190051.

AMAP (2018). Arctic Ocean Acidification, Arctic Monitoring and Assessment Programme, Tromsø, Norway.

Anderson L. and Dyrssen D. (1981). Excess calcium and alkalinity in the Baltic and southern Kattegatt. *Oceanologica Acta* **4** (1), 3–6.

Andersson A. *et al.* (2015). Projected future climate change and Baltic Sea ecosystem management. *Ambio* **4** (3), 345–356.

Årthun M. and Eldevik T. (2016). On anomalous ocean heat transport toward the Arctic and associated climate predictability. *Journal of Climate* **29** (2), 689–704.

Årthun M. *et al.* (2012). Quantifying the influence of Atlantic heat on Barents Sea ice variability and retreat. *Journal of Climate* **25**, 4736–4743.

Årthun M. *et al.* (2017). Skilful prediction of northern climate provided by the ocean. *Nature Communications* **8**, 15875.

Årthun M. *et al.* (2018a). Time scales and sources of European temperature variability. *Geophysical Research Letters* **4** (8), 3597–3604.

Årthun M. *et al.* (2018b) Climate based multi-year predictions of the Barents Sea cod stock. *PLoS ONE* **1** (10), e0206319.

Årthun M., Eldevik T. and Smedsrud L.H. (2019). The role of Atlantic heat transport in future Arctic winter sea ice loss. *Journal of Climate* **32**, 3327–3341.

BACC II Author Team (editors) (2015). *Second Assessment of Climate Change for the Baltic Sea Basin*. Springer. XXXVIII + 501 pp. https://doi.org/10.1007/978-3-319-16006-1.

Bach L.T. *et al.* (2017). Simulated ocean acidification reveals winners and losers in coastal phytoplankton. *PLoS ONE* **12**, e0188198–22.

Bakker P. *et al.* (2016). Fate of the Atlantic Meridional Overturning Circulation: strong decline under continued warming and Greenland melting. *Geophysical Research Letters* **43**, 12,252–12,260.

Bamber J.L. *et al.* (2019). Ice sheet contributions to future SLR from a structured expert judgment. *Proceedings of the National Academy of Sciences of the United States of America* **116** (23), 11195–11200.

Barange M. *et al.* (editors). (2018). Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. Rome: FAO. 628 pp.

Barnston A.G. and Livezey R.E. (1987). Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Monthly Weather Review* **115** (6), 1083–1126.

Barrier N. *et al.* (2014). Response of North Atlantic Ocean Circulation to Atmospheric Weather Regimes. *Journal of Physical Oceanography* **4** (1), 179–201.

Barton B.I., Lenn Y.-D. and Lique C. (2018). Observed Atlantification of the Barents Sea causes the polar front to limit the expansion of winter sea ice. *Journal of Physical Oceanography* **48** (8), 1849–1866.

Becker M. *et al.* (2021). The northern European shelf as increasing net sink for CO_2. *Biogeosciences* **18**, 1127–1147.

Bednaršek N. *et al.* (2014). *Limacina helicina* shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. *Proceedings of the Royal Society B* **281**, 20140123.

Bigg J.R. *et al.* (2003). The role of the oceans in climate. *International Journal of Climatology* **23** (10), 1127–1159.

BIM (2018). *The Business of Seafood*. Ireland: Bord Iascaigh Mhara.

BIM (2019). *The Business of Seafood*. Ireland: Bord Iascaigh Mhara.

Bisoi S. and Haldar S. (2016). Impact of climate change on dynamic behavior of offshore wind turbine. *Marine Georesources and Geotechnology* **3** (7), 905–920.

Bode A. *et al.* (2011). Decadal variability in chlorophyll and primary production off NW Spain. *Climate Research* **48**, 293–305.

Bode A. *et al.* (2019). Changes in phytoplankton production and upwelling intensity off A Coruña (NW Spain) for the last 28 years. *Ocean Dynamics* **69**, 861–873.

Bonaduce A. *et al.* (2020). Sea-state contributions to sea-level variability in the European Seas. *Ocean Dynamics* **70**, 1547–1569.

Borges A.V. and Frankignoulle M. (2002). Distribution of surface carbon dioxide and air-sea exchange in the upwelling system off the Galician coast. *Global Biogeochemical Cycles* **1** (2), 1020.

Bradley R.S. and England J.H. (2008). The Younger Dryas and the Sea of Ancient Ice. *Quaternary Research* **70**, 1–10.

Brands S. (2013). Skillful Seasonal Predictions of Boreal Winter Accumulated Heating Degree-Days and Relevance for the Weather Derivative Market. *Journal of Applied Meteorology and Climatology* **52** (6),1297–1302.

Brierley A.S. and Kingsford M.G. (2009). Impacts of climate change on marine organisms and ecosystems. *Current Biology* **19**, R602–R614.

Bryden H. *et al.* (2005). Slowing of the Atlantic meridional overturning circulation at 25° N. *Nature* **438**, 655–657.

Bryden H.L. and Kinder T.H. (1991). Steady two-layer exchange through the Strait of Gibraltar. *Deep Sea Research A* **38**, S445–S463.

Buchan J. *et al.* (2014). North Atlantic SST anomalies and the cold north European weather events of winter 2009/10 and December 2010. *Monthly Weather Review* **14** (2), 922–932.

Bulgin C.E., Merchant C.J. and Ferreira D. (2020). Tendencies, variability and persistence of sea surface temperature anomalies. *Scientific Reports* **10**, 7986.

Caesar L. *et al.* (2018). Observed fingerprint of a weakening Atlantic Ocean Overturning Circulation. *Nature* **556**, 191–196.

Caesar L. *et al.* (2021). Current Atlantic Meridional Overturning Circulation weakest in last millennium. *Nature Geoscience* **14**, 118–120.

Carstensen J. *et al.* (2014). Deoxygenation of the Baltic sea during the last century. *Proceedings of the National Academy of Sciences of the United States of America* **111**, 5628–5633.

Cashion T. *et al.* (2020). Shifting seas, shifting boundaries: Dynamic marine protected area designs for a changing climate. *PLoS ONE* **1** (11), e0241771.

Chafik L., Nilsen J.E.Ø. and Dangendorf S. (2017). Impact of North Atlantic teleconnection patterns on Northern European sea level. *Journal of Marine Science and Engineering* **5** (3), 43.

Chen X. and Tung K. (2018). Global surface warming enhanced by weak Atlantic Overturning Circulation. *Nature* **559**, 387–391.

Cheng L. *et al.* (2020). Record-setting ocean warmth continued in 2019. *Advances in Atmospheric Science* **37**, 137–142.

Cherry J. *et al.* (2005). Impacts of the North Atlantic Oscillation on Scandinavian hydropower production and energy markets. *Water Resources Management* **19**, 673–691.

Church J.A. and White N.J. (2011). Sea level rise from the late 19th to the early 21st century. *Surveys in Geophysics* **3** (4–5), 585–602.

Clausen L.W. *et al.* (2017). Shifts in North Sea forage fish productivity and potential fisheries yield. *Journal of Applied Ecology* **51**, 45.

Cobb A. and Czaja A. (2019). Mesoscale signature of the North Atlantic Oscillation and its interaction with the ocean. *Geophysical Research Letters* **4** (10), 5575–5581.

Comeau S., Alliouane S. and Gattuso J.-P. (2012). Effects of ocean acidification on overwintering juvenile Arctic pteropods *Limacina helicina*. *Marine Ecology Progress Series* **456**, 279–284.

Condron A. and Winsor P. (2012). Meltwater routing and the Younger Dryas. *Proceedings of the National Academy of Sciences of the United States of America* **109** (49), 19928–19933.

Conley D.J. *et al.* (2009). Hypoxia-related processes in the Baltic Sea. *Environmental Science and Technology* **43**, 3412–3420.

Cooper J.A.G. *et al.* (2020). Sandy beaches can survive SLR. *Nature Climate Change* **10**, 993–995.

Costello C. *et al.* (2020). The Future of Food from the Sea. *Nature* **588**, 95–100.

Coumou D. *et al.* (2018). The influence of Arctic amplification on mid-latitude summer circulation. *Nature Communications* **9**, 2959.

Cózar A. *et al.* (2017). The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the Thermohaline Circulation. *Scientific Advances* **3**: e1600582.

Cranmer A. and Baker E. (2020). The global climate value of offshore wind energy. *Environmental Research Letters* **15**, 054003.

Crawfurd K.J. *et al.* (2017). Alterations in microbial community composition with increasing fCO_2: a mesocosm study in the eastern Baltic Sea. *Biogeosciences* **14**, 3831–3849.

Curtin R. and Prellezo R. (2010). Understanding marine ecosystem based management: a literature review. *Marine Policy* **34** (5), 821–830.

Dangendorf S. *et al.* (2017). Reassessment of 20th century global mean sea level rise. *Proceedings of the National Academy of Sciences of the United States of America* **114**, 5946–5951.

Darelius E. (2020). On the effect of climate trends in coastal density on deep water renewal frequency in sill fjords—a statistical approach. *Estuarine, Coastal and Shelf Science* **243**, 106904.

Davini P., Hardenberg J.V. and Corti S. (2015). Tropical origin for the impacts of the Atlantic multidecadal variability on the Euro-Atlantic climate. *Environmental Research Letters* **1** (9), 094010.

DeConto R.M. *et al.* (2021). The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* **593**, 83–89.

de Jong M.F. and de Steur L. (2016). Strong winter cooling over the Irminger Sea in winter 2014-2015, exceptional deep convection, and the emergence of anomalously low SST. *Geophysical Research Letters* **4** (13), 7106–7113.

Deshayes J., Frankignoul C. and Drange H. (2007). Formation and export of deep water in the Labrador and Irminger seas in a GCM. *Deep Sea Research I* **54**, 510–532.

Dickson R.R. and Brown J. (1994). The production of North Atlantic deep water: sources, rates, and pathways. *Journal of Geophysical Research: Oceans* **9** (C6), 12319–12341.

Doney S. *et al.* (2012). Climate change impacts on marine ecosystems. *Annual Review of Marine Science* **4**, 11–37.

Drange H. *et al.* (2005). The Nordic seas: an overview. *Geophysical Monograph Series* **158**, 199–220. doi:10.1029/158GM02.

Drijfhout S., van Oldenborgh G. and Cimatorobus A. (2012). Is a decline of AMOC causing the warming hole above the North Atlantic in observed and modeled warming patterns? *Journal of Climate* **25** (24), 8373–8379.

Drinkwater K.F. *et al.* (2014). The Atlantic Multidecadal Oscillation: its manifestations and impacts with special emphasis on the Atlantic region north of 60 degrees. *Journal of Marine Systems* **133**, 117–130.

Duchez A. *et al.* (2016). Drivers of exceptionally cold North Atlantic Ocean temperatures and their link to the 2015 European heat wave. *Environmental Research Letters* **1** (7), 074004.

Durack P. *et al.* (2012). Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science* **336** (6080), 455–458.

EASAC (2013). *Extreme Weather Events in Europe*. Halle, Germany: EASAC.

EASAC (2016). *Marine Sustainability in An Age of Changing Oceans*. Halle, Germany: EASAC.

EASAC (2018). *Extreme Weather Events in Europe: An Update*. Halle, Germany: EASAC.

EASAC (2020a). *Towards A Sustainable Future: Transformative Change and Post-COVID-19 Priorities*. Halle, Germany: EASAC.

EASAC (2020b). *Packaging Plastics in The Circular Economy*. Halle, Germany: EASAC.

EC (2008). Marine Strategic Framework Directive. 2008/56/EC.

EC (2014). Maritime Spatial Planning Directive. 2014/89/EU.

EC (2019a). Blue Economy Report 2019.

EC (2019b). The European Green Deal.

EC (2020a). Blue Economy Report 2020.

EC (2020b). REPORT on the implementation of the Marine Strategy Framework Directive (Directive 2008/56/EC). EC COM (2020) 259.

EC (2020c). European Biodiversity Strategy for 2030.

EC (2020d). Delivering on the UN's Sustainable Development Goals – A comprehensive approach. SWD (2020) 400 final.

EC (2020e). Mission Starfish 2030: restore our oceans and waters. Report of the Mission Board Healthy Oceans, Seas, Coastal and Inland Waters.

Edwards T.L. *et al.* (2021). Projected land ice contributions to twenty-first-century sea level rise. *Nature* **593**, 74–82.

EEA (2015). State of Europe's seas. EEA Report 02/2015.

EEA (2019). Adaptation challenges and opportunities for the European energy system. EEA Report 01/2019.

EEA (2019b). Nutrient enrichment and eutrophication in Europe's seas-moving towards a healthy marine environment EEA Report 14/2019.

EEA (2020). Indicator Assessment. Global and European sea level rise. Available at: https://www.eea.europa.eu/data-and-maps/indicators/sea-level-rise-7/assessment.

Eldevik T. and Haugan P.M. (2020). That's a lot of water. *Nature Physics* **1** (4), 496.

Eldevik T. and Nilsen J.E.Ø. (2013). The Arctic–Atlantic thermohaline circulation. *Journal of Climate* **26**, 8698–8705.

Feely R.A. *et al.* (2008). Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science* **320** (5882), 1490–1492.

Feely R.A. *et al.* (2018). The combined effects of acidification and hypoxia on pH and aragonite saturation in the coastal waters of the Californian Current Ecosystem and the northern Gulf of Mexico. *Continental Shelf Research* **152**, 50–60.

Feistel S. *et al.* (2016). Hypoxic and anoxic regions in the Baltic Sea, 1969 - 2015. *Meereswissenschaftlichte Berichte Warnemünde* No. 100, doi:10.12754/msr-2016-0100.

Fernandes J.A. *et al.* (2017). Estimating the ecological, economic and social impacts of ocean acidification and warming on UK fisheries. *Fish and Fisheries* **18**, 389–411.

Fogarty M. (2013). The art of ecosystem-based fishery management. *Canadian Journal of Fisheries and Aquatic Sciences* **71** (3), https://doi.org/10.1139/cjfas-2013-0203.

Fogelqvist E. *et al.* (2003). Greenland-Scotland overflow studied by hydro-chemical multivariate analysis. *Deep Sea Research I* **50** (1), 73–102.

Fossheim M. *et al.* (2015). Recent warming leads to a rapid Borealization of fish communities in the Arctic. *Nature Climate Change* **5**, 673–677.

Frajka-Williams E., Bamber J.L. and Våge K. (2016). Greenland melt and the Atlantic Meridional Overturning circulation. *Oceanography* **2** (4), 22–33.

Frederikse T. *et al.* (2020). The causes of sea level rise since 1900. *Nature* **584**, 393–397.

Free C. M. *et al.* (2019). Impacts of historical warming on marine fisheries production. *Science* **363** (6430), 979–983.

Fu Y. *et al.* (2020). A stable Atlantic Meridional Overturning Circulation in a changing North Atlantic Ocean since the 1990s. *Science Advances* **6** (48), eabc7836.

Gallagher S. *et al.* (2016). Wave climate projections for Ireland for the end of the 21st century including analysis of EC-Earth winds over the North Atlantic Ocean. *International Journal of Climatology* **36**, 4592–4607.

Gillebrand P.A. *et al.* (2006). Identifying the Risk of Deoxygenation in Scottish Sea Lochs with Isolated Deep Water. A report to The Scottish Aquaculture Research Forum.

Gomis D. *et al.* (2016). Regional marine climate scenarios in the NE Atlantic sector close to the Spanish shores. In J.L. Pelegrí and D. Vaqué (editors), *Planet Ocean*, Scientia Marina, 80S1, pp. 215–234.

González-Pola C. *et al.* (editors) (2019). ICES Report on Ocean Climate 2018. ICES Cooperative Research Report No. 349. 122 pp.

Grinsted A. and Christensen J.H. (2021). The transient sensitivity of sea level rise. *Ocean Science* **17**, 181–186.

Gulev S.K. *et al.* (2013). North Atlantic Ocean control on surface heat flux on multidecadal timescales. *Nature* **49** (7459), 464–467.

Haarsma R.J., Selten F.M. and Drijjfhout S.S. (2015). Decelerating Atlantic Meridional Overturning circulation main cause of future west European summer atmospheric circulation changes. *Environmental Research Letters* **10**, 094007.

Hagens M. *et al.* (2014), Biogeochemical context impacts seawater pH changes resulting from atmospheric sulfur and nitrogen deposition. *Geophysical Research Letters* **41**, 935–941.

Häkkinen S. and Rhines P.B. (2004). Decline of subpolar North Atlantic circulation during the 1990s. *Science* **304** (5670), 555–559.

Hall J.W. *et al.* (2019). Adaptation thresholds and pathways for tidal flood risk management in London. *Climate Risk Management* **24**, 42–58.

Han W. *et al.* (2017). Decadal variability of the Indian and Pacific Walker cells since the 1960s: do they covary on decadal timescale? *Journal of Climate* **30**, 8447–8468.

Hansen B. *et al.* (2008). The inflow of Atlantic water, heat and salt across the Greenland-Scotland ridge. In *Arctic–Subarctic Ocean Fluxes: Defining the Role of the Northern Seas in Climate* (editors Dickson B., Meincke J. and Rhines P.), pp. 15–44. Springer.

Hansen B. *et al.* (2016). A stable Faroe Bank Channel overflow 1995–2015. *Ocean Science* **12**, 1205–1220.

Hansen J. *et al.* (2016). Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling and modern observations that 2 °C global warming could be dangerous. *Atmospheric Chemistry and Physics* **16**, 3761–3812.

Hátún H. *et al.* (2005). Influence of the Atlantic subpolar gyre on the thermohaline circulation. *Science* **309** (5742), 1841–1844.

Hátún H. *et al.* (2009a). Large bio-geographical shifts in the north-eastern Atlantic Ocean: from the subpolar gyre, via plankton, to blue whiting and pilot whales. *Progress in Oceanography* **80** (3–4), 149–162.

Hátún H., Payne M.R. and Jacobsen J.A. (2009b). The North Atlantic subpolar gyre regulates the spawning distribution of blue whiting (*Micromesistius poutassou*). *Canadian Journal of Fisheries and Aquatic Sciences* **66** (5), 759–770.

Havenhand J. *et al.* (2019). Ecological and functional consequences of coastal ocean acidification: perspectives from the Baltic-Skagerrak System. *Ambio* **48**, 831–854.

Hdidouan D. and Staffell I. (2016). The impact of climate change on the levelised costs of wind energy. *Renewable Energy* **101**, 575–592.

Heinze C. *et al.* (2021). The quiet crossing of ocean tipping points. *Proceedings of the National Academy of Sciences of the United States of America* **118** (9), e2008478118.

Helland-Hansen B. and Nansen F. (1909). The Norwegian Sea. *Fiskeridirektoratet Skrifter Serie Havundersøkelser* **1** (2), 1–360.

High-Level Panel For A Sustainable Ocean Economy (2020a). Transformations for a sustainable ocean economy. Available at: https://www.oceanpanel.org/ocean-action/files/transformations-sustainable-ocean-economy-eng.pdf.

High-Level Panel For A Sustainable Ocean Economy (2020b). Ocean solutions that benefit people, nature and the economy. Available at: https://www.oceanpanel.org/ocean-action/files/executive-summary-ocean-solutions-report-eng.pdf.

Holliday N.P. *et al.* (2020). Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic. *Nature Communications* **1** (1), 585.

Holsman K.K. *et al.* (2020). Ecosystem-based fisheries management forestalls climate-driven collapse. *Nature Communications* **11**, 4579.

Hong B. *et al.* (2017). Advances in NANI and NAPI accounting for the Baltic drainage basin: spatial and temporal trends and relationships to watershed TN and TP fluxes. *Biogeochemistry* **133**, 245–261.

Hordoir R. *et al.* (2015). Influence of sea level rise on the dynamics of salt inflows in the Baltic Sea. *Journal of Geophysical Research: Oceans* **120** (10), 6653–6668.

Hoyt E. (2010). Marine protected areas. In *Encyclopedia of Marine Mammals*, 2nd edition (editors Perrin W.F., Würsig B and Thewissen J.G.M.). pp. 696–704. Academic Press.

Hugonnet R. *et al.* (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature* **592**, 726–731.

Humphreys J. and Clark R.W.E. (2020). *Marine Protected Areas; Science, Policy and Management*. Elsevier.

Hurrell J.W. and van Loon H. (1997). Decadal variations in climate associated with the North Atlantic Oscillation. *Climatic Change* **36**, 69–94.

Hurrell J.W. (1995). Decadal trends in the North Atlantic Oscillation. *Science* **269**, 676–679.

IPCC (2013). *Climate change 2013: the physical science basis. Contribution of Working Group I to The Fifth Assessment Report of The Intergovernmental Panel on Climate Change*. Cambridge University Press.

IPCC (2014). *Impacts, adaptation, and vulnerability. Contribution of Working Group II to The Fifth Assessment Report of The Intergovernmental Panel on Climate Change*. Cambridge University Press.

IPCC (2019). Special report on the ocean and cryosphere in a changing climate. Summary for Policymakers.

Jackson L. C. *et al.* (2015). Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate Dynamics* **4** (11), 3299–3316.

Jaiser J.R. *et al.* (2012). Impact of sea ice cover changes on the Northern Hemisphere atmospheric winter circulation. *Tellus A* **64**, 11595.

JBA (2020). The impact of climate change on offshore wind operations. Available at: https://www.jbaconsulting.com/knowledge-hub/impact-of-climate-change-on-offshore-wind-operations/.

Jiang Z.-P. *et al.* (2013), Key controls on the seasonal and interannual variations of the carbonate system and air-sea CO_2 flux in the Northeast Atlantic (Bay of Biscay). *Journal of Geophysical Research: Oceans* **118** (2), 785–800.

Jochumsen K. *et al.* (2017). Revised transport estimates of the Denmark strait overflow. *Journal of Geophysical Research: Oceans* **12** (4), 3434–3450.

Johansson M.M. *et al.* (2014). Global sea level rise scenarios adapted to the Finnish Coast. *Journal of Marine Systems* **129**, 39–46.

Johnson H.L. *et al.* (2019). Recent contributions of theory to our understanding of the Atlantic Meridional Overturning Circulation. *Journal of Geophysical Research: Oceans* **12** (8), 5376–5399.

Jónsson S. and Valdimarsson H. (2012). Water mass transport variability to the north Icelandic shelf, 1994–2010. *ICES Journal of Marine Science* **6** (5), 809–815.

Josey S.A. *et al.* (2018). The recent Atlantic Cold Anomaly: causes, consequences, and related phenomena. *Annual Review of Marine Science* **1** (1), 475–501.

Joyce T.M. *et al.* (2019). Meridional Gulf Stream shifts can influence wintertime variability in the North Atlantic storm track and Greenland blocking. *Geophysical Research Letters* **4** (3), 1702–1708.

Keil P. *et al.* (2020). Multiple drivers of the North Atlantic warming hole. *Nature Climate Change* **10**, 667–671.

Kersting D.K. (2016). Cambio climático en el medio marino español: impactos, vulnerabilidad y adaptación. Oficina Española de Cambio Climático, Ministerio de Agricultura, Alimentación y Medio Ambiente. Madrid. 166 pp.

Kitidis V. *et al.* (2019). Winter weather controls net influx of atmospheric CO_2 on the north-west European shelf. *Scientific Reports* **9**, 20153.

Kniebusch M. *et al.* (2019). Temperature variability of the Baltic Sea since 1850 and attribution to atmospheric forcing variables. *Journal of Geophysical Research: Oceans* **124** (6), 4168–4187.

Knight J.R., Folland C.K. and Scaife A.A. (2006). Climate impacts of the Atlantic Multidecadal Oscillation. *Geophysical Research Letters* **33** (L17706), doi:10.1029/2006GL026242.

Kopp R.E. *et al.* (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* **2** (8), 383–406.

Kuliński K. and Pempkowiak J. (2011). The carbon budget of the Baltic Sea. *Biogeosciences* **8**, 3219–3230.

Kulp S.A. and Strauss B.H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications* **1** (1), 4844.

Lambert E., Eldevik T. and Haugan P.M. (2016). How northern freshwater input can stabilize thermohaline circulation. *Tellus A* **68**, 31051.

Laurian A. *et al.* (2010). Response of the Western European climate to a collapse of the thermohaline circulation. *Climate Dynamics* **3** (5), 689–697.

Lavin A. *et al.* (2006). The Bay of Biscay: the encountering of the ocean and the shelf. In *The Sea* (editors Robinson A.R. and Brink K.H.), pp. 933–1001. Harvard University Press.

Lehmann A. *et al.* (2017). Pathways of deep cyclones associated with large volume changes (LVCs) and Major Baltic Inflows (MBIs). *Journal of Marine Systems* **167**, 11–18.

Lehmann A., Getzlaff K. and Harlaß J. (2011). Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. *Climate Research* **4** (2), 185–196.

Leppäranta, M. and Myrberg K. (2009). *Physical Oceanography of the Baltic Sea*. Springer.

Limburg K.E. and Cassini M. (2018). Effect of marine hypoxia on Baltic Sea cod Gadus morhua: evidence from otolith chemical proxies. *Frontiers in Marine Science* **5**, 482.

Liu W. *et al.* (2017). Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Science Advances* **3** (1), e16011666.

Liu W. *et al.* (2020). Overturning circulation in a warming climate. *Science Advances* **6** (26), eaaz4876.

Llope M. *et al.* (2006). Hydrography of the southern Bay of Biscay shelf-break region: Integrating the multiscale physical variability over the period 1993-2003. *Journal of Geophysical Research: Oceans* **111**, C09021.

Lowe A. *et al.* (2009). *UK climate projections science report: marine and coastal projections*. UK: Met Office Hadley Centre. Available at: http://ukclimateprojections.defra.gov.uk.

Lozier M.S. *et al.* (2019). A sea change in our view of overturning in the subpolar North Atlantic. *Science* **36** (6426), 516–521.

Lucey S.M. and Nye J.A. (2010). Shifting species assemblages in the Northeast US Continental Shelf Large Marine Ecosystem. *Marine Ecology Progress Series* **415**, 23–33.

Maltby K.M. *et al.* (2020). Projected impacts of warming seas on commercially fished species at a biogeographic boundary of the European continental shelf. *Journal of Applied Ecology* **57** (11), 2222–2233.

Mann M. *et al.* (2014). On forced temperature changes, internal variability, and the AMO. *Geophysical Research Letters* **41** (9), 3211–3219.

Mann M.E. *et al.* (2021). Multidecadal climate oscillations during the past millennium driven by volcanic forcing. *Science* **37** (6533), 1014–1019.

Marsh R. *et al.* (2017). Large-scale forcing of the European Slope Current and associated inflows to the North Sea. *Ocean Science* **1** (2), 315–335.

Mauritzen C. (1996). Production of dense overflow waters feeding the North Atlantic across the Greenland-Scotland ridge. Part 2: an inverse model. *Deep Sea Research I* **4** (6), 807–835.

McCarthy G.D. *et al.* (2015). Ocean impact on decadal Atlantic climate variability revealed by sea-level observations. *Nature* **52** (7553), 508–510.

McEvoy S. *et al.* (2021). How are European countries planning for sea level rise? *Ocean and Coastal Management* **203**, 10552.

McQuatters-Gollop A. (2012). Challenges for implementing the Marine Strategy Framework Directive in a climate of macroecological change. *Philosophical Transactions of the Royal Society A* **370**, 5636–5655.

Mechoso, C.R. (editor) (2020). *Interacting Climates of Ocean Basins*. Cambridge University Press.

Meinen C.S., Baringer M.O. and Garcia R.F. (2010). Florida Current transport variability: An analysis of annual and longer-period signals. *Deep Sea Research I* **5** (7), 835–846.

Mengel M. *et al.* (2018). Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. *Nature Communications* **9** (1), 601.

Miesner A.K. and Payne M.R. (2018). Oceanographic variability shapes the spawning distribution of blue whiting (*Micromesistius poutassou*). *Fisheries Oceanography* **2** (6), 623–638.

Mitrovica J.X., Gomez N. and Clark P.U. (2009). The sea-level fingerprint of West Antarctic collapse. *Science* **323**, 753.

Moat B.I. *et al.* (2019). Insights into decadal North Atlantic sea surface temperature and ocean heat content variability from an eddy-permitting coupled climate model. *Journal of Climate* **3** (18), 6137–6161.

Moat B.I. *et al.* (2020). Pending recovery in the strength of the meridional overturning circulation at 26°N. *Ocean Science* **16**, 863–874.

Mohrholz V. (2018). Major Baltic inflow statistics. *Frontiers in Marine Science* **5**, 384.

Mollica N.R. *et al.* (2018). Ocean acidification affects coral growth by reducing skeletal density. *Proceedings of the National Academy of Sciences of the United States of America* **115** (8), 1754–1759.

Mueter F.J. and Litzow M.A. (2008). Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecological Applications* **18**, 309–320.

Nicholls R.J. *et al.* (2021). A global analysis of subsidence, relative sea-level rise and coastal flood exposure. *Nature Climate Change* **11**, 338–342.

Norton M.G. *et al.* (2019). Serious mismatches continue between science and policy in forest bioenergy. *GCB-Bioenergy* **11** (11), 1256–1263.

Nye J.A. *et al.* (2009). Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Marine Ecology Progress Series* **393**, 111–129.

O'Hagan A.M. (2020). Ecosystem-based management (EBM) and ecosystem services in EU law, policy and governance. In *Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity* (editors O'Higgins T., Lago M. and DeWitt T.). Springer. https://doi.org/10.1007/978-3-030-45843-0_18.

O'Reilly C.H., Woollings T. and Zanna L. (2017). The dynamical influence of the Atlantic multidecadal oscillation on continental climate. *Journal of Climate* **3** (18), 7213–7230.

Olafsson J. *et al.* (2009). Rate of Iceland Sea acidification from time series measurements. *Biogeosciences* **6**, 2661–2668.

Olsen E. *et al.* (2007). The Norwegian ecosystem-based management plan for the Barents Sea. *ICES Journal of Marine Science* **6** (4), 599–602.

Olsen E. *et al.* (2016). How integrated ocean governance in the Barents Sea was created by a drive for increased oil production. *Marine Policy* **71**, 293–300.

Omstedt A. *et al.* (2012). Future changes in the Baltic Sea acid–base (pH) and oxygen balances. *Tellus B* **64**, 19586.

Onarheim I.H. *et al.* (2015). Skillful prediction of Barents Sea ice cover. *Geophysical Research Letters* **42**, 5364–5371.

Ortega P. *et al.* (2015). Reconciling two alternative mechanisms behind bi-decadal variability in the North Atlantic. *Progress in Oceanography* **137**, 237–249.

Østerhus S. *et al.* (2019). Arctic Mediterranean exchanges: a consistent volume budget and trends in transports from two decades of observations. *Ocean Science* **15**, 379–399.

Ostle C. *et al.* (2016). Carbon dioxide and ocean acidification observations in UK waters: Synthesis report with a focus on 2010 - 2015.

Paul M. *et al.* (2017). A comparative review of fisheries management experiences in the European Union and in other countries worldwide: Iceland, Australia, and New Zealand. *Fish and Fisheries* **17** (3), 803–824.

Payne M.R. *et al.* (2015). Uncertainties in projecting climate change impacts in marine ecosystems. *ICES Journal of Marine Science* **73**, 1272–1282.

Pérez F. *et al.* (2010). Plankton response to weakening of the Iberian coastal upwelling. *Global Change Biology* **16**,1258–1267.

Pérez F.F., Rios A.F. and Roson G. (1999). Sea surface carbon dioxide off the Iberian Peninsula (North Eastern Atlantic Ocean). *Journal of Marine Systems* **19**, 27–46.

Perry A.L. *et al.* (2005). Climate change and distribution shifts in marine fishes. *Science* **308**, 1912–1915.

Piecuch C.G. (2020). Likely weakening of the Florida Current during the past century revealed by sea-level observations. *Nature Communications* **11**, 3973.

Pikitch E. *et al.* (2004). Ecosystem-based fishery management. *Science* **305**, 346–347.

Polovodova A.I. and Nordberg K. (2013). Foraminiferal fauna from a deep basin in Gullmar fjord: the influence of seasonal hypoxia and North Atlantic Oscillation. *Journal of Sea Research* **79**, 40–49.

Polunin N.V.C. (2008). *Aquatic Ecosystems: Trends and Global Prospects*. Cambridge University Press.

Polyakov I.V. *et al.* (2017). Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. *Science* **356**, 285–291.

Potts T. *et al.* (2014). Do Marine Protected Areas deliver flows of ecosystem services to support human welfare? *Marine Policy* **44**, 139–148.

Queirós A.M. *et al.* (2016). Solutions for ecosystem-level protection of ocean systems under climate change. *Global Change Biology* **22** (12), 3927–3936.

Queirós A.M. *et al.* (2018). Climate change alters fish community size-structure, requiring adaptive policy targets. *Fish and Fisheries* **19** (4), 613–621.

Rabalais N.N. *et al.* (2009). Global change and eutrophication of coastal waters. *ICES Journal of Marine Science* **66**, 1528–1537.

Rahmstorf S. *et al.* (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change* **5**, 475–480.

Rhein M. *et al.* (2013). Observations: Ocean. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Richardson A.J. and Schoeman D.S. (2004). Climate impact on plankton ecosystems in the Northeast Atlantic. *Science* **305**, 1609–1612.

Rickels W. *et al.* (2016). Indicators for monitoring sustainable development goals: an application to oceanic development in the European Union. *Earth's Future* **4** (5), 252–267.

Rickels W. *et al.* (2019). Does the European Union achieve comprehensive blue growth? Progress of EU coastal states in the Baltic and North Sea, and the Atlantic Ocean against sustainable development goal 14. *Marine Policy* **106**, 103515.

Riebesell U. *et al.* (2017). Competitive fitness of a predominant pelagic calcifier impaired by ocean acidification. *Nature Geoscience* **10**, 19–23.

Ritchie P. *et al.* (2020). Shifts in national land use and foof produciton in Great Britain after a climate tipping point. *Nature Food* **1**, 76–83.

Robins P.E. *et al.* (2016). Impact of climate change on UK estuaries: a review of past trends and potential projections. *Estuarine, Coastal and Shelf Science* **169**, 119–135.

Robinson N.M. *et al.* (2017). A systematic review of marine-based species distribution models (SDMs) with recommendations for best practice. *Frontiers in Marine Science* **4**, 421.

Robson J., Ortega P. and Sutton R. (2016). A reversal of climatic trends in the North Atlantic since 2005. *Nature Geoscience* **9**, 513–517.

Rossby T. *et al.* (2014). On the long-term stability of Gulf Stream transport based on 20 years of direct measurements. *Geophysical Research Letters* **41** (1), 114–120.

Rossby T., Chafik L. and Houpert L. (2020). What can hydrography tell us about the strength of the Nordic Seas MOC over the last 70 to 100 years? *Geophysical Research Letters* **47**, e2020GL087456.

Rudels B. *et al.* (2012). Observations in the ocean. In Lemke, P. (editor), *Arctic Climate Change: The ACSYS Decade and Beyond*, pp. 117–198. Springer.

Rutgersson A. *et al.* (2014). Observed changes and variability of atmospheric parameters in the Baltic Sea region during the last 200 years. *Climate Research* **6** (2), 177–190.

Rutterford L. *et al.* (2015). Future fish distributions constrained by depth in warming seas. *Nature Climate Change* **5**, 569–573.

Sarafanov A. *et al.* (2012). Mean full-depth summer circulation and transports at the northern periphery of the Atlantic Ocean in the 2000s. *Journal of Geophysical Research: Oceans* **11** (C1), doi:10.1029/2011jc007572.

Scaife A.A. *et al.* (2014). Skillful long-range prediction of European and North American winters, *Geophysical Research Letters* **41** (7), 2514–2519.

Schenk F. *et al.* (2018). Warm summers during the Younger Dryas cold reversal. *Nature Communications* **9**, 1634.

Schimanke S., Dieterich C. and Meier H.E.M. (2014). An algorithm based on sea level pressure fluctuations to identify major Baltic inflow events. *Tellus A* **16**, 5864.

Screen J.A. (2017a). Far-flung effects of Arctic warming. *Nature Geoscience* **1** (4), 253–254.

Screen J.A. (2017b). The missing Northern Europe cooling response to Arctic ice loss. *Nature Communications* **8**, 14603.

Seager R. *et al.* (2002). Is the Gulf Stream responsible for Europe's mild winters? *Quarterly Journal of the Royal Meteorological Society* **128** (586), 2563–2586.

Sgubin G. *et al.* (2017). Abrupt cooling over the North Atlantic in modern climate models. *Nature Communications* **8**, 1–12.

Siegert M. *et al.* (2020). Twenty-first century sea-level rise could exceed IPCC projections for strong-warming futures. *One Earth* **3**, 691–703.

Simpson J.H. and Sharples J. (2012). *Introduction to the Physical and Biological Oceanography of Shelf Seas*. Cambridge University Press.

Slangen A.B. *et al.* (2016). Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change* **6**, 701–705.

Slangen A.B. *et al.* (2017). A review of recent updates of sea-level projections at global and regional scales. *Surveys in Geophysics* **3** (1), 385–406.

Slater T. *et al.* (2021). Earth's ice imbalance. *The Cryosphere* **15**, 233–246.

Smeed D.A. *et al.* (2014). Observed decline of the Atlantic Meridional Overturning Circulation 2004–2012. *Ocean Science* **1** (1), 29–38.

Smeed D.A. *et al.* (2018). The North Atlantic Ocean is in a state of reduced overturning. *Geophysical Research Letters* **4** (3), 1527–1533.

Smith D.M. *et al.* (2020). North Atlantic climate far more predictable than models imply. *Nature* **58** (7818), 796–800.

Solbrekke I.M., Kvamstø N.G. and Sorteberg A. (2020). Mitigation of offshore wind power intermittency by interconnection of production sites. *Wind Energy Science* **5**, 1663–1678.

Spencer P. (2008). Density-independent and density-dependent factors affecting temporal changes in spatial distributions of eastern Bering Sea flatfish. *Fisheries Oceanography* **17**, 396–410.

Spinoni J., Vogt J. and Barbosa P. (2015). European degree-day climatologies and trends for the period 1951–2011. *International Journal of Climatology* **35**, 25–36.

Stigebrandt A. (1981). A model for the thickness and salinity of the upper layer in the Arctic Ocean and the relationship between the ice thickness and some external parameters. *Journal of Physical Oceanography* **11**, 1407–1422.

Stigebrandt A. (1983). A model for the exchange of water and salt between the Baltic and the Skagerrak. *Journal of Physical Oceanography* **13**, 411–427.

Sutton R.T. and Allen M.R. (1997). Decadal predictability of North Atlantic sea surface temperature and climate. *Nature* **388**, 563–567.

Sutton R.T., Norton W.A. and Jewson S.P. (2000). The North Atlantic Oscillation—what role for the ocean? *Atmospheric Science Letters* **1**, 89–100.

Talandier C. *et al.* (2014). Improvements of simulated Western North Atlantic current system and impacts on the AMOC. *Ocean Modelling* **76**, 1–19.

Talley L.D. (2008). Freshwater transport estimates and the global overturning circulation: shallow, deep and throughflow components. *Progress in Oceanography* **78**, 257–303.

Tenore K.R. *et al.* (1995). Fisheries and oceanography off Galicia, NW Spain: mesoscale spatial and temporal changes in physical processes and resultant patterns of biological productivity. *Journal of Geophysical Research* **100**, 10943–10966.

Thomas T. *et al.* (2005). The carbon budget of the North Sea. *Biogeosciences* **2**, 87–96.

Timmermans M.L. and Marshall J. (2020). Understanding Arctic Ocean circulation: a review of ocean dynamics in a changing climate. *Journal of Geophysical Research: Oceans* **125**, e2018JC014378.

Townsend H. *et al.* (2019). Progress on implementing ecosystem-based fisheries management in the United States through the use of ecosystem models and analysis. *Frontiers in Marine Science* **6**, 641.

Trenberth K.E. and Fasullo J.T. (2017). Atlantic meridional heat transports computed from balancing Earth's energy locally. *Geophysical. Research Letters* **44**,1919–1927.

Trochta J.T. *et al.* (2018). Ecosystem-based fisheries management: perception on definitions, implementations, and aspirations. *PLoS ONE* **13** (1), e0190467.

UK Foresight (2017). Current and future impacts of sea level rise in the UK. UK Government Office for Science. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/663885/Future_of_the_sea_-_sea_level_rise.pdf

Uotila P., Vihma T. and Haapala J. (2015). Atmospheric and oceanic conditions and the extremely low Bothnian Bay sea ice extent in 2014/2015. *Geophysical Research Letters* **4** (18), 7740–7749.

van Beusekom J.E.E. and Diel-Christiansen S. (2009). Global change and the biogeochemistry of the North Sea: the possible role of phytoplankton and phytoplankton grazing. *International Journal of Earth Sciences* **98**, 269–280.

van Beusekom J.E.E. *et al.* (2019). Wadden Sea eutrophication: long-term trends and regional differences. *Frontiers in Marine Science* **6**, 370.

Vautard R. (1990). Multiple weather regimes over the North Atlantic: analysis of precursors and successors. *Monthly Weather Review* **118** (10), 2056–2081.

VGB (2018). Facts of hydropower in the EU. Available at: https://www.vgb.org/hydropower_fact_sheets_2018–dfid-91827.html.

Vousdoukas M.I *et al.* (2020). Sandy coastlines under threat of erosion. *Nature Climate Change* **10**, 260–263.

Vousdoukas M.I. *et al.* (2017). Extreme sea levels on the rise along Europe's coasts. *Earth's Future* **5** (3), 304–323.

Wakefield J. (2018). The ecosystem approach and the Common Fisheries Policy. In *The Ecosystem Approach in Ocean Planning and Governance: Perspectives from Europe and Beyon* (editors Langlet D. and Rayfuse R.), pp. 287–316. Leiden, The Netherlands: Brill. Available at: https://doi.org/10.1163/9789004389984_011.

Wallace J.M. and Gutzler D.S. (1981). Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Monthly Weather Review* **109**, 784–812.

Wang J. *et al.* (2017). Internal and external forcing of multidecadal Atlantic variability over the past 1,200 years. *Nature Geoscience* **10**, 512–517.

Wang X.L., Feng Y. and Swail V.R. (2015). Climate change signal and uncertainty in CMIP5-based projections of global ocean surface wave heights. *Journal of Geophysical Research: Oceans* **120**, 3859–3871.

Weatherdon L.V. *et al.* (2016). Observed and projected impacts of climate change on marine fisheries, aquaculture, coastal tourism, and human health: an update. *Frontiers in Marine Science* **3**, 48.

Weisse R. *et al.* (2021). Sea level dynamics and coastal erosion in the Baltic Sea region. [Preprint] *Earth System Dynamics Discussions*. Available at: https://doi.org/10.5194/esd-2021-6.

White M. and Bowyer P. (1997). The shelf-edge current north-west of Ireland. *Annales Geophysicae* **1** (8), 1076–1083.

WindEurope (2019). Our energy, our future. How offshore wind will help Europe go carbon-neutral. Available at: https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf

WindEurope (2020). Offshore wind in Europe. Key trends and statistics 2019. Available at: https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2019.pdf

Wittmann A.C. and Pörtner H.-O. (2013). Sensitivities of extant animal taxa to ocean acidification. *Nature Climate Change* **3**, 995–1001.

Woollings T. *et al.* (2012). Response of the North Atlantic storm track to climate change shaped by ocean–atmosphere coupling. *Nature Geoscience* **5**, 313–317.

Woollings T., Hannachi A. and Hoskins B. (2010). Variability of the North Atlantic eddy-driven jet stream. *Quarterly Journal of the Royal Meteorological Society* **13** (649), 856–868.

Worthington E.L. *et al.* (2021). A 30-year reconstruction of the Atlantic meridional overturning circulation shows no decline. *Ocean Science* **17**, 285–299.

Xu W. *et al.* (2015). Seasonality and interannual variability of the European Slope Current from 20 years of altimeter data compared with in situ measurements. *Remote Sensing of Environment* **162**, 196–207.

Yan Y, Uotila P., Huang K. and Gu W. (2020). Variability of sea ice in the Bohai Sea from 1958 to 2015. *Environment* **709**, 136164.

Yashayaev I. and Loder J.W. (2016). Recurrent replenishment of Labrador Sea water and associated decadal-scale variability. *Journal of Geophysical Research: Oceans* **12** (11), 8095–8114.

Yeager S.G. and Robson J.I. (2017). Recent progress in understanding and predicting Atlantic decadal climate variability. *Current Climate Change Reports* **3**, 112–127.

Yeager S.G., Karspeck A.R. and Danabasoglu G. (2015). Predicted slowdown in the rate of Atlantic sea ice loss. *Geophysical Research Letters* **4** (24), 10704–10713.

Young I.R. and Ribal A. (2019). Multiplatform evaluation of global trends in wind speed and wave height. *Science* **364** (6440), 548–552.

Zeebe R.E., Ridgwell A. and Zachos J.C. (2016). Anthropogenic carbon release rate unprecedented during the past 66 million years. *Nature Geoscience* **9**, 325–329.

EASAC, the European Academies' Science Advisory Council, consists of representatives of the following European national academies and academic bodies who have issued this report:

The Austrian Academy of Sciences
The Royal Academies for Science and the Arts of Belgium
The Bulgarian Academy of Sciences
The Croatian Academy of Sciences and Arts
The Cyprus Academy of Sciences, Letters and Arts
The Czech Academy of Sciences
The Royal Danish Academy of Sciences and Letters
The Estonian Academy of Sciences
The Council of Finnish Academies
The Académie des sciences (France)
The German National Academy of Sciences Leopoldina
The Academy of Athens
The Hungarian Academy of Sciences
The Royal Irish Academy
The Accademia Nazionale dei Lincei (Italy)
The Latvian Academy of Sciences
The Lithuanian Academy of Sciences
The Royal Netherlands Academy of Arts and Sciences
The Norwegian Academy of Science and Letters
The Polish Academy of Sciences
The Academy of Sciences of Lisbon
The Romanian Academy
The Slovak Academy of Sciences
The Slovenian Academy of Sciences and Arts
The Spanish Royal Academy of Sciences
The Swiss Academies of Arts and Sciences
The Royal Swedish Academy of Sciences
The Royal Society (United Kingdom)

Academia Europaea
ALLEA

For further information:

EASAC Secretariat
Deutsche Akademie der Naturforscher Leopoldina
German National Academy of Sciences
Postfach 110543
06019 Halle (Saale)
Germany

tel +49 (0)345 4723 9833
fax +49 (0)345 4723 9839
secretariat@easac.eu

EASAC Brussels Office
Royal Academies for Science and the
Arts of Belgium (RASAB)
Hertogsstraat 1 Rue Ducale
1000 Brussels
Belgium

tel +32 (2) 550 23 32
brusselsoffice@easac.eu

The affiliated network for Europe of

iap SCIENCE HEALTH POLICY
the interacademy partnership

EASAC contributes to the implementation of the

SUSTAINABLE DEVELOPMENT GOALS

Printed by Schaefer Druck und Verlag GmbH, Teutschenthal, Germany