Climate Change in the Baltic Sea
2021 Fact Sheet
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Connections between parameters

Projections under a medium climate scenario

Baltic Sea Expert Network on Climate Change – EN CLIME

The Baltic: A sea of change

Baltic Sea Expert Network on Climate Change – EN CLIME

Climate future of the Baltic Sea

Projections under a medium climate scenario

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In memory of Christian Dieterich
Climate change effects on the Baltic Sea environment are manifold. It is for example expected that water temperature and sea level will rise, and sea ice cover will decrease. This will affect ecosystems and biota; for example, range shifts are expected for a number of marine species, benthic productivity will decrease, and breeding success of ringed seals will be reduced. The impacts will hence affect the overall ecosystem function and also extend to human uses of the sea; trawling will follow the fish towards southern areas, aquaculture will likely face a shift towards species diversification, and the value of most ecosystem services is expected to change — to name a few.

This Climate Change Fact Sheet provides the latest scientific knowledge on how climate change is currently affecting the Baltic Sea and how it is expected to develop in the foreseeable future. It is aimed at guiding policy makers to take climate change into account, but also to the general public. Updated Baltic Sea Climate Change Fact Sheets are expected to be published approximately every seven years.
The Baltic: A sea of change

Introduction

Climate change impacts are evident in the Baltic Sea: water temperature is rising, ice extent is decreasing, and annual mean precipitation is increasing over the northern part of the region. All these changes affect the nature of the sea, its ecosystems, and ecosystem services, as well as the human activities depending on the sea. For example, many wintering birds have shifted their wintering range northwards; the numbers of warm water fish species (such as sticklebacks) are increasing; the risk of infection of human-pathogenic Vibrio spp. has increased through surface water warming, and trawl fishing now begins earlier in the year.

The Baltic Sea is facing a complex system of effects and feedbacks between climatic and non-climatic factors. Multiple environmental pressures affect the ecosystem, and climate change adds further cumulative pressures to the existing anthropogenic ones. These various climate change effects are not straightforward to understand and are difficult to distinguish from certain human pressures. Climate and other human-induced pressures vary significantly between different regions in the Baltic Sea, making it impossible to find simple management solutions that can work everywhere. In order to mitigate these negative effects, policymakers need to be aware of these differences and utilise an adaptive management approach based on the best available science.

This Fact Sheet provides the latest scientific knowledge on how climate change is affecting the Baltic Sea in a concise format. It is the first of a series of successive Baltic Sea Climate Change Fact Sheets aiming to track advances in the understanding of how climate change impacts the state of marine systems, drawing on the best available science for the region.

How climate change already has and is expected to impact the Baltic Sea is described through 34 parameters that have been identified by EN CLIME as being of relevance for science and management. These parameters constitute physicochemical parameters that are directly affected by climate change, referred to as direct parameters (page 18), as well as ecosystem and human use parameters that are indirectly affected, referred to as indirect parameters (page 36). The full list of parameters is shown in Table 1 (page 8).

The first part of this report provides summary information of climate change impacts on each parameter (pages 12-17), as well as an impact map showing the projected regional changes for a selected suite of parameters under the RCP4.5 climate scenario across the Baltic Sea.

The second part of the report (pages 18-59) gives a more detailed, yet concise, overview of climate change impacts on each parameter – described as key messages.

Baltic Sea Expert Network on Climate Change – EN CLIME

In 2018, the Baltic Sea Environment Protection Commission (HELCOM) and Baltic Earth formed a joint Expert Network on Climate Change in the Baltic Sea region (EN CLIME). This Expert Network involves more than 110 scientists from around the Baltic Sea. The purpose of the network is to function as a coordinating framework and a platform to harness the expertise of leading scientists on both direct and indirect effects of climate change on the Baltic Sea environment and ecosystems and make this expertise available to and open up for closer dialogue with policy makers.

Impact map

The impact map (pages 10-11) depicts projected regional changes for some of the most relevant parameters in a particular subbasin of the Baltic Sea under the RCP4.5 scenario. While there is also important information on the other parameters, there was a need to reduce the total 34 parameters to the presented parameters to make the map more legible. The presented parameters have 1) direct societal relevance/experience and/or relevance for other parameters, 2) medium to high confidence of the changes relative to the noise and model/expert judgement uncertainty under the RCP4.5 scenario, and 3) a hotspot sub-region in the Baltic with medium to high confidence of patterns of the regional changes.

Confidence assessment

The level of confidence of statements is shown with confidence assessments using the scale low-medium-high (Figure 1). The authors were asked to consider both the level of consensus and the amount of evidence when defining an overall confidence of a statement and to select the overall confidence by using the precautionary principle (e.g., in case the level of consensus is low and the amount of evidence medium, the overall confidence is low).

Figure 1. The overall confidence is resulting from the confidence assessment of the agreement/consensus on and evidence of the assessed data.
Parameters covered
The 34 parameters have been categorized into six different categories: Energy cycle, Water cycle, Carbon and Nutrient cycles, Sea level and wind, Biota and ecosystems, Human activities, and Services. The following parameters were considered as important to include, but due to the lack of lead authors, they were not included in this version of the fact sheet:
- Pelagic habitats (incl. phytoplankton and zooplankton community structure, spring blooms, functional traits etc.)
- Harmful algal blooms (HABs)
- Pollution and hazardous substances
- Ecotoxicology
- Human health
- Pathogens

Table 1. Full list of EN CLIME parameters. The asterisk (*) indicates those parameters that include information on extreme events.

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameters</th>
</tr>
</thead>
</table>
| Energy cycle | Air temperature*  
Water temperature*  
Large-scale atmospheric circulation  
Sea ice*  
Solar radiation  
Salinity and subarctic influence*  
Precipitation*  
River run-off*  
Carbon and nutrient cycles  
Sea level*  
Water level and wind  
Waves*  
Sediment transportation*  |
| Water cycle | Oxygen  
Microbial community and processes  
Waterbirds  
Marine mammals  
Non-indigenous species  
Marine protected areas (MPAs)  
Nutrient concentrations and eutrophication  
Ecosystem function  
Offshore wind farms  
Coastal protection  
Shipping  
Tourism  
Aquaculture  |}

Peer review of key messages
The key messages have been peer reviewed and improved in a two-step process. The first review round was carried out by six external scientists and the second round was carried out by the Co-chairs and HELCOM Secretariat.

Climate change & climate mitigation
The global climate is changing, and this is due to human influence in the form of greenhouse gas emissions (GHG) from fossil fuel use and land use change. The current changes in the climate systems have already had widespread impacts on human and natural systems.

According to the Intergovernmental Panel on Climate Change (IPCC), human activities are estimated to have caused approximately 1.1°C of global warming above pre-industrial levels and global warming will continue during the coming decades. The pace and magnitude of warming will depend on how global greenhouse gas emissions evolve.

In order to reduce the impacts of rising temperature on Earth, all global policy actions aiming at the mitigation of greenhouse gas emissions are highly relevant. With the help of climate models and various emission scenarios, projections of global and regional climates have been performed to support policymaking such as the Paris Agreement.

Different Representative Concentration Pathways (RCPs) are used to describe different climate futures depending on the greenhouse gas emissions in the coming years. The RCPs indicate a possible range of radiative forcing (difference between solar energy absorbed by the Earth and radiated back to space) in the year 2100. The RCPs include a “mitigation” scenario which aims to keep global warming below 2°C above pre-industrial temperatures (RCP2.6) and high emissions “worst case” scenario (RCP8.5), that corresponds to a future without climate mitigation. One intermediate scenario is the RCP4.5 which is used in the impact map of this Fact Sheet and likely results in global mean temperature rise between 2-3°C by 2100. When the IPCC Assessments: have been referred to in this Climate Change Fact Sheet, the information is based on the IPCC Assessment Report 5 (2013); the Special Report on the Ocean and Cryosphere in Changing Climate (2019) and earlier publications, as the most recent Assessment Report 6 had not yet been published by the time this Fact Sheet was produced. Information about regional climate change is based upon the BACC Reports (BALTEX and Baltic Earth Assessments of Climate Change for the Baltic Sea Basin, BACC Author Team, 2008; BACC II Author Team, 2015; see www.baltic-earth).

Connections between parameters
Links between the different parameters have been shown in Figure 2, depicting complex interconnections between the different abiotic, biotic and ecosystem, and human dimension parameters. The colour of each arrow comes from the parameter it originates from.
Climate future of the Baltic Sea

Projections under the RCP4.5 climate scenario

The impact map depicts projected regional changes for some of the most relevant parameters in a particular subbasin of the Baltic Sea under the RCP4.5 scenario. While there is also important information on the other parameters, there was a need to reduce the total 34 parameters to the presented parameters to make the map more legible. The presented parameters have 1) direct societal relevance/experience and/or relevance for other parameters, 2) medium to high confidence of the changes relative to the noise and model/expert judgement uncertainty under the RCP4.5 scenario, and 3) a hotspot sub-region in the Baltic with medium to high confidence of patterns of the regional changes.

Bothnian Sea
- Sea surface temperature would rise everywhere in the Baltic and in all seasons. Most pronounced would be summer warming in the Bothnian Bay and Bothnian Sea. Winter precipitation including high-intensity extremes would increase. Increased freshwater discharge would bring more dissolved organic carbon to the sea, affecting benthic habitats by decreasing pelagic primary production and phytoplankton sedimentation. In the Bothnian Sea, Gulf of Finland and Gulf of Riga, the decline in sea ice cover would be largest. Waves would be higher and shipping might increase if the ice cover is reduced. Food accessibility for migratory water birds would improve causing a northward shift of breeding and wintering areas towards ice-free coastal areas. In the Archipelago Sea, ringed seal populations might decrease.

Baltic Proper
- Sea surface temperature would rise. If BSAP measures on nutrient loads were to be implemented, phosphorus concentrations and algal blooms would decrease and oxygen conditions of the deep water would improve. Without load reductions, only minor changes in nutrient concentrations are expected. The combined effects of warming and planned nutrient reductions will eventually lead to less carbon reaching the seafloor, reducing benthic animal biomass. In shallow archipelago waters, the fates of benthic animal and plant populations depend on local variations in biogeochemistry and primary productivity. In the southern Baltic, mean sea level would rise relative to the land, and higher storm surges would occur. Sediment transports would change.

Gulf of Riga
- Sea surface temperature would rise and sea ice cover would decline, affecting ringed seal populations in the northern Gulf of Riga. Likewise, breeding and wintering areas of migratory water birds would be affected. Wave heights would increase and the potential for shipping would increase if the ice cover is reduced, but shipping intensity is more dependent on market development than climate change. In the eastern Gulf of Finland, mean sea level would rise relative to the land, and higher storm surges would occur.

Gulf of Finland
- Sea surface temperature would rise and sea ice cover, ice thickness and the length of the ice season would decrease, affecting ringed seal breeding and probably causing a decline of the populations in the eastern Gulf of Finland. Likewise breeding and wintering areas of migratory water birds would be affected. Wave heights would increase and the potential for shipping would increase if the ice cover is reduced, but shipping intensity is more dependent on market development than climate change. In the eastern Gulf of Finland, mean sea level would rise relative to the land, and higher storm surges would occur.

Assessment sub-basins
1. Bothnian Bay (Bothnian Bay and the Quark)
2. Bothnian Sea (Bothnian Sea and Åland Sea)
3. Gulf of Finland
4. Gulf of Riga
5. Baltic Proper (Northern Baltic Proper; Eastern Gotland Basin, Eastern Gotland Basin, Bornholm basin and Gdansk Basin)
6. Entrance area (Kalmar, Great Belt, the Sound, Kat Bay, Bay of Mecklenburg and Arkona Basin)

Introduction
Direct parameters

Physiochemical parameters directly affected by climate change

Air temperature
The marginal seas around the globe have become warmer during the past 40 years. The sea surface temperature of the Baltic Sea has warmed more than the average for the global ocean and will continue to warm.

Sea ice
Sea ice forms every winter, the most important factor being air temperature, but also wind, snow cover and ocean currents. Over the past 100 years, the winters have become milder, the ice season shorter and the maximum ice extent decreased. This development is expected to continue in a changing climate.

Large scale atmospheric circulation
The climate of the Baltic Sea region is strongly influenced by the large-scale atmospheric circulation, in particular the North Atlantic Oscillation, atmospheric blocking patterns, and Atlantic Multidecadal Oscillation are dominant patterns. As the response of these atmospheric circulation patterns to climate change differs among models, future projections are very uncertain.

Solar radiation
Solar radiation is the engine of the climate system. The solar radiation reaching the surface strongly depends on cloudiness, and also on aerosols. There is an indication of decline in cloudiness during the past decades. For the future, there is very limited knowledge.

Salinity and saltwater inflows
Salinity affects the dynamics of ocean currents and ecosystem functioning. Salinity decreases gradually from Kattegat to the Bothnian Bay. Inflows from the North Sea sporadically renew the deep water with saline, oxygen rich water. No statistically significant trends in salinity have been found, and uncertainties of future projections are high.

Stratification
Seawater is layered (stratified) according to its density, a property governed by temperature and salinity. Over the last 40 years, stratification in the Baltic Sea has become stronger. This trend may continue in the future and cause harm to the marine ecosystem by decreasing the mixing between surface waters and deep waters.

River run-off
Runoff describes the amount of water vapor in the air, the temperature and the land-sea contrast. Annual mean precipitation has significantly increased over the northern Baltic Sea lately while in the south, changes are small – a trend that may continue in the future.

Carbonate chemistry
The carbonate system regulates seawater pH. The amount of CO₂ in the Baltic Sea water changes seasonally mostly due to biologically driven processes (photosynthesis and respiration), which induces seawater pH oscillations. In the long term, atmospheric CO₂ increase will raise seawater CO₂ concentration and cause pH decrease.

Riverine nutrient loads and atmospheric deposition
External nutrient inputs from land and atmosphere are the major long term drivers of the Baltic Sea eutrophication. Substantial reductions in nutrient loads have occurred since the 1980s, however, no large-scale effects on ecosystem status can be detected yet. In the future, land-based nutrient management will have greater effect on loads than greenhouse gases emissions.

Sea level
Baltic Sea mean level responds to global sea level rise and regional land uplift and varies with season and climate. Baltic sea level is rising and will continue to rise. Storm surges are sensitive to changes in atmospheric circulation and future changes are uncertain.

Wind
The wind climate and storms over the Baltic Sea are determined by the large-scale atmospheric circulation. Storms are typically more frequent and stronger during winter. The large natural variability over the Baltic Sea masks possible past and future trends.

Waves
The wave climate in the Baltic Sea strongly depends on the wind field and shows large long term variability. Significant trends in the wave height have not been detected. For northern and eastern parts of the Baltic a slight increase is significant and extreme wave height is projected.

Sediment transportation
Near shore sediment transport is triggered by waves and wind and leads to erosion and accumulation of sediments. Sandy beaches along the southern and eastern coaslines of the Baltic Sea are especially vulnerable and rising sea level will increase sediment transport.

Categories
- Energy cycle
- Water cycle
- Carbon and nutrient cycle
- Sea level and wind
- Biota and ecosystem
- Human activities
- Services
Indirect parameters: Ecosystem

Ecosystem parameters indirectly affected by climate change

- **Oxygen**
  - Oxygen concentration is controlled by physical transport and remineralization of organic matter. Bottom water oxygen deficiency observed in a vast area of the Baltic Sea is a consequence of water column stratification and eutrophication. Thus, future oxygen availability will depend on nutrient loads, while projected warming may reinforce eutrophication.

- **Microbial community and processes**
  - Bacterially-mediated processes as well as the occurrence of pathogenic Vibrios are expected to increase with current environmental changes. However, only small changes in bacterial biomass and growth were detected during the past decades. The potential genetic adaptation to climate change and lack of proper models including ecosystems and microbioplankton make predictions for the future uncertain.

- **Benthic habitats**
  - In the Baltic Sea, many benthic species exist at the edge of their distribution, and even small fluctuations in temperature and salinity can impact their abundance, biomass, and spatial distribution. In concurrence with trophic cascades and eutrophication, climate change might lead to major changes in biodiversity and ecosystem functions of benthic habitats.

- **Coastal and migratory fish**
  - Coastal and migratory fish respond to changes in temperature, ice-cover, salinity and river-discharge. Spring and summer spawning species (e.g. perch, cyprinids, pike) will benefit from increasing temperatures, whereas autumn spawning (e.g. salmonids) may be disfavoured. Future actions must consider eutrophication, fishing, food web interactions and habitat exploitation, for migratory fish also in rivers.

- **Pelagic and demersal fish**
  - Fish of marine origin mainly respond to changes in temperature, salinity, water stratification and circulation influencing oxygen conditions. Actions to reduce eutrophication, anoxic conditions, and fishing, while considering food web interactions will be important.

- **Waterbirds**
  - Most obvious effects of climate change on Baltic waterbirds are range shifts in winter (migratory birds stay closer to breeding areas). Food supply (fish, bivalves) and breeding conditions are influenced in various ways.

- **Marine mammals**
  - Grey and particularly ringed seal breeding success will be reduced by decreased sea ice quality and quantity. Harbour and grey seal southern Baltic distribution will be reduced by flooding of haul-outs. Changed temperature, stratification, prey distribution, quality and quantity will affect marine mammals, but aggregate effects are unpredictable.

- **Non-indigenous species**
  - While shipping is the main driver of new non-indigenous species (NIS) introductions, climate change related changes in abiotic environment may support their establishment and range expansion. Increasing water temperature may favour species of warm water origin, and potential salinity decrease will benefit NIS of freshwater origin, impacting likely estuarine ecosystems.

- **Marine protected areas**
  - Climate change may impact Marine protected areas (MPAs) via changes in abiotic environment causing diverse changes in ecosystem structure and functions, thus altering MPAs’ conservation values. Changes are expected first in seal and water bird populations, followed by potential large-scale changes in benthic habitats if possible salinity decrease starts affecting the distribution of key species.

- **Nutrient concentrations and eutrophication**
  - Nitrogen and phosphorus pools are controlled by loads from land and atmosphere and influenced by oxygen-sensitive biogeochemical processes. Future load changes will have a stronger influence on nutrients than climate change, even though projected warming will increase nutrient cycling and reduce bottom water oxygenation.

- **Ecosystem function**
  - Baltic Sea ecosystems provide an array of functions related to nutrient- and carbon circulation, biomass production and regulation. Climate impacts ecosystem functions via temperature, water circulation, salinity, river discharges, and solar radiation. In the future, increased productivity, stronger impact of nutrients and reduced influence of predators will influence Baltic Sea ecosystem functioning.
Indirect parameters: Human use

Human use parameters indirectly affected by climate change

**Offshore wind farms**
Wind farms are the most significant offshore structures in the Baltic Sea. Declining ice cover and rising sea level can affect offshore wind farms. Offshore wind farms affect many oceanographic processes and have a substantial effect on the structural and functional biodiversity of the benthic system. They account for 10% of European offshore wind energy and are crucial for reaching new energy and climate targets.

**Coastal protection**
The shorelines of the Baltic Sea vary from bedrock-dominated stable coasts in the north to soft, sandy shores in the south, where periods of storminess cause coastal erosion. Declining ice cover and rising sea level increase the potential for coastal erosion.

**Shipping**
Shipping is primarily affected by ice and extreme weather, and the potential for shipping will increase if the ice cover is reduced. However, shipping intensity is more dependent on market development than climate change. Regulatory measures to decarbonise shipping are increasing and driving important adaptations across the industry.

**Tourism**
Climate change shapes the spatial and temporal distribution of tourism resources within and between regions. The future competitiveness of coastal and maritime tourism in the Baltic Sea region will be conditional to the adaptive capacity of the sector to climate change, changing consumer values, natural and human-made hazards, and economic and political disturbances.

**Fisheries**
Most notable impacts to fisheries will take place in the northern Baltic Sea. Trawl fishing season will be extended, trawling areas shifted towards the south and shallower areas, target species compositions shifted towards species preferring warmer waters, and winter-time coastal fishing decreased due to diminishing ice cover.

**Aquaculture**
Baltic Sea aquaculture is dominated by open-cage rainbow trout farms with low climate impact. Cultivation of blue catch-crops, including plants and invertebrates, is increasing. Warmer conditions will promote offshore locations and species diversification. Industrial scale, land-based aquaculture farms are unlikely in rural parts due to their external resource- and infrastructure dependents.

**Blue carbon storage capacity**
Blue Carbon (BC) refers to the carbon marine organisms sequester in oceanic carbon sinks. Climate change effects on BC habitats, such as effects on carbon sink capacity and changed amount of macrophytes, are expected to increase in the future, with associated effects on climate change mitigation.

**Marine and coastal ecosystem services**
Ecosystem services in the northmost and coastal semi-enclosed areas with lower salinities will be affected first. Most ecosystem services are expected to decline, while only the cultural services, connected to recreation, could gain from the climatic changes due to longer summers and higher air and water temperatures. Other anthropogenic pressures could both offset positive and strengthen negative trends in ecosystem services supply.
Direct parameters
Air temperature

**What is already happening?**

- **Mean change:** An increase in air temperature is seen during the last century, with an accelerated increase during the last decades. Annual mean temperature trends during 1876–2018 indicate that air temperature has increased more in the Baltic Sea region than the global mean. Regional scenarios project an annual mean near-surface temperature increase over the Baltic Sea of 0.4°C (1.2–1.9°C, RCP 2.6) to 3.9°C (1.1–4.8°C, RCP 8.5) by the end of this century, compared to 1976–2005. The air temperature increase is larger in the North than in the South because of the snow and sea-ice cover decline enhancing absorption of sunlight by soil and water.

- **Extremes:** During the recent decade, record-breaking heat waves have hit the region, with an increasing trend of warm spell duration. A decrease is seen in the length of the frost season and in the number of frost days.

**What can be expected?**

- **Mean change:** Air temperatures are projected to increase more in the Baltic Sea region than the global mean. Regional scenarios project an annual mean near-surface temperature increase over the Baltic Sea of 1.4°C (1.2–1.9°C, RCP 2.6) to 3.9°C (1.1–4.8°C, RCP 8.5) by the end this century, compared to 1976–2005. The air temperature increase is larger in the North than in the South because of the snow and sea-ice cover decline enhancing absorption of sunlight by soil and water.

- **Extremes:** Larger warming is expected for cold extremes than for the mean temperature. In summer, warm extremes are expected to become more pronounced. Warm extremes presently with a 20-year return probability will occur around once every five years in Scandinavia by 2071–2100.

**Knowledge gaps**

The variability in temperature and temperature extremes are to a large extent determined by the large-scale circulation patterns. There is limited knowledge primarily concerning changes in large-scale atmospheric circulation patterns in a changing climate because of model differences.

**Policy relevance**

Higher temperatures trigger marine heatwaves, and will have direct and indirect effects on habitats, species, and populations in terrestrial and aquatic ecosystems. Higher mean temperatures and increased number of heatwaves will increase the risks of droughts and forest fires. There is a need for better urban planning, for example adapting building standards for warmer climate and increasing urban green areas. Areas such as Gotland have increased the capacity of their desalination plants, to ensure sufficient drinking water during droughts. Further measures to better manage heat and drinking water need to be implemented.

Water temperature

**What is already happening?**

- As air temperature increases, also water temperature rises. Starting at the surface, the heat spreads downward through different processes and may warm up even the deep water of the Baltic Sea. The ocean plays an important role for the climate because by far the largest amount of the heat from global warming is stored in the oceans. Due to their huge heat capacity, oceans respond slowly, and moderate temperature increases in the atmosphere. Oceans are also important in providing moisture to the atmosphere, the more the warmer the water is.

- **Mean change:** Global ocean temperatures are rising at accelerating rates. Scenario simulations for the Baltic Sea project a sea surface temperature increase of 1.1°C (0.8–1.6°C, RCP 2.6) to 3.2°C (2.5–4.1°C, RCP 8.5) by the end of this century compared to 1976–2005.

- **Extremes:** With reference to 2020, the summer of 2018 was the warmest on instrumental record in Europe, and also the warmest summer in the past 38 years in the southern half of the Baltic Sea, with surface-water temperatures 4–5°C above the 1990-2018 long-term mean. The heat wave has also been recorded in bottom temperatures.

**What can be expected?**

- **Mean change:** Marginal seas around the globe have warmed faster than the global ocean, and the Baltic Sea has warmed the most of all marginal seas. Average surface-water temperature increased by +0.59°C/decade for 1990–2018 and between +0.03 and +0.06°C/decade for 1856–2005 in northeastern and southwestern areas, respectively.

- **Extremes:** The RCP4.5 and RCP8.5 scenarios project more tropical nights over the Baltic Sea, increasing the risk of record breaking water temperatures.

**Knowledge gaps**

For the projection of water temperatures in the Baltic Sea, regional climate models are needed. However, the effect of aerosols in regional climate models has not been investigated. More knowledge on natural variability of Baltic Sea temperature and its connection to large-scale patterns of climate variability is needed. The occurrence of marine heatwaves is projected to increase. However, their potential to affect the ecosystem in the Baltic Sea is not well known.

**Policy relevance**

Water temperature has profound effects on the marine ecosystem. Climate change mitigation is the only way to counteract temperature increase. The best adaptation response available is to scale up environmental pressures to the Baltic Sea, thus building climate change resilience. The protection of marine areas where the temperature increase is expected to be lower, so-called climate refuges, focuses on areas where climate change impacts are not contributing to multiple stressors. These could become a last outpost for species affected by climate change.
The climate of the Baltic Sea region is influenced by the large-scale atmospheric circulation. The variability of the circulation can be decomposed into various dedicated modes of variability:

1. The North Atlantic Oscillation (NAO) describes the intensity of the westerly flow. A positive NAO is related to mild, wet winters and increased storminess1-3.
2. Atmospheric blocking occurs when persistent high-pressure systems interrupt the normal westerly flow over middle and high latitudes4-6. The maximum ice extent of coastal protection, and policies for this region should have an influence on the planning of coastal protection, and policies for this region.

The importance of sea-ice change is high in the northern part of the Baltic Sea, especially for ringed seals and shipping. Shipping will be affected through less restrictions on routes and less need for icebreakers, but less ice cover on average does not mean absence of severe ice winters nor of the presence of pack-ice/ridging. Diminishing ice cover also increases the risk and severity of coastal erosion in vulnerable areas. A lack of ice cover should have an influence on the planning of coastal protection, and policies for this may need to be adapted.

What can be expected?

Mean change: In the future, the ice extent is very likely to decrease (by between 6,400 (RCP4.5) and 10,900 (RCP8.5) km² per decade). The thickness of level ice is also very likely to decrease, but there are still large uncertainties for the thickness of ridged ice. The number of days with ice and length of the ice season are likely to continue to exhibit large natural variability, similar to those observed in the past. It is likely to become slightly more positive (more frequent wet and mild winters) on average, as a response to global warming14. Trends in the intensity and persistence of blocking remain uncertain15. Even under weak global warming the AMO is expected to respond very sensitively, that is, a shortening of time scale and weakening in amplitude16-18.

Large scale atmospheric circulation

Description

What is already happening?

The NAO has high interannual variability but shows no significant trend during the last century. After an increase from 1950 to 1990 (with more frequent wet and mild winters), the NAO index returned to lower values and after 1990 the blocking pattern shifted eastwards19-21 and the duration increased, with more stationary circulation patterns as a consequence22. However, there is low confidence in the changes concerning blocking patterns23. The AMO warmed from the late 1970s to 2014 as part of natural variability. Recently, the AMO began transitioning to a negative phase again24. Paleoclimate reconstructions and model simulations suggested that the AMO might change its dominant frequency over time25,26. However, the impact of the AMO on Northern European climate is independent of its frequency27,28.

Knowledge gaps

The impact of anthropogenic greenhouse gas emissions might change the large-scale atmospheric circulation that connects northern Europe with the North Atlantic region. Small changes in the flow would have large consequences for the climate in the Baltic Sea region, i.e., more a maritime or continental climate.

Policy relevance

Sea ice as a brittle material is not well represented in numerical climate models3. The fact that ice dynamics, like rafting and ridging, are not well-represented also leads to large uncertainties in sea-ice thickness and albedo (i.e., amount of sunlight reflected/absorbed). There is only limited information about sea-ice thickness and ice categories and long data sets for these parameters are sparse.

Linked parameters:

Knowledge gaps

Policy relevance
**Solar radiation**

Solar radiation is the engine of the climate system. Radiation emitted by the sun varies little. Hence, apart from the variation with the time of the year and day, radiation at the surface depends largely on cloudiness. Total cloudiness comprises clouds at all levels (low, medium, and high) and is related to the general atmospheric circulation as well as the water cycle. A cloud layer often reflects 40% to 80% of incoming solar radiation. Atmospheric aerosols have a smaller, but significant effect on solar radiation, both directly and indirectly, through interaction with clouds.

**Multidecadal variations in surface solar radiation** are generally not well captured by multidecadal variations in surface solar radiation could be expected also over oceans. But long-term measurements are lacking. Satellite cloudiness trends since the 1980s differ for many areas but seem to agree on a decline over the Baltic Sea region. Records indicate weak but significant negative trends (0.5–1.9% per decade) for global as well as for northern mid-latitude cloudiness.

**What is already happening?**

- Multidecadal variations in solar radiation, called “dimming” and “brightening”, have been observed in Europe and other parts of the world, especially in the northern hemisphere. Aerosol-induced multidecadal variations in surface solar radiation could be expected also over oceans, but long-term measurements are lacking. Satellite cloudiness trends since the 1980s differ for many areas but seem to agree on a decline over the Baltic Sea region. Records indicate weak but significant negative trends (0.5–1.9% per decade) for global as well as for northern mid-latitude cloudiness.

**What can be expected?**

- Future change is uncertain. Global climate models indicate an increase in surface solar radiation, highest over southern Europe and decreasing towards north, but still showing a slight increase over the Baltic Sea region. However, regional climate model runs could instead show a decrease in surface solar radiation over the Baltic Sea region. Unknown future aerosol emissions add to the uncertainty.

**Salinity and saltwater inflows**

Salinity is an important variable for density, which controls the dynamics of currents in the ocean. Salinity also affects Baltic Sea communities, for example species distribution. Due to freshwater supply from the Baltic Sea catchment and the limited water exchange with the global ocean, surface salinity gradiates from > 20 g kg⁻¹ in Kattegat to < 2 g kg⁻¹ in the Bothnian Bay. The dynamics of the Baltic Sea are characterized by a pronounced, perennial vertical gradient in salinity.

**What is already happening?**

- Mean change: There are no statistically significant trends in salinity, river flow or MBIs on centennial timescales since 1850, but pronounced multidecadal variability, with a period of about 30 years. Model results suggest that a decade of decreasing salinity, like the 1983-1992 stagnation, appears approximately once per century due to natural variability. Baltic Sea salinity is also influenced by the Atlantic Multidecadal Oscillation with a 50–90-year period. Since the 1980s, bottom salinity has increased, and surface salinity has decreased. Extremes: The frequency of MBIs shows no statistically significant trend during instrumental (1886–2017) and paleoestimation periods.

**What can be expected?**

- Mean change: An increase in river runoff from the northern catchment area will tend to decrease salinity, but a global sea level rise will tend to increase salinity, because the water level above the sills at the Baltic Sea entrance and the saltwater inputs from the Kattegat would be higher. A 0.5 m higher sea level would increase the average salinity by about 0.7 g kg⁻¹. Due to the large unprojected freshwater supply from the catchment area, wind and global sea level rise, salinity projections show a widespread trend, and no robust changes have been identified.
**Stratification**

The complex interplay between changes in temperature, wind and precipitation makes it difficult to project the impacts of future climate on stratification. The circulation and its influence on stratification is not well understood, and the same is true for the influence of mixing processes (e.g., winter convection) on stratification. Surface sea temperature can be expected to follow air temperature, due to air-sea heat exchange, but the fate of salinity, related to evaporation and precipitation, is not well understood, and the same is true for the influence of mixing processes.

The halocline, which is the lowermost region of continuous stratification, is an important factor in many processes. The halocline is the layer in the sea where the effects of cooling and warming become apparent. The halocline is important for the growth of phytoplankton and the reproduction of cod. In addition, the halocline is an important barrier for the movement of heat and salt. The halocline is also important for the movement of nutrients, which are important for the growth of phytoplankton.

**Policy relevance**

Stratification is an important driver of ecosystem functioning and structure, controlling the vertical flux of oxygen between the well-ventilated surface waters and oxygen-poor deep waters, affecting for example benthic habitats and the reproduction of cod. In addition, an increased thermal stratification during summer can decrease vertical nutrient transport from deeper layers to the euphotic zone, thereby limiting nutrient supply and potentially affecting algal and cyanobacterial blooms, at least at the species level. To counteract oxygen depletion in the deep water, various geoengineering methods such as pumping of water below the halocline reducing vertical stratification have been discussed, but their effectiveness at basin-scale has been questioned in scientific literature.

**Knowledge gaps**

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## What is already happening?

- In the past, the haline stratification has been dominated by sporadic inflows from the adjacent North Sea and river discharge. Long-term trends in Baltic Sea salinity1 or halocline depth2 have not been demonstrated, but a trend towards increased horizontal sea surface salinity difference between the northern and southern Baltic Sea during 1920-2005 has been detected, resulting in increased horizontal gradients3. In addition, during 1856-2005 sea surface temperatures increased by about 0.03 and 0.06 °C decade−1 in the northeastern and southwestern areas, respectively, probably resulting in increased vertical stratification4.

## What can be expected?

- Theoretical considerations imply that stronger stratification is favoured by increased freshwater supply to the Baltic Sea drainage basin accompanied by the supply of deep salt-rich waters from the North Sea, as well as warming of the surface layer. Thus, future development of stratification mainly depends on how much the Baltic Sea surface will warm compared to deeper layers and how freshwater supply and saltwater inflows will change. Multi-model scenario simulations have confirmed increased vertical summer stratification due to warming1, whereas projections of salinity and related haline stratification changes are rather uncertain1,4-6.

## What can be expected?

- Furthermore, stratification increased in most of the Baltic Sea during 1982-2016, with the seasonal thermocline and the perennial halocline strengthening3.

**Precipitation**

Precipitation forms in the atmosphere when air is saturated with water vapor, and cloud droplets or ice crystals grow large enough by condensation or deposition, respectively, to precipitate from the cloud under gravity. Depending on the conditions in the cloud and along the way to the ground, the falling particles are in liquid or frozen form (drops, flakes, hail, etc.). Precipitation is strongly linked with other variables of the water cycle. As the amount of water vapour that can be held in air increases with temperature, so does precipitation. Generally, there is more precipitation in summer than in winter in large parts of the Baltic Sea region1,2. Precipitation is strongly modified by the ground surface elevation and land-sea contrasts, implying that the large-scale circulation of the atmosphere including wind direction and vertical stability are important factors.

**Policy relevance**

Adaptation to changes in precipitation will have to involve consideration of both increasing precipitation with a risk for flooding and decreasing precipitation with a risk for drought. This will have implications for agricultural policies as well as urban flood and storm-water management.
### Policy relevance

The impacts of observed precipitation changes on stream flow are unclear. The effects of how climate model results are currently transferred to the hydrological model are still inadequately understood, due to an observed period after the spring bloom (from March to May) and significant change in total annual river runoff and flood policies, with wind pressure of CO₂ (pCO₂) and the atmosphere is controlled by biological processes (organic matter production and remineralization) and by changes in the mixed layer depth and the sea surface temperature. Ocean acidification is the decrease of seawater pH, mainly due to the rising CO₂ concentration in the atmosphere and its exchange with the surface seawater. The exchange of CO₂ between the water and the atmosphere is controlled by the air-sea surface difference in partial pressure of CO₂ (pCO₂) and the efficiency of the transfer processes, with wind speed being the dominating parameter. The projected runoff increase to the northern Baltic Sea may lower alkalinity and pH, due to decreased salinity. Higher atmospheric pCO₂ will enhance weathering on land and release alkalinity from the catchment, while eutrophication may increase internal alkalinity generation, leaving the net effect unknown. Even if alkalinity in the Baltic Sea should increase, a doubling of atmospheric pCO₂ will still result in lower pH.

### Knowledge gaps

The impacts of observed precipitation changes on stream flow are unclear. The effects of how climate model results are currently transferred to the hydrological model are still inadequately understood. More research is needed to quantify the accuracy and uncertainty associated with various bias correction methods. Several uncertainties are associated with the impact modelling, including parameter calibration against historical data and model structure uncertainty.
Riverine nutrient loads and atmospheric deposition

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| Substantial reductions of riverine nutrient loads have been achieved since the 1980s. Since there are no statistically significant trends in annual river discharges, these reductions are attributed to socio-economic development, including protective measures, rather than to climate-related effects. The total nitrogen deposition to the Baltic Sea has also been substantially decreasing since the 1980s, due to overall reduction of European emissions. However, the reduction of nitrogen emission and deposition has slowed down since the beginning of the 21st century. Atmospheric phosphorus deposition amounts have also been substantially decreasing since the 1980s, where breaking waves increase the sea-to-air exchange of phosphorus, and high pressure systems prevent the export of phosphorus to the open sea. Atmospheric phosphorus deposition amounts are among the least known processes controlling the atmospheric phosphorus deposition.
| Knowledge gaps include large uncertainties from Antarctic ice sheet melting and climate change in the Baltic Sea. The Baltic Sea is still faster than absolute sea level rise so that, relative to land, sea level is still falling. Projections suggest that riverine nutrient loads than greenhouse gas emissions can be affected by changes in emissions, for example by increased ammonia evaporation due to rising temperature.
| Reduction of nutrient inputs is considered the most important measure for mitigating Baltic Sea eutrophication. Both in coastal and offshore waters, implementation of corresponding measures within the Water Framework Directive, Baltic Sea Action Plan, Marine Strategy Framework Directive, and National Emissions Ceilings Directive has already resulted in significant decreases of land loads and atmospheric deposition. However, effects of climate change on the transfer of nutrients from land to sea have not yet been appropriately incorporated in these policies. Additionally, the ammonia (NH₃) emissions, which unlike the nitrogen oxide (NOx) emissions have been largely disregarded, will require large reduction efforts and policy and public support.

What is already happening?

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| Projections suggest that river discharge will increase in the northern Baltic Sea region, while the discharge will decrease in the southern regions, thus potentially increasing and decreasing waterborne nutrient inputs, respectively. Leaking of excessive phosphorus, accumulated in agricultural soils, will delay the effects of mitigation measures. Simulations with a range of scenarios suggest that land-based nutrient management will have greater effect on nutrient loads than greenhouse gas emissions. Atmospheric deposition can be affected by changes in emissions, for example by increased ammonia evaporation due to rising temperature.
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The wind climate in the Baltic Sea region is determined by the large-scale atmospheric circulation. Typically, the strongest wind speeds are associated with the passage of strong extratropical cyclones. These systems, and thus wind extremes, are most frequent and intense in the winter half of the year. In addition, strong local winds can occur in association with thunderstorms that are most pronounced in summer.

Knowledge gaps:
Changes in wind climate are among the least certain aspects of climate change in the Baltic Sea area. This is because there are several differing projections of atmospheric circulation between different climate models, reflected in a large spread of future wind speed changes. Enhancing the ensemble sizes and improving high-resolution climate models can help in extracting possible anthropogenic signals from the large natural variability.

Policy relevance:
Changes in wind extremes are relevant for example for coastal infrastructure, coastal tourism, and shipping in the Baltic Sea. Storm surges, which are typically associated with high wind speed events, can cause harm to various parts of the coast, and can damage densely populated coastal cities. Knowledge of wind extremes in combination with sea ice events is central for constructing and managing offshore wind and wave energy installations. Adaptation to such events is often considered in the management of coastal infrastructures. Future infrastructure would benefit from better wind models and from considering a higher wind stress tolerance.

What is already happening?
- **Mean change:** Owing to the large climate variability in the Baltic Sea region, it is unclear whether there is an overall trend in mean wind speed. Detected trends in the wind climate differ between seasons and depend on the chosen time period for which the trend is calculated because the internal variability is large. For example, mean wind speeds at the Finnish and Swedish coastlines show a slightly negative trend since the 1950s.
- **Extremes:** Maximum wind speeds at the Finnish coastline show a weakening trend, attributed to storm tracks shifting northwards. Many studies show contradicting storminess trends in the Baltic region.

What can be expected?
- **Mean change:** Projected changes in wind climate are highly uncertain due to large natural variability in the Baltic Sea area. Climate model simulations project a slight but significant wind speed increase in autumn and a decrease in spring. Some studies mention increased future wind speeds in areas no longer covered by sea ice.
- **Extremes:** Projected changes in extreme winds are uncertain due to differences in atmospheric circulation among climate model projections. It is projected that by 2100, severe wind gusts associated with thunderstorms can increase in frequency during summer.

Knowledge gaps:
There are only a few projections of future wind-wave climate, and assessments of changes in longshore sediment transport including its spatial and temporal variability are not available. Larger ensembles of scenario simulations driven by many global climate models are needed. Little is known on the role of coastal processes for the development of waves, e.g., wave set-up. Given the pronounced inter-decadal variability, detection of significant trends and attribution studies to disentangle the impact of changing climate and other drivers, together with the development of decadal predictions of wave climate, would be useful.

Policy relevance:
Increase in offshore wave action will directly impact the safety of shipping, fisheries, and offshore operations. Increase in coastal wave action will affect coastal sea level and erosion and be of immediate relevance for coastal protection. Adaptation to changes in wave climate may require for example increasing demands on hull integrity for ships and maritime structures and changes to coastal protection strategies and policies. So far, this is not the case and policymakers need to take this prospective change into account, especially when developing more windfarms in the Baltic Sea region to meet renewable energy goals.
Sediment transportation

Description

Sediment transport in marine environment is triggered mainly by currents and waves. Its direct consequence is erosion or accretion, leading to a gradual change of coastal landform and seabed morphology. Short-term, small-scale sediment transport is driven by a variety of local conditions including winds, water level, waves, currents, as well as the initial state of the system. Long-term, large-scale sediment transport is primarily controlled by the type of sediment and its supply, modulated by large-scale processes, notably sea level, storms, regional wind and wave pattern, and local engineering structures.

What is already happening?

- **Mean change**: Baltic Sea coastlines currently show a gradient from a maximum land-rise of +9 mm year\(^{-1}\) in the North to a subsidence by -2 mm year\(^{-1}\) in the South. Dominance of mobile sediments makes the southern and eastern coasts vulnerable to wind-wave induced transport\(^6\). Dominating westerly winds lead to mainly west-east sediment transport and an alternation of glacial till cliffs (sources), sandy beaches, and spits (sinks)\(^2\).
- **Extremes**: Many sandy beaches and moraine cliffs are frequently eroded by storm surges and subsequently transported by currents\(^7\). Land uplift exposes shallow seafloor sediment to erosion by storm waves and transportation by currents.

What can be expected?

- **Mean change**: Global sea level rise is accelerating\(^4\). Consequently, sediment transportation can be expected to increase in coastal areas. The rate depends both on sea level rise and storm frequency and trajectory\(^5\). Due to prevailing westerly winds in the Baltic Sea region, the dominant regional transport pattern is expected to be the same, but with high local variability along coastal sections which are featured by a small incidence angle of incoming wind waves\(^6,7\).
- **Extremes**: Coastal sediment transport by storms depends on surge and wave impact level and is likely to increase as the sea level rises\(^8\).

Knowledge gaps

There is a lack of comprehensive understanding of the spatial and temporal variability of sediment transportation along the Baltic Sea coastal zone. In general, primary sediment transport is driven by currents and waves produced by the prevailing westerly winds\(^2\). However, the intensity of secondary transport induced by easterly and northerly winds is poorly understood\(^6\). Combination with changes in sea level, storm surges (including storm tracks) and sea ice further complicate the understanding of sediment transport\(^9\). Man-made engineering structures add to the uncertainty in the prediction of sediment transport and coastal erosion patterns\(^9\).

Policy relevance

Sediment transport, especially erosion, is important to coastal planning, construction, and protection. Management strategies include 1) protection by soft or hard measures and 2) leaving some parts in an unguarded state. Soft protection includes, e.g., beach nourishment and vegetation planting in front of foredunes. Hard protection includes groynes, dykes, seawalls, revetments, artificial headlands, and breakwaters. Management efforts differ among countries and are complex when coastal protection in one place leads to morphodynamic changes that disrupt downstream areas and possibly biodiversity\(^11\). There are no synergistic measures to address these effects if they occur in other countries, due to differing legislations.
Indirect parameters:
Ecosystem
**Policy relevance**

- Oxygen depletion in the Baltic Sea by reducing air-sea and vertical transports of oxygen and by reinforcing eutrophication through intensifying internal nutrient cycling and stimulating nitrogen-fixing cyanobacteria blooms. However, the future development of deep-water oxygen concentrations will mainly depend on the nutrient load scenario. If nutrient loads are high, the impact of warming will be considerable and negative; if low, the effect will be small. Scenario simulations suggest that full implementation of the Baltic Sea Action Plan resulting in required load reductions will lead to a significantly improved ecosystem state of the Baltic Sea, irrespective of the driving global climate model.

**Linked parameters:**
- Drivers: Eutrophication, climate change, eutrophication, climate change
- Indirect parameters: Ecosystem function, Oceanography
- Description: Despite decreasing nutrient loads after the 1980s, recently calculated oxygen consumption rates are higher than earlier observed, counteracting the effect of natural ventilation of deep water. Improved oxygen conditions have been observed in some coastal waters, where inputs of nutrients and organic matter have been abated. However, hypoxia remains common in other coastal areas, with unaltered or even worsening conditions. In 2016, the annual maximum extent of hypoxia covered an area of about 70,000 km², whereas 150 years ago the hypoxic area was presumably small.

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**Microbial community and processes**

**What is already happening?**

- Light (influenced by, e.g., cloudiness and turbidity) influences algal growth and the production of bacterial substrates. Light also cleaves refractory compounds to usable food for bacterioplankton. Environmental toxicants and pharmaceuticals may also influence bacterioplankton, either by being food for bacterioplankton or by hampering bacterial growth.

**What can be expected?**

- Continued eutrophication together with a longer algal growth season and higher sea surface temperature, will intensify bacterially mediated transformation of organic matter, CO₂ production, and oxygen consumption in the Baltic Sea. Counteracting this, increased riverine dissolved organic carbon (DOC) discharge due to precipitation will hamper light and thereby algal productivity, while maintaining bacterial production. No reliable modelling of these processes is currently available to help project the net outcome for, e.g., marine oxygen consumption. Warming and extended heatwaves will increase the risk of infection of humans by pathogenic bacterioplankton like the Vibrio.

**Other drivers**

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Benthic habitats in the Baltic Sea are characterized by a mixture of species from marine and freshwater origins. In the deep benthic areas, communities are dominated by only a few invertebrate species, whereas in the shallow photic areas, various macroalgae and vascular plants provide food and shelter for a large number of invertebrates and fish at both hard and soft bottoms. Climate change may affect the composition, abundance, biomass and spatial distribution of benthic species and habitats, with potential biodiversity and ecosystem functions as a result.

**What can be expected?**

- Many Baltic species exist on their geographical distribution limit, and small fluctuations in temperature and salinity can have a large impact on, e.g., bladderswack, blue mussel and eelgrass[4,10]. Increasing temperature affects species turnover rates and physiology[23-26]. In coastal ecosystems, increased precipitation and runoff might cause salinity fluctuations[27], affecting species reproduction and survival[11].

- Sea level rise[12-14] will change prerequisites for important environments like shallow coastal habitats. In the profundal areas, macrobenthos productivity will decrease if oxygen conditions deteriorate[28]. In areas with increasing riverine load of dissolved organic carbon (DOC), pelagic primary production may decrease, affecting the benthic system[15,16].

**What is already happening?**

- Benthic soft substrate communities in large parts of the Baltic Sea have drastically changed during the past decades, with amphipods decreasing[29].

- Baltic clam Limnocola bothrico increasing, and the non-indigenous polychaete Marenzelleria becoming dominant[30].

- Changes have been explained to some degree by abiotic factors such as temperature, fluctuations in salinity and oxygen, and precipitation and runoff related changes in pelagic food webs[31].

- Decreasing amount of sea ice has consequences for stratification, nutrient dynamics, and hence benthic communities. Despite decreasing nutrient loads, hypoxic areas continue to prevail in the central Baltic Sea[32] and increase in the coastal zone[33], causing loss of communities and ecosystem functions[14,34].

- Salinity decline has been hypothesized to be the major driver of geographic species shifts, but according to recent regional climate modelling the magnitude of change is uncertain[35-37]. Effects of climate change on benthic habitats are difficult to project, due to cumulative and changing impacts of stressors, as well as confounding food web interactions[35,38].

- The interactions of climate change with other stressors are not well known, nor is the capability of organisms to adapt to climate change. For instance the key species bladderswack has in some studies been shown to adapt to climate change[39,40], while others have suggested that the species cannot keep pace with the projected salinity change, with large effects on biodiversity and ecosystem functioning[14,38].

- What can be expected? What is already happening? Description Knowledge gaps Policy relevance

**Benthic habitats**

**What can be expected?**

- Higher water temperature has improved the reproduction of many spring and summer spawners[2-4].

- In contrast, the reproduction of autumn-spawners, e.g., vendace and whitefish, is disfavourd by warm winters and their distribution decreases with less ice cover and higher winter temperatures[41-44].

- Species preferring warm waters have become more common relative to winter-spawning species[45].

- Migratory anadromous species, like salmon, return earlier to rivers after warm winter/spring. However, high water temperature in autumn and winter seems to lower the survival of salmon migrating back to the sea[46,47].

**What is already happening?**

- Earlier spawning, faster egg, and larval development, increased larval survival of spring spawning freshwater coastal fish species[48-50] (*).

- Earlier migration from nursery habitats may influence food web interactions with negative effects on piscivorous species[48] (*).

- Reproduction of autumn-spawning migratory fish is expected to expand. Further increasing temperatures and spawning areas reduced if ice cover decreases further[41-44].

- The effect of water temperature on body growth differs among species and size classes; growth is generally expected to increase for small but not for large fish[51,52,53].

- Possible brownification of coastal waters may decrease body growth[54].

**Coastal and migratory fish**

**What can be expected?**

- Indirect and interactive effects of different natural and anthropogenic drivers in combination are poorly studied. To identify causal relationships, modelling based on monitoring data in combination with experimental studies is needed.

- The effects of some expected climate induced changes, e.g., shrinking ice cover and browner waters, on coastal and migratory fish stocks are poorly studied.

- The importance of extreme weather events under climate change for fish population development and status is furthermore insufficiently studied. Follow-up studies after extreme weather events (like heatwaves, and ice-free winters) are of key importance for understanding the recovery and resilience of fish populations and communities.

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**Other drivers**

- Anthropogenic pressures, such as eutrophication, fishing, and habitat exploitation, affect fish in coastal areas.

- Pharmaceutical residues and plastics might negatively affect fish locally.

- Increased coral cover and seal populations consume substantial amounts of coastal fish[46], but the impact on fish populations is disputed[48].

- Migratory anadromous fish are affected by a similar set of pressures as coastal fish, and in rivers also by altered hydrological regimes, migration barriers and climate change, caused by dams, and increased sedimentation due to land-use changes in the drainage area[46].

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**Knowledge gaps**

- Climate Change in the Baltic Sea Fact Sheet 2021

**Authors**

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Fish of marine origin, such as cod, herring, sprat, and flatfish (flounder, plaice, turbot, and dab), dominate pelagic and demersal habitats of the Baltic Sea. These species occur in large, often internationally managed, stocks. Currently, stock-levels make a significant part of the pelagic fish biomass. Temperature impacts the recruitment (successful reproduction and survival of the offspring), body growth and mortality of pelagic and demersal fish, resulting in changes in spatial and seasonal distributions.

**What is already happening?**
- Increasing water temperature causes earlier spawning, shorter development, and increased recruitment of sprat19,20,21.
- Increasing annual growth of herring, sprat, and flatfish, and body growth of adult sticklebacks22,23,24. Herring and cod recruits may miss optimal temperature windows resulting in lowered recruitment23,24,25,26,27.
- Increasing temperature especially if the halocline shifts upwards and nutrient loads are not reduced, may reduce oxygen in water and sea bottom. This will lead to reduced reproduction and feeding areas, increased food competition, and dependency on shallow areas for cod and flatfish24,25.
- Recruitment of sprat is higher in warmer waters after winters with low ice cover but opposite for herring26,27.

**What can be expected?**
- If salinity decreases, this may also reduce recruitment, abundance, and distribution of flatfish, sprat, and cod28,29,30.
- The northward distributional shifts are expected to continue24,30.
- Rising sea level and erosion are expected to influence the availability of breeding habitats21,26,27 and rising sea level may reduce breeding success due to flooding of the breeding and wintering foraging habitats.
- Some waterbird species migrate earlier in spring11,12.
- As most Baltic waterbirds are migratory, they are affected by climate change also outside the Baltic Sea, for example during breeding in the Arctic and migration and wintering between southern Europe and western Africa16.

**Knowledge gaps**
- Indirect and interactive effects of climate parameters and other pressures on fish need to be better studied26,30. To explain causal relationships, modelling of monitoring data in combination with experiments is required. Furthermore, impacts of changes related to climate, like ice cover, brownification, and acidification, are poorly studied in the Baltic Sea.
- The importance of average changes relative to extreme weather events (e.g., heatwaves vs. average temperature) are poorly studied. There is a need to analyse monitoring data before, during, and after extreme events, supplemented with experiments and long-term data to understand the recovery and resilience of fish species and communities after extreme weather events.

**Policy relevance**
- Demersal and pelagic fish are key elements for Baltic Sea offshore food web structure and function, and offshore fisheries. Management of demersal and pelagic fish, e.g., quotas, fishing closures and protected areas, takes historic changes in stock productivity into account but does not consider predicted climate change effects. Furthermore, management of these stocks needs to be adaptive to react to long-term effects of climate change. Targeted short-term actions, e.g., temporary, or spatial closures, could help affected fish populations to recover from extreme weather events. Targets and measures in future management plans need to consider long-term impact of climate change on fish populations and communities.

**Other drivers**
- Impacts of multiple drivers on offshore fish communities are perceivable20,21. High nutrient discharges have resulted in enhanced hypoxic conditions affecting many fish species negatively22,23, but also benefiting others24,25.
- Nutrient loads have decreased since the 1980s, but the response in nutrient concentrations is slow and also affected by runoff and climate related variables such as temperature and stratification25.
- Fishing strongly affects cod, herring, and sprat. Harmful substances, marine litter, and pharmaceutical residues might have negative impacts on individuals while effects on populations appear to be small, yet uncertain. Food web interactions and competition/predation (food quality) among populations are evident.
- Vitamin deficiency (e.g., thiamine) may impact fish species.
Three seal species and one cetacean live in the Baltic Sea: ringed seal (Phoca hispida), grey seal (Halichoerus grypus), harbour seal (Phoca vitulina) and the harbour porpoise (Phocoena phocoena). Being at the top of the marine food web, these predators are sensitive to changes throughout the ecosystem, including those related to climate. Furthermore, the extent and quality of sea ice are important particularly to the ice-breeding ringed seals and also the facultatively ice-breeding grey seals. In some areas, seals are dependent on low-lying haul-outs (land areas for resting, breeding, foraging etc.).

### Other drivers
- Ice-breaking and winter shipping may worsen effects of reduced ice on seal breeding.
- Bycatch affects marine mammals.
- Anthropogenic disturbance affects seal distribution and recruitment.
- Epidemics can reduce seal abundance and possibly distribution.
- Ecosystem changes and overfishing influence prey availability.
- Pollutants impair marine mammals’ immune function and fertility.
- Underwater noise may for all species cause injury and displacement from habitats and disturb natural behavior, and for harbour porpoise interfere with echolocation.

### Knowledge gaps
- Sea ice, Sea level, Waves, Pelagic and demersal fish, Coastal and migratory

### Policy relevance
- As the vast majority of NIS arrive with ships, the main driver of biological invasions is the occasional, unintended, and unpredictable introduction of organism into Baltic Sea ecosystem. Also, aquaculture has a significant impact on the arrival of NIS. Eradication after introduction is mostly impossible and the main focus must be on preventing any NIS from arriving in the first place. Anthropogenic disturbances, like eutrophication and habitat degradation, interact with biological invasions by affecting the conditions for NIS establishment.

### Other drivers
- Higher temperature and a possible salinity decrease can increase recruitment and growth of certain NIS, e.g., dreissenid mussels, several freshwater crustaceans, and the round goby.
- Changes may first be seen in estuaries, where the contribution of NIS is already high.
- If oxygen deficiency increases in warmer coastal waters, it may constrain the growth of the round goby, but more tolerant species, like the polycheate worm Marenzelleria spp., may increase and change sediment nutrient fluxes and resuspend contaminated sediments.
- Warmer winters will facilitate survival for introduced warm-water species.

### Knowledge gaps
- Most NIS are ecologically unique, and it is therefore important to predict how introduced species will behave and interact in a new environment. It is important to identify the potential threats they pose to native species and ecosystem functions.

### Policy relevance
- Once NIS are established, they are practically impossible to remove. Policies are thus focused on preventive measures. Targets for minimizing adverse effects of NIS on biodiversity and ecosystems have been set in the EU Marine Strategy Framework Directive, the EU Invasive Alien Species Regulation, and the HELCOM Baltic Sea Action Plan but reaching these goals will be difficult if climate change promotes successful establishment of NIS. Policy focus should be on preventing new introductions, for example by implementing the regulations related to aquaculture, Ballast Water Management Convention, and by working to manage biofouling on shipping hulls (commercial as well as recreational).
Marine protected areas

Marine protected areas (MPAs) are intended to conserve ecologically significant parts of the marine and coastal environment, including biological and genetic diversity and ecosystem functions. Biodiversity, including genetic diversity, is needed for species’ adaptation and long-term survival under changing environmental conditions. Sufficiently sized and adequately located MPAs will likely help marine organisms adapt to climate change and increase their survival by reducing impacts of other human pressures. In 2021, HELCOM MPAs covered 17% of the Baltic Sea. The effect of climate change can be evaluated by assessing consequences to MPA conservation values and function based on biodiversity, fish stocks, birds, and seals.

What is already happening?

In comparison to other marine areas, the Baltic Sea is prone to climate change related warming and oxygen depletion. Until now, negative effects of climate change on the Baltic Sea ecosystem have already become apparent through pelagic regime shifts (i.e., persistent change in the ecosystem). Milder winters with shorter ice periods and increased ice cover restrict breeding habitats for the ringed seal (see “marine mammals”).

Simultaneously, northward distributional shifts of birds may increase the importance of MPAs as overwintering areas (see “waterbirds”). Habitat change through higher temperatures and oxygen depletion (related to eutrophication) may harm fish stocks and benthic communities, impacting MPA conservation values.

What can be expected?

If sea ice is reduced, while water level, erosion, and flooding increase, some MPAs may lose parts of their function as breeding and feeding sanctuaries for marine mammals and waterbirds.

Distributional changes of biological communities caused by climate change may impact the function of MPAs and, together with other anthropogenic pressures, prevent MPAs from meeting their objectives.

Policy relevance

There is no commonly agreed method to assess the ecological and management effectiveness of MPAs, which impedes evaluations and optimization of MPAs as a management tool. Moreover, totally protected no-access areas, which would provide reference sites for the determination of a baseline for natural conditions, are lacking, which also complicates defining objectives of MPAs. Knowledge gaps also exist in understanding connectivity of areas, affecting the ecological coherence of the MPA network.

Cumulative pressures caused by a variety of human activities both inside and outside the Baltic Sea are crucial drivers of ecosystem damage and biodiversity loss in the Baltic Sea. Intensive shipping and fishing, sand and gravel extraction, offshore installations, as well as inputs of nutrients and hazardous substances from land represent major threats to the whole Baltic Sea ecosystem and its adaptability to climate change. Pressures are further exacerbated by the limited water exchange.

Other drivers

Knowledge gaps

There is no commonly agreed method to assess the ecological and management effectiveness of MPAs, which impedes evaluations and optimization of MPAs as a management tool. Moreover, totally protected no-access areas, which would provide reference sites for the determination of a baseline for natural conditions, are lacking, which also complicates defining objectives of MPAs. Knowledge gaps also exist in understanding connectivity of areas, affecting the ecological coherence of the MPA network.

Policy relevance

Effectively managed MPAs can mitigate impacts of climate change to conserve biodiversity and healthy, resilient marine ecosystems, which also act as carbon sinks. International and national policies would benefit from fostering a change in reasoning behind MPAs, from protecting threatened species and biotopes towards securing functional diversity and biodiversity and ensuring ecosystem services. As of 2021, HELCOM supports a network of 177 MPAs, which could act as a reservoir of resilience for climate change resilience. However, an expansion of the HELCOM MPA network, with climate refugees in which food web perspectives and genetic diversity are considered, is needed.

Nutrient concentrations and eutrophication

Nitrogen and phosphorus pools are controlled by inputs from land and atmosphere and modified by biogeochemical transformations. Both these nutrients cycle intensely between the water column, biota, and bottom sediment. Nitrogen fixation and denitrification act as major biogeochemical sources and sinks, whereas phosphorus tends to accumulate in bottom sediments. Furthermore, considerable amounts of nutrients are exported to the North Sea.

Bottom oxygen conditions regulate denitrification rates and the distribution of phosphorus between sediments and the water. Higher nitrogen loss and phosphorus release from sediments occur when hypoxia expands.

Dissolved inorganic nitrogen is described in this text with the abbreviation DIN and dissolved inorganic phosphorus with the abbreviation DIP.

What is already happening?

Climate change impacts on nitrogen and phosphorus pools cannot yet be separated from other pressures. Effects of warming and sea level rise are masked by changes in nutrient loads and bottom water oxygen levels. Nitrogen concentrations have decreased in most Baltic Sea basins since 1990, but phosphorus pools have fluctuated without trend.

Eutrophication has made shallow areas with restricted water exchange more prone to hypoxic events.

Nutrients liberated from sediments during the hypoxic events fuel summer phytoplankton blooms. Changes in stratification and cloud cover currently prevent the phytoplankton growth season, with earlier spring onset and extended autumn blooms, without clear effect on nutrient concentrations.

What can be expected?

The development of nutrient loads will dominate future nutrient concentrations, with warming expected to reduce near-bottom oxygen by increasing internal nutrient cycling and by strengthening thermal stratification.

A decline in the DIP pool is projected. DIP surface concentrations in the Baltic Proper will decrease with ISAB load scenarios and slightly increase with current load scenarios while surface DIN concentrations remain unchanged under both scenarios.

In the Gulf of Finland and Bothnian Sea, it is expected that DIN levels will increase with both load scenarios, while DIP changes will be similar to the Baltic Proper.

- nitrogen-fixing cyanobacteria blooms are expected to expand.

Other drivers

Knowledge gaps

The magnitude of future nutrient loads, the bioavailability of their organic fraction, and their retention in the coastal zone are uncertain, as are future nutrient inputs at the Skagerrak boundary. Freshening of the water would have the potential to increase phosphorus binding in sediments, but both the magnitude of future salinity change, and the sediment response are uncertain. Feedbacks between climate change, phytoplankton community structure and sedimentation are poorly known and more quantitative knowledge about the factors controlling nitrogen pathways is needed, especially for coastal areas.

Dissolved organic forms of nitrogen and phosphorus are important biogeochemical components with poorly described dynamics in models.

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**Ecosystem function**

**Description**
Baltic Sea ecosystems provide an array of ecosystem functions related to, for example, nutrient and carbon circulation, biomass production, and regulation.

Climate-related factors structure Baltic Sea food webs both through top-down (predation) and bottom-up (biomass production) processes, which are fundamental for ecosystem functioning.

Climate change will likely impact several processes related to food web interactions, nutrient recycling, and ecosystem properties.

**What is already happening?**
- Long-term eutrophication has increased primary production and during the last decades more frequent algal blooms are observed during warmer years. This causes increased decomposition and oxygen-depleted bottom sediments.
- Changes in ice cover, cloudiness, and wind condition in spring may have resulted in changed timing of algal blooms, affecting benthic productivity.
- Changes in hydroclimatic conditions in combination with fishing and eutrophication have resulted in a shift from larger zooplankton to smaller zooplankton, and stronger impact of nutrients on ecosystem structure (bottom-up control) and reduced the regulatory capacity of predators on ecosystem structure (top-down control) in both pelagic and coastal Baltic Sea food webs.

**What can be expected?**
- Warmer water may increase pelagic and benthic primary production.
- Unless nutrient loads are reduced, oxygen levels in the water and close to the seabed will decrease. Responses at higher trophic levels will differ among organism groups.
- If salinity decreases, this will likely affect the species composition of zooplankton and fish, and the associated functions, e.g., predation rates.
- If inflow of dissolved organic matter increases, this may increase benthic production, and increase bacterial production over phytoplankton production. Reduced light conditions may reduce total primary production of both species of pelagic food webs.

**Knowledge gaps**
Several parameters are intercorrelated and there are potentially indirect and interactive effects of, for example, oxygen, salinity, and temperature on ecosystem functioning. The magnitude and interactive effects of climate change relative to other human pressures are hence important to estimate. There are knowledge gaps on how changes in Baltic Sea food web structure, resilience and functioning depend on long-term changes in climate relative extreme weather events, like heatwaves. It would be important to analyse monitoring data before, during, and after extreme events, such as the heat waves or low ice cover.

**Other drivers**
- Fishing is a strong pressure on some fish species and results in reduced natural control of their prey.
- Nutrient concentrations are main drivers of biomass production, causing negative impacts on oxygen levels and water clarity that can severely worsen climate change-related effects on ecosystem functioning.
- Seals and cormorants have increased in the Baltic Sea, but food web effects are poorly known and uncertain. Toxins, marine litter, pharmaceutical residues and vitamin deficiency (e.g., thiamine) have negative impacts on individuals of different functional groups, but the ecosystem effects at the Baltic Sea scale are uncertain.

**Policy relevance**
Ecosystem functions are essential processes structuring ecosystems and food webs, including key ecosystem services to human well-being. Management actions in general focus on populations (fishing/hunting, protection) or inputs (nutrients, toxic compounds) that influence ecosystem functions, but these hardly consider climate change effects. Current management plans need to consider long-term impacts of climate change on ecosystem functions, and how extreme weather events should trigger additional short-term actions to avoid ecosystem regime shifts (level of confidence: medium). Long-term management plans and measures should consider projected changes in primary production and trophic structure of Baltic Sea ecosystems.
Indirect parameters:
Human use
**Policy relevance**

- Knowledge gaps
- Offshore wind farms
- Coastal protection

**What is already happening?**

- The world’s first offshore wind farm was installed in Vindeby, Denmark, in 1991. Currently, as of 2021, offshore wind farms are found in the waters of four countries: Germany (3,074 MW), Denmark (872 MW), Sweden (192 MW) and Finland (66 MW). Climate change impacts, such as ice conditions, wind, and wave fields, do not have any major influence on the deployment of offshore structures. Investment in offshore renewable energy has been emphasized in the European Green Deal, and a dedicated EU strategy on offshore renewable energy was published in November 2020 proposing ways forward to support the long-term sustainable development of this sector.

**What can be expected?**

- The European Commission estimates that Europe will need 240–450 GW of offshore wind by 2050, equaling up to 30% of Europe’s estimated electricity demand at the time. The wind energy industry argues that reaching 450 GW would require the Baltic Sea offshore wind capacity to grow to 83 GW. The latter would suggest the annual rate of consent to increase from 2.2 GW (430 km²) to 3.6 GW (720 km²) per year between 2030 and 2040. The increasing spatial demands, contrasting interests and risks to ecosystems call for environmental impact assessments and marine spatial planning to optimize the use of the sea.

**Linked parameters:**

- What is already happening?
- What can be expected?
- What is already happening?
- What can be expected?
### What is already happening?

- **Shipping:**
  - In recent decades, the number and size of ships in the Baltic Sea have increased. Climate has changed, with a shorter ice season and earlier ice break-up, facilitating shipping in usually ice-covered areas. Changes in wind fields have also been small and depend on the time period and area studied. Extreme waves have not changed significantly in strength or intensity. Changes in wind and waves could potentially influence safety and fuel consumption.
  - Ports and shipping lanes may have to move location or increase or decrease dredging due to sea level rise and increased sedimentation from coastal erosion and river runoff.

- **Tourism:**
  - Although coastal tourism is a major economic activity in the Baltic Sea region, there is only limited information on how tourism may be affected by changes in the marine environment. The importance of various qualities of coastal tourism forms, including spas, sunbathing and beach activities, boating, fishing, ice-skating and recreational homes. The share of international tourism is substantial, especially in cruise-ship tourism. The Baltic Sea is a major international passenger port in Europe with a total of 12.2 million passengers.

### What can be expected?

- **Shipping:**
  - Modelling predicts an annual shipping increase of 2.5% for cargo and 3.9% for passenger traffic in Europe. Less sea ice will require less ice-breaking, but the ice will be more mobile. Wave climate in the northern and eastern Baltic Sea is estimated to become more severe, and icing by freezing sea-spray is expected to become more frequent.

- **Tourism:**
  - Changing climate may either increase or reduce the provision of ecosystem services and resources relevant to different forms of coastal and maritime tourism. On the one hand, warmer summers attract increasing numbers of coastal tourists to northern Europe. On the other hand, fewer below-freezing days shorten the winter sports season. The growing season of cyanobacteria has significantly prolonged during the past few decades, making bathing less attractive. Introduction of non-indigenous species alter opportunities for fishing and recreation. Tourists are rather flexible in substituting the place, timing, and type of holiday at short notice depending on the conditions and services at the destination.

### Knowledge gaps

- **Shipping:**
  - A knowledge gap in how new regulations driven by climate change mitigation efforts will affect the fleet composition, fuel selection, and additional technological development. The response of future Baltic Sea shipping to changes in climate cannot be fully quantified.

- **Tourism:**
  - The potential for developing coastal and maritime tourism in the Baltic Sea region depends not only on climate change, but also on associated socio-economic developments, frequency and type of yet unknown hazards, other changes in the state of marine and coastal environments and changing customer preferences. As a result, it is difficult to project the future demand for tourism services in the Baltic Sea region, or even to assign probabilities for different future outcomes. The relative importance of various qualities of coastal and marine environments for customer destination choice is poorly understood.

### Policy relevance

- **Shipping:**
  - The tourism industry is vulnerable to external changes and pressures, including global and regional economic and political processes. The changing environmental conditions and their local effects can either promote or hamper the development potential and demand for coastal and maritime tourism in the Baltic Sea region. Although coastal tourism has long been increasing, global health crises or security issues may quickly reduce demand for visits globally. Increased shipping in previously ice-covered areas may increase environmental pressures, but new regulations on noise and emissions may exclude vessels from sensitive areas. Establishment of offshore windfarms should be taken into account in marine spatial planning. The environmental impacts of shipping need to be better compared and prioritized with industry on land, including land transportation.

- **Tourism:**
  - The touristic importance of higher latitude destinations (such as the Baltic Sea region) is expected to grow due to climate warming, and with a higher probability of climate extremes and health risks (such as malaria resurgence) in the currently most popular destinations in southern and central Europe. On the other hand, depending on the magnitude of future mitigation efforts, the coastal areas of the Baltic Sea may suffer from even more frequent and extended blooms of cyanobacteria, with related health and image risks. The future growth of coastal and maritime tourism in the Baltic Sea region has the potential to exceed the global average.
**Aquaculture**

**Description**

Baltic aquaculture is currently dominated by open cage rainbow trout farms and contributes <0.5% of the total nutrient load to the Baltic Sea. Farms located throughout the Baltic at Åland and Åbo Archipelago (Finland), the Danish straits, and a few other scattered locations. In both Finland and Sweden, farm closure and relocations have significantly reduced local-scale farm impacts on the marine environment. Finland and Estonia are evaluating offshore locations with a first pilot farm in the Bothnian and Tagulainen bays. Extractive farming, where blue mussels and macro-algae are harvested as a way to recover excessive nutrients for terrestrial use, is also being explored.

**What is already happening?**

- Summer surface-water temperatures periodically exceed the optimal for rainbow trout in the whole Baltic and especially in the northern areas reducing physical fitness, impairing growth, and increasing mortality. Fish species presently farmed are unlikely to be affected by changing salinity, but any increase in terrestrial nutrient loading could be negative for aquaculture. Warmer water could promote farming of more temperature resilient species, such as perch and pikeperch.

- Farming of blue mussels and macro-algae is negatively affected by both warmer water and lower salinity. Increased waves and more heatwaves, as well as increased predation by fish and birds would increase mussel losses.

**What can be expected?**

- Any temperature increase, especially in combination with high algae concentrations, will further stress currently farmed organisms. A possible salinity decrease will limit mussel farming and force a shift to cultivation of freshwater tolerant plants and invertebrates. Increasing policies promoting farming in more exposed locations will raise production costs. Offshore aquaculture, especially for mussels, but also for fish, could be co-located with offshore wind farms, offering moorings at locations with high water exchange, with reduced risk of conflict with shipping and recreation.

**Other drivers**

- Policies promoting circular production and rural development will be positive for aquaculture. Regional differences are incompletely understood. Reliable, local-scale projections of future water temperatures, salinity, occurrence and toxicity of algae blooms, and ice cover are needed for siting new farms. Use of native species tolerant of possible future conditions requires knowledge of technical and ecosystem effects, including use of sterilized fish. New farming technologies offering an economically feasible solution for particle recapture and deep-water siting must also be developed and evaluated. Credible environmental assessment of both sediment and total nutrient budgets of offshore farms using Baltic feed sources are also needed. Furthermore, alternative, and new species, especially those on lower trophic levels, and their acceptance by consumers is not well investigated.

**Knowledge gaps**

- There are multiple knowledge gaps related to climate change effects on Baltic Sea aquaculture. Regional differences are incompletely understood. Reliable, local-scale projections of future water temperatures, salinity, occurrence and toxicity of algae blooms, and ice cover are needed for siting new farms. Use of native species tolerant of possible future conditions requires knowledge of technical and ecosystem effects, including use of sterilized fish. New farming technologies offering an economically feasible solution for particle recapture and deep-water siting must also be developed and evaluated. Credible environmental assessment of both sediment and total nutrient budgets of offshore farms using Baltic feed sources are also needed. Furthermore, alternative, and new species, especially those on lower trophic levels, and their acceptance by consumers is not well investigated.

**Policy relevance**

- Aquaculture has the potential to provide sustainable, climate-smart local food while countering marine eutrophication and making economic investments. A socially, economically and environmentally sustainable aquaculture sector requires science-based solutions incorporating marine spatial planning. Reliable, local-scale projections of future water temperatures, salinity, occurrence and toxicity of algae blooms, and ice cover are needed for siting new farms. Use of native species tolerant of possible future conditions requires knowledge of technical and ecosystem effects, including use of sterilized fish. New farming technologies offering an economically feasible solution for particle recapture and deep-water siting must also be developed and evaluated. Credible environmental assessment of both sediment and total nutrient budgets of offshore farms using Baltic feed sources are also needed. Furthermore, alternative, and new species, especially those on lower trophic levels, and their acceptance by consumers is not well investigated.

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**Fisheries**

**Description**

The commercial fishery in the Baltic Sea includes pelagic offshore and demersal fleets that contribute to 95% of total landings, and a variety of small-scale coastal fisheries. The main species targeted are Baltic herring, sprat, cod, and flounder. In addition, a variety of coastal freshwater and anadromous fish species are targeted. Mid-water and bottom trawls, gillnets, and trap-nets are the main gears used. Recreational fishing is common in coastal areas. For certain coastal species, the recreational catch is comparable or even higher than the commercial catch.

**What is already happening?**

- In the northern Baltic Sea, trawl fishing has already seen an earlier seasonal start in some years, with better operating conditions due to a shorter ice-covered period. Coastal recreational ice fishing opportunities have been reduced. In much of the Baltic Sea, small-scale wintertime coastal fishing has also suffered from competition with seals that find ice-free fishing sites easier to access. The species composition targeted especially by the coastal and demersal fisheries is changing due to eutrophication and climate change. Also, increased effort is needed for fishing-gear maintenance, due to accumulating stocks of targeted species, and harm).

**What can be expected?**

- The potential trawling season in the northern Baltic Sea will likely be extended due to a shorter ice-covered period. The main trawling areas for pelagic species are likely to shift towards more southern, shallower areas. The coastal and recreational fisheries will increasingly target species that prefer warmer and more nutrient-rich waters. Some winter-time fishing will suffer from a shortage of ice and increased conflicts with seals. The recreational fisheries may become more popular with longer seasons for boat-trips and rod-fishing.

**Other drivers**

- Scientific evidence for alteration in Baltic Sea fisheries driven by climate change is still sparse. Complicated interacting and potentially additive effects in the environment, ecosystem and society make it very challenging to predict the potential consequences of climate change on different fisheries. Therefore, conclusions are confined to the currently observed trends.

**Knowledge gaps**

- Fishery has an important role in marine economy, providing work and healthy food. Fisheries activities are regulated by the EU Common Fisheries Policy and on national level. Fish stocks’ monitoring and management plans should be adaptive and adjustable to mitigate climate change effects and ensure resilience. To acknowledge the potentially negative effect on fish stocks and other factors affecting the prospects of fisheries under climate change, a precautionary approach has to be applied. Climate change is only one of many challenges facing the fisheries sector: competition with apex predators and other fisheries sectors, low profitability, conflicts over shared resources, decreasing stocks of targeted species, and harmful substances are major concerns.

**Policy relevance**

- Policies promoting circular production and rural development will be positive for aquaculture. Regional differences are incompletely understood. Reliable, local-scale projections of future water temperatures, salinity, occurrence and toxicity of algae blooms, and ice cover are needed for siting new farms. Use of native species tolerant of possible future conditions requires knowledge of technical and ecosystem effects, including use of sterilized fish. New farming technologies offering an economically feasible solution for particle recapture and deep-water siting must also be developed and evaluated. Credible environmental assessment of both sediment and total nutrient budgets of offshore farms using Baltic feed sources are also needed. Furthermore, alternative, and new species, especially those on lower trophic levels, and their acceptance by consumers is not well investigated.

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**Aquaculture**

**Knowledge gaps**

- Other drivers, such as changes in society, fish stocks, fishing regulations and fish markets, are likely to have as profound effects on the fisheries sector as climate change. For example, changes in consumer demand or changes of subsidies might affect the profitability of fisheries. Other environmental issues, partly interacting with climate change, such as increasing eutrophication if nutrient reductions according to the Baltic Sea Action Plan are not achieved, changes in the regulation of harmful substances, parasite infection rates in fish, and decreasing water exchange and sand deposition of non-indigenous species, will also affect the quantity and quality of fish, and the demand for the catch.
Blue Carbon (BC) refers to organic carbon that is captured and stored by marine and coastal ecosystems. Vegetated coastal ecosystems, which fringe global coastlines, support disproportionately large carbon sinks and are, therefore, the focus here1-4. These “BC ecosystems” are under pressure and have experienced major global losses in area15 and, hence, losses of carbon sink capacity16-18. Management strategies to protect and restore them therefore contribute to mitigating climate change. This is a win-win strategy as these ecosystems also contribute to natural coastal protection and support biodiversity and other ecosystem services19,20. In the Baltic Sea, vegetated coastal ecosystems encompass tidal marsh/coastal meadows, eelgrass/seagrass meadows, and macroalgae beds.

**Ecosystem services (ES) are commonly assessed as supply (mostly related to biophysical or ecological characteristics of the environment), demand (mostly societal drivers) and flow (actual provision and use). The values of ES supply relate directly to ecosystem components21-23, which in turn, are altered by climate change. The assessment of ES demand is based mostly on the global societal changes like alteration of lifecycles or climate change induced alterations in ES supply at global scales (e.g., increase of water temperature). Southern Europe could trigger recreational demand in the Baltic. While ES flow functionally is a result of interaction between supply and demand functions, it could, in some cases, be easily assessed (even using economic methods).**

**The cultural ecosystem services (mainly relevant to tourism and recreation, including recreational boating24) may benefit from a longer bathing season and increased air and water temperature in the summer. However, warming may counteract these benefits due to impact on human health. Furthermore, ice fishing possibilities along with an expected shift towards smaller fish will negatively affect recreational fisheries. The supply of provisioning ecosystem services (mainly the most valuable fish stocks in the Baltic) are expected to decrease both in quantity, but especially in quality25, while aquaculture is not expected to counteract such a potential development by providing more high-quality fish. Moreover, the anticipated climatic changes are expected to reduce the role of semi-enclosed areas as coastal filters26.**

**Marine and coastal ecosystem services** are critical for both strategic and territorial planning in the Baltic-Sea region, because of the societal reliance on them. Mitigation measures for the ES parameters are diverse and described in the other key messages. The essence of ES is agreed in most of the major international agreements on environmental protection, and especially highlighted in the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) 2019 Global Assessment Report. The ES concept should be guiding for Baltic Sea policies, but as there is no commonly agreed method to calculate or assess ES, such a method needs to be developed.
Glossary, policy linkages and references
accretion — deposition of sediment, opposite of erosion

albedo — amount of sun light reflected by a surface or a cloud

alkalinity — the capacity of water to resist acidification and maintain a stable pH level

anaoxia — oxygen-free conditions in the environment or tissues of a body of an organism

anthropogenic — human derived, for example greenhouse gases from fossil fuel use

Atlantic Multidecadal Oscillation (AMO) — describes fluctuations in North Atlantic Sea surface temperature with a 50–90- year period

atmospheric blocking — occurs when persistent high-pressure systems disrupt the normal westerly flow over middle and high latitudes

atmospheric deposition — movement of matter (e.g., nutrients, pollution) from the atmosphere to the Earth’s surface

bioclastoplankton — single-celled planktonic algae, i.e., small organisms that lack a nucleus (Bacteria and Archaea), in the water column, mainly consuming organic carbon as energy and carbon source

benthic — related to the bottom of the sea including the top sediment layers

biota — plant and animal life in an area, habitat, or period

blue carbon (BC) — in marine sciences, organic carbon that is captured and stored by marine and coastal ecosystems (the abbreviation clashes with black carbon in atmospheric sciences)

blue carbon ecosystems — vegetation of coastal ecosystems that capture organic carbon

biogeochemical cycle — a set of processes by which a chemical element is transformed to different chemical substances through the biotic and abiotic parts of an ecosystem

biomass production — production of organic matter

browning — darker water due to more organic substances and iron in the water column

carbon flux — amount of carbon exchanged between carbon pools on Earth

carbon sink — accumulates carbon more than releases and thus lowers the atmospheric concentration of CO₂, for example the ocean

carbon source — releases more carbon than absorbs and thus increases the atmospheric concentration of CO₂, for example burning of fossil fuels

climate change — a change in average or invariance of conditions in the state of the climate over a long period of time, typically decades or longer, and can be caused by natural processes or external activities, such as changes in solar cycles, volcanic eruptions and changes in atmosphere and land use caused by humans

climatic change — the change in climate conditions in the state of the climate over a long period of time, typically decades or longer, and can be caused by natural processes or external activities, such as changes in solar cycles, volcanic eruptions and changes in atmosphere and land use caused by humans

classification method — a set of processes for the development of new species by mutation of the genome and natural selection

coastal ecosystems — external skeleton that protects an organism; acidification may impair marine organisms, such as mussels, that build their exoskeleton out of calcium carbonate

catastrophic flooding — a situation where sea levels rise very rapidly

catch — the development of new species by mutation of the genome and natural selection

clearing — a situation where sea levels rise very rapidly

coastal ecosystems — external skeleton that protects an organism; acidification may impair marine organisms, such as mussels, that build their exoskeleton out of calcium carbonate

catastrophic flooding — a situation where sea levels rise very rapidly

coastal ecosystems — external skeleton that protects an organism; acidification may impair marine organisms, such as mussels, that build their exoskeleton out of calcium carbonate

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catastrophic flooding — a situation where sea levels rise very rapidly
Policy linkages

Figure 3. Linkages between the different parameters that were used in the assessment of the effects of climate change in the Baltic Sea and major policies.
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Air temperature


Water temperature


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River run-off


Baltic sea model.


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