Climate Change in the Baltic Sea
2021 Fact Sheet

Climate change

BSEP n°180

In memory of Christian Dieterich

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Authors:
Markus Ahola, Lena Bergström, Mats Blomqvist, Dieter Boedeker, Florian Börgel, Ida Carlén, Thomas Carlund, Jacob Carstensen, Jesper Philip Aagaard Christensen, Martyn Futter, Elie Gaget, Oksana Glibko, Matthias Gröger, Volker Dierschke, Christian Dieterich, Morten Frederiksen, Anders Galatius, Bo Gustafsson, Claudia Frauen, Antti Halkka, Christina Halling, Jürgen Holfort, Magnus Huss, Kari Hyytiäinen, Klaus Jürgens, Mart Jüssi, Meri Kallasvuo, Markus Kankainen, Agnes ML Karlsson, Martin Karlsson, Anders Kiessling, Erik Kjellström, Antanas Kontautas, Dorte Krause-Jensen, Karol Kuliński, Sanna Kuningas, Jukka Käyhkö, Janika Laht, Ari Laine, Gesine Lange, Antti Lappalainen, Terhi Laurila, Maiju Lehtiniemi, Knut-Olof Lerche, Urmas Lips, Georg Martin, Michelle McCrackin, H.E. Markus Meier, Noora Mustamäki, Bärbel Müller-Karulis, Rahmat Naddafi, Lauri Niskanen, Antonia Nyström Sandman, Jens Olsson, Diego Pavón-Jordán, Jonas Pålsson, Mika Rantanen, Artūras Razinkovas-Baziukas, Gregor Rehder, Jan H. Reißmann, Martin Reutgård, Stuart Ross, Anna Rutgersson, Jarkko Saarinen, Lauri Saks, Oleg Savchuk, Mikhail Sofiev, Katarzyna Spich, Jani Särkkä, Markku Viitasalo, Jouni Vielma, Joonas Virtasalo, Isa Wallin, Ralf Weisse, Johan Wikner, Wenyan Zhang, Eduardo Zorita, Örjan Östman

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Editors: Jannica Haldin, Petra Kääriä, H.E. Markus Meier, Jonas Pålsson
Layout: Dominik Littfass

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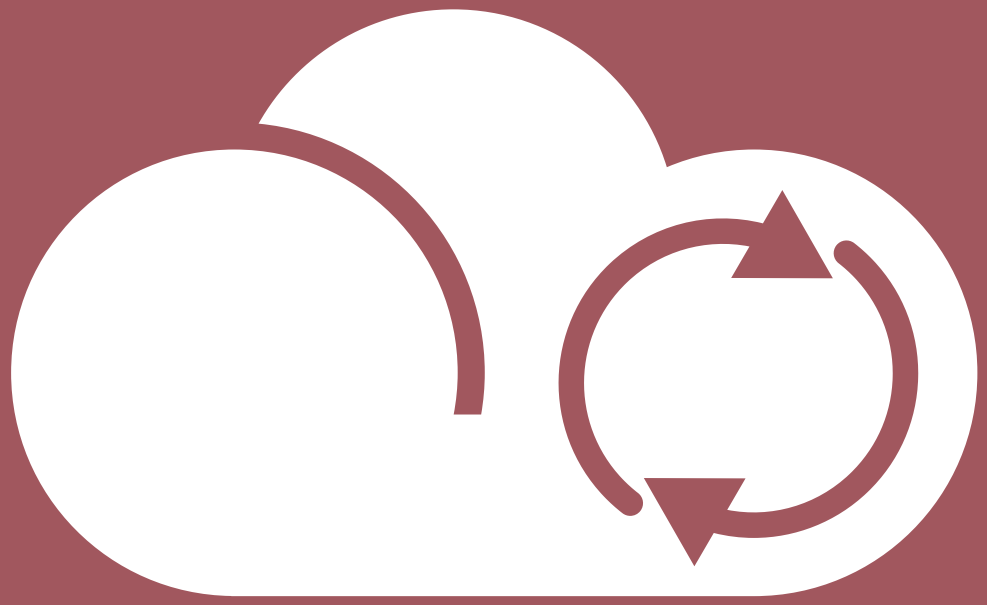
Contents



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 physiochemical 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).

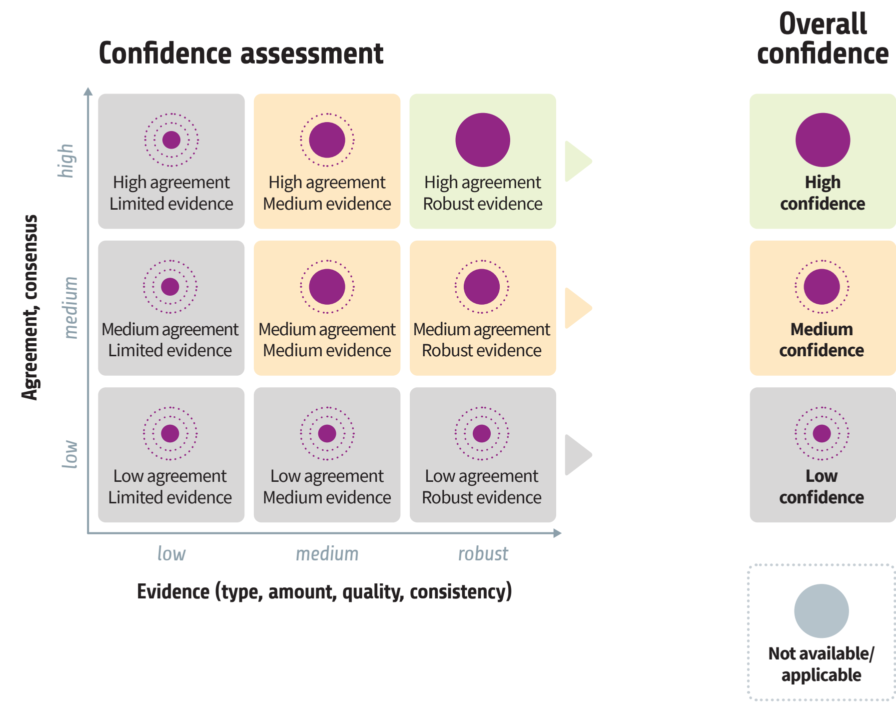


Figure 1. The overall confidence is resulting from the confidence assessment of the agreement/consensus on and evidence of the assessed data.

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.

Direct parameters	Categorization
Air temperature*	Energy cycle
Water temperature*	Energy cycle
Large scale atmospheric circulation	Energy cycle
Sea ice*	Energy cycle
Solar radiation	Energy cycle
Salinity and saltwater inflows*	Water cycle
Stratification	Water cycle
Precipitation*	Water cycle
River run-off*	Water cycle
Carbonate chemistry	Carbon and nutrient cycles
Riverine nutrient loads and atmospheric deposition	Carbon and nutrient cycles
Sea level*	Sea level and wind
Wind*	Sea level and wind
Waves*	Sea level and wind
Sediment transportation*	Sea level and wind

Indirect parameters	Categorization
Oxygen	Carbon and nutrient cycles
Microbial community and processes	Biota and ecosystems
Benthic habitats	Biota and ecosystems
Coastal and migratory fish	Biota and ecosystems
Pelagic and demersal fish	Biota and ecosystems
Waterbirds	Biota and ecosystems
Marine mammals	Biota and ecosystems
Non-indigenous species	Biota and ecosystems
Marine protected areas (MPAs)	Biota and ecosystems
Nutrient concentrations and eutrophication	Biota and ecosystems
Ecosystem function	Biota and ecosystems
Offshore wind farms	Human activities
Coastal protection	Human activities
Shipping	Human activities
Tourism	Human activities
Fisheries	Human activities
Aquaculture	Human activities
Blue carbon storage capacity	Services
Marine and coastal ecosystem services	Services

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)[1], 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 a 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)[2], the Special Report on the Ocean and Cryosphere in Changing Climate (2019)[3] 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[4]; BACC II Author Team, 2015[5]; see www.baltic.earth).

Climate Change in the Baltic Sea Fact Sheet 2021
Introduction

Connections between parameters

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

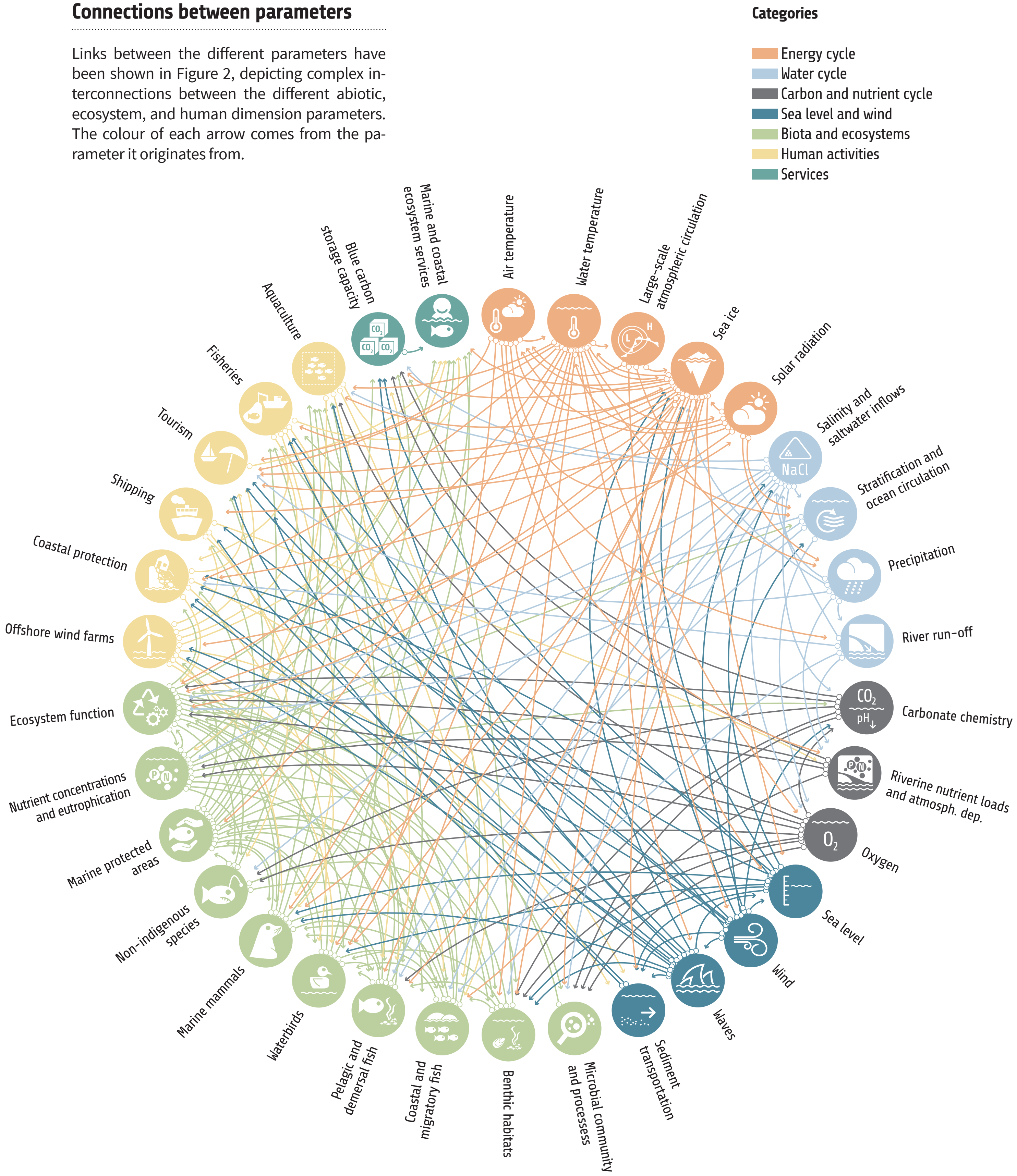
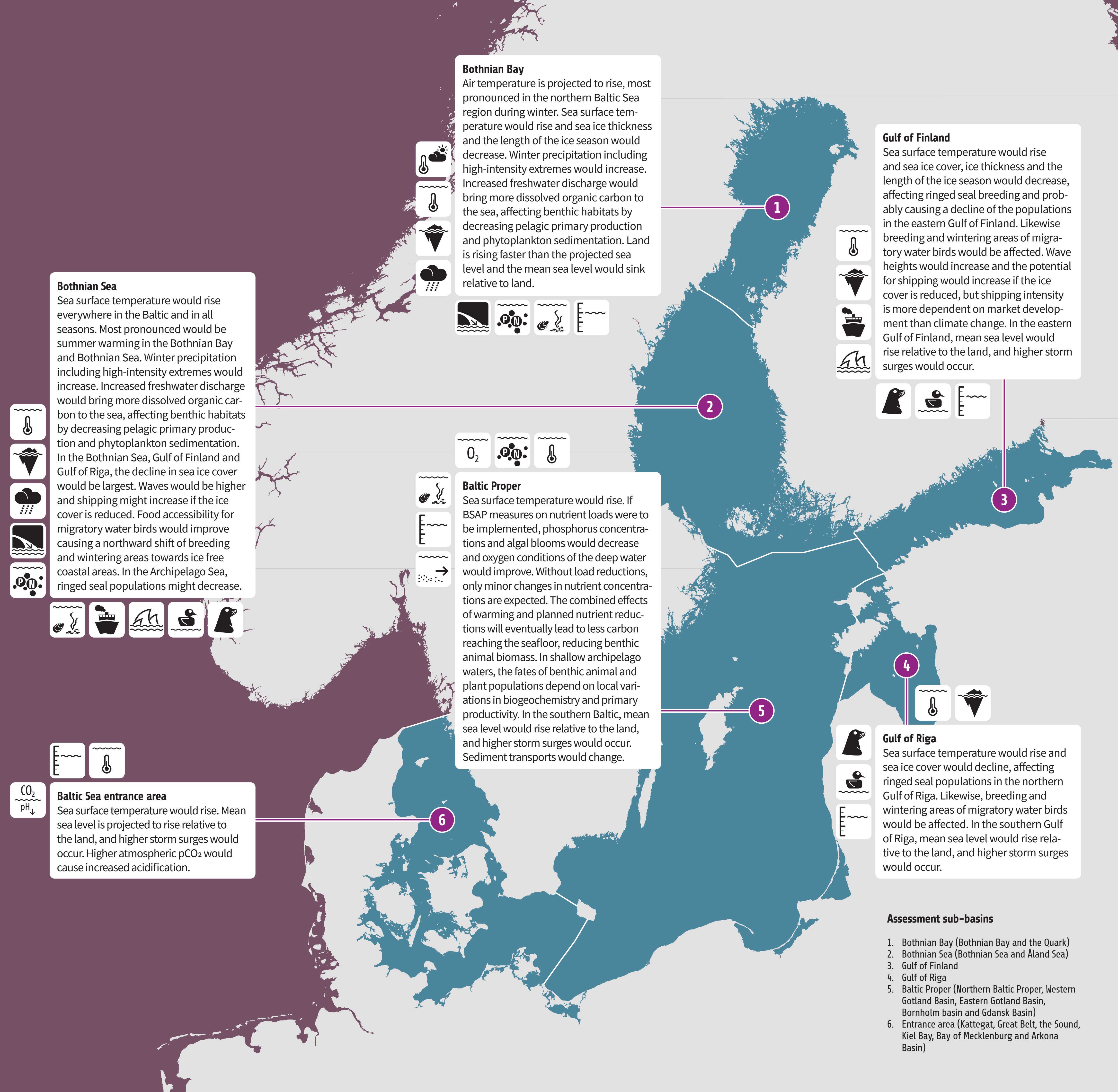


Figure 2. Linkages between the different parameters that were used in the assessment of the effects of climate change in the Baltic Sea.

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.



Direct parameters

Physiochemical parameters directly affected by climate change

Air temperature

Air temperature shows the clearest response to increased greenhouse gas emissions. A significant air temperature increase in the Baltic Sea region has been observed during the last century, larger than the global trend, and this increase is expected to continue. In addition, warm extremes are projected to become more pronounced.

Water 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.

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.

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.

River run-off

Runoff describes the amount flowing water entering the sea. The total annual river runoff has not changed over the last 500 years, but a significant increase in winter river discharge and a decrease in spring floods has been observed lately. The total runoff to the Baltic Sea may increase with warming temperatures.

Carbonate chemistry

The carbonate system regulates seawater pH. The amount of CO_2 in the Baltic Sea surface water changes seasonally mostly due to biologically driven processes (photosynthesis and respiration), which induces seawater pH oscillations. In the long term, atmospheric CO_2 increase will raise seawater CO_2 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.

Climate Change in the Baltic Sea Fact Sheet 2021
Direct parameters

Categories

- Energy cycle
- Water cycle
- Carbon and nutrient cycle
- Sea level and wind
- Biota and ecosystems
- Human activities
- Services

Solar radiation

The 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.

Precipitation

Precipitation depends on the circulation, 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.

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 coastlines of the Baltic Sea are especially vulnerable and rising sea level will increase sediment transport.

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 bacterioplankton 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.

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.

Categories

- Energy cycle
- Water cycle
- Carbon and nutrient cycle
- Sea level and wind
- Biota and ecosystems
- Human activities
- Services

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.

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.

Climate Change in the Baltic Sea Fact Sheet 2021
Indirect parameters

Categories

- Energy cycle
- Water cycle
- Carbon and nutrient cycle
- Sea level and wind
- Biota and ecosystems
- Human activities
- Services

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

Authors
Anna Rutgersson, Uppsala University, Sweden

Energy cycle

Air temperature

Linked parameters:
Water temperature, Large-scale atmospheric circulation, Sea ice, Solar radiation, River runoff, Riverine nutrient loads and atmospheric deposition, Waterbirds, Tourism

Links to main policies:
UN Sustainable Development Goal 13
EU Biodiversity Strategy

Description

Since air temperature shows the clearest response to the increased green-house effect, the near-surface mean air temperature is often used as the main indicator of a changing climate globally and regionally. Changes in temperature extremes may influence biological and human activities much more than changes in average 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[1-3]. Annual mean temperature trends during 1876–2018 indicate that air temperature has increased more in the Baltic Sea region than globally. The increase is accompanied by large multi-decadal variations, in particular during winter, but the warming is seen for all seasons and is largest during spring.

Extremes: During the recent decade, record breaking heat waves have hit the region, with an increasing trend of warm spell duration[4,5]. 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, RCP2.6) to 3.9°C (3.1-4.8°C, RCP8.5)* by the end this century[6], 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[2].

Extremes: Larger warming is expected for cold extremes than for the mean winter temperature[7]. In summer, warm extremes are projected 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[8].

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.

*) Changes in mean, 5th and 95th percentiles indicating the spread in an ensemble of 9 climate models.

Climate Change in the Baltic Sea Fact Sheet 2021
Direct parameters

Authors
Christian Dieterich, Swedish Meteorological and Hydrological Institute (SMHI), Sweden
H.E. Markus Meier, Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany, and Swedish Meteorological and Hydrological Institute (SMHI), Sweden

Energy cycle

Water temperature

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 13 and 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Maritime Spatial Planning Directive (MSP)
EU Habitats Directive
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Linked parameters:
Air temperature, Sea ice, Solar radiation, Stratification, Carbonate chemistry, Oxygen, Microbial community and processes, Benthic habitats, Coastal and migratory fish, Pelagic and demersal fish, Waterbirds, Non-indigenous species, Nutrient concentrations and eutrophication, Ecosystem function, Tourism, Aquaculture, Blue carbon storage capacity

Description

As air temperature increases, also water temperature rises[1]. 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.

What is already happening?

Mean change: Marginal seas around the globe have warmed faster than the global ocean[2], and the Baltic Sea has warmed the most of all marginal seas[2]. Average surface-water temperature increased by +0.59°C/decade for 1990-2018[3] and between +0.03 and +0.06°C/decade for 1856-2005 in northeastern and southwestern areas, respectively[4].

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 30 years in the southern half of the Baltic Sea[5], with surface-water temperatures 4-5°C above the 1990-2018 long-term mean. The heat wave has also been recorded in bottom temperatures[6].

What can be expected?

Mean change: Global ocean temperatures are rising at accelerating rates[7,8]. Scenario simulations for the Baltic Sea project a sea surface temperature increase of 1.1°C (0.8-1.6°C, RCP2.6) to 3.2°C (2.5-4.1°C, RCP8.5)* by the end of this century compared to 1976-2005[9-12]. In all scenarios, sea surface temperature changes at the end of the century significantly exceed natural variability.

Extremes: The RCP4.5 and RCP8.5 scenarios project more tropical nights over the Baltic Sea, increasing the risk of record-breaking water temperatures[13].

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 reduce 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[14,15]. These could become a last outpost for species affected by climate change.

*) Changes in mean, 5th and 95th percentiles indicating the spread in an ensemble of 9 climate models.

Large scale atmospheric circulation

Authors
Claudia Frauen, Leibniz Institute for Baltic Sea Research Warnemünde, (IOW), Germany
Anna Rutgersson, Uppsala University, Sweden
Florian Börgel, Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany
H.E. Markus Meier, Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany, and Swedish Meteorological and Hydrological Institute (SMHI), Sweden

Energy cycle

Linked parameters:
Air temperature, Solar radiation, Precipitation, Wind

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 13
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Green Deal
EU Biodiversity Strategy

Description

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 storminess[1-8].
2. Atmospheric blocking occurs when persistent high-pressure systems interrupt the normal westerly flow over middle and high latitudes[9,10].
3. The Atlantic Multidecadal Oscillation (AMO) describes fluctuations in North Atlantic sea surface temperature with a 50–90 year period[11-15] affecting the large-scale atmospheric circulation[15].

What is already happening?

The NAO has high interannual variability but shows no significant trend during the last century. After an increase from 1960 to 1990 (with more frequent wet and mild winters), the NAO index returned to lower values and after 1990 the blocking pattern shifted eastwards[16,17] and the duration increased, with more stationary circulation patters as a consequence[18]. However, there is low confidence in the changes concerning blocking patterns[19].

The AMO warmed from the late 1970s to 2014 as part of natural variability. Recently, the AMO began transitioning to a negative phase again[20]. Paleoclimate reconstructions and model simulations suggested that the AMO might change its dominant frequency over time[21,22]. However, the impact of the AMO on Northern European climate is independent of its frequency[14,15].

What can be expected?

In the future, the NAO is very likely to continue to exhibit large natural variations, 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 warming[19]. Trends in the intensity and persistence of blocking remain uncertain[23]. Even under weak global warming the AMO is expected to respond very sensitively, that is, a shortening of time scale and weakening in amplitude[24].

Knowledge gaps

While climate models are able to simulate the main features of the NAO, its future changes may be sensitive to boundary processes, like e.g. stratosphere-troposphere interactions or atmospheric response to Arctic sea ice decline, which are not yet well represented in many climate models[19]. Most global climate models still underestimate the frequency of blocking over the Europe-an-Atlantic sector[19].

Policy relevance

The impact of anthropogenic greenhouse gas emissions might change the large-scale 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.

Sea ice

Authors
Jürgen Holfort, Federal Maritime and Hydrographic Agency (BSH), Germany

Energy cycle

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 13 and 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Maritime Spatial Planning Directive (MSP)
EU Habitats Directive
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Linked parameters:
Air temperature, Water temperature, Solar radiation, Precipitation, Sea level, Wind, Waves, Sediment transportation, Microbial community and processes, Benthic habitats, Pelagic and demersal fish, Coastal and migratory fish, Waterbirds, Marine Mammals, Coastal protection, Offshore wind farms, Ecosystem function, Shipping, Tourism, Fisheries, Aquaculture, Blue carbon storage capacity, Marine and coastal ecosystem services

Description

In the northern regions of the Baltic Sea, ice is present every winter, while further south sea ice occurs only sporadically. As water effectively absorbs heat, whereas sea ice mostly reflects it, the influence of sea ice on the Baltic energy balance is high. A sea-ice cover also limits the atmosphere-ocean exchange and dampens surface waves. While air temperature has the largest influence on the formation and decay of sea ice, wind has a large influence on the spatial distribution and deformation (ridging, rafting).

What is already happening?

Mean change: During the last 100+ years, ice winters have become milder, the ice season shorter (-18 days at Kemi/Bothnian Bay and -41 days at Loviisa/Gulf of Finland)[1] and the maximum ice extent has decreased by about 30% (6,700 km^2 $decade^{-1}$). Indices based on the total winter ice volume show a decreasing trend in the period 1985-2015 (more than 10%/decade in many regions)[2].

Extremes: The maximum ice extent in the Baltic Sea, including Kattegat, varies from year to year between 40,000 and 420,000 km^2. The probability of severe ice winters has decreased, an extent larger than 300,000 km^2 occurred in 16% of the last 100 winters, compared to 3.3% of the last 30.[3]

What can be expected?

Mean change: In the future, it is very likely that the maximum sea-ice extent will decrease (by between 6,400 (RCP4.5) and 10,900 (RCP8.5) km^2 per decade)[4]. The thickness of level ice is also very likely to decrease, but there are still large uncertainties for the thickness of ridged ice[5]. The number of days with ice and length of the ice season are likely to decrease, but with considerable regional differences in the magnitude[6].

Extremes: Inter-annual ice variability is likely to continue to be large, but the probability of severe to very severe winters will likely decrease[5].

Knowledge gaps

Sea ice as a brittle material is not well represented in numerical climate models[7]. 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 sun light reflected/absorbed). There is only limited information about sea-ice thickness and ice categories and long data sets for these parameters are sparse.

Policy relevance

The importance of sea-ice change is higher 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.

Solar radiation

Authors
Anna Rutgersson, Uppsala University, Sweden
Thomas Carlund, Swedish Meteorological and Hydrological Institute (SMHI), Sweden

Energy cycle

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 2 and 14
EU Green Deal
EU Water Framework Directive (WFD)
EU National Emissions Ceilings Directive (NECD)
EU Common Agricultural Policy (CAP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Linked parameters:
Air temperature, Water temperature, Large-scale atmospheric circulation, Sea ice, Stratification, Precipitation, Ecosystem function, Tourism

Description

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.

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[1-3]. Aerosol-induced multidecadal variations in surface solar radiation could be expected also over oceans[4], 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[5]. 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[6]. Unknown future aerosol emissions add to the uncertainty.

Knowledge gaps

Multidecadal variations in surface solar radiation are generally not well captured by current climate model simulations[7,8]. The extent, to which the observed surface solar radiation variations are caused by natural variation in cloudiness induced by atmospheric dynamic variability[9,10], anthropogenic aerosol emissions[2,8,11,12] or perhaps other causes, is not well understood.

Policy relevance

Solar radiation influences biological activity and ecosystems, through effects on phytoplankton and algal blooms. Altered solar radiation would either increase or decrease biological activities (e.g., photosynthesis). Policy actions to reduce air pollution will impact solar radiation and thus climate change, as reduced air pollution increases the solar radiation reaching the surface. Reducing atmospheric aerosol particle concentrations is important to improve air quality and public health. Currently there is a lively debate related to geoengineering, including methods of increasing reflection of solar radiation back into space, to reduce its heating effect on a global scale.

Salinity and saltwater inflows

Authors
H.E. Markus Meier, Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany and Swedish Meteorological and Hydrological Institute (SMHI), Sweden
Jan H. Reißmann, Federal Maritime and Hydrographic Agency (BSH), Germany

Water cycle

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 14
UN Convention on Biological Diversity
EU Marine Strategy Framework Directive (MSFD)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Linked parameters:
Stratification, Precipitation, River runoff, Carbonate chemistry, Sea level, Wind, Oxygen, Microbial community and processes, Benthic habitats, Pelagic and demersal fish, Coastal and migratory fish, Non-indigenous species, Ecosystem function, Aquaculture, Blue carbon storage capacity

Description

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 gradates 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.

Large, meteorologically driven saltwater inflows, so-called Major Baltic Inflows (MBIs), sporadically renew the deep water with saline, oxygen rich water and this is the only process that effectively ventilates the deep water[1,2].

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[2-8]. Model results suggest that a decade of decreasing salinity, like the 1983-1992 stagnation, appears approximately once per century due to natural variability[9]. Baltic Sea salinity is also influenced by the Atlantic Multidecadal Oscillation with a 50–90-year period[10]. Since the 1980s, bottom salinity has increased, and surface salinity has decreased[11].

Extremes: The frequency of MBIs shows no statistically significant trend during instrumental (1886–2017) and paleoclimate periods[2,9].

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 imports 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} [12]. Due to the large uncertainty in projected 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[13-16].

Extremes: The frequency of MBIs is projected to slightly increase[17].

Knowledge gaps

Due to the large natural variability and uncertain changes in the regional water cycle, including precipitation over the Baltic Sea catchment area, in wind fields and in global sea level, the confidence in future salinity projections is low[14]. Modelling data show that the north-south gradient has changed with an increase in runoff in the North, and a decrease in the South[5]. Not much is known about changes in salinity composition and their large decadal variability. Changes in total salt import have not been adequately investigated. Changes in the large-scale circulation in the Baltic Sea are not well understood[18,19].

Policy relevance

Salinity and the ventilation of the deep water with oxygen that is associated with MBIs, are important drivers of the Baltic Sea ecosystem functioning and structure, including reproduction of commercially important marine fish species, such as cod[20,21]. The distribution of freshwater and marine species and the overall biodiversity depends strongly on salinity and oxygen concentrations[20]. Hence, the salinity dynamics is a major factor for the implementation of marine policies[21].

Stratification

Authors
Matthias Gröger, Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany
H.E. Markus Meier, Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany, and Swedish Meteorological and Hydrological Institute (SMHI), Sweden
Urmas Lips, Tallinn University of Technology, Estonia
Jan H. Reißmann, Federal Maritime and Hydrographic Agency (BSH), Germany

Water cycle

Linked parameters:
Water temperature, Solar radiation, Salinity and saltwater inflows, Wind, Oxygen, Pelagic and demersal fish, Nutrient concentrations and eutrophication, Ecosystem function

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 13 and 14
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Description

Stratification is determined by density gradients resulting from the temperature and salinity distributions in the sea. Stratification controls vertical and horizontal circulation and transport of water masses.

In the Baltic Sea, the strongest vertical density gradients correspond to the thermocline (maximum temperature gradient) and halocline (maximum salinity gradient). The thermocline develops at 10–20 m depth during the warm season, whereas a pronounced halocline persists over the year at 60-80 m in most deep regions. Wind stress working on the sea surface can potentially homogenize the water column fully in some shallow water regions or partly in deep water regions, thus influencing stratification.

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 salinity[1] or halocline depth[2] 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 gradients[3]. 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 stratification[4].

Furthermore, stratification increased in most of the Baltic Sea during 1982-2016, with the seasonal thermocline and the perennial halocline strengthening[5].

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 warming[3] whereas projections of salinity and related haline stratification changes are rather uncertain[6-8].

Knowledge gaps

The complex interplay between changes in temperature, wind and precipitation makes it difficult to project the impact 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. Sea surface temperature can be expected to follow air temperature, due to air-sea heat exchange, but the fate of salinity, and hence vertical salinity gradients, is uncertain. Due to the pronounced multidecadal variability in measured water temperature and salinity, projections of long-term trends based on past changes in climate cannot be made.

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[9]. 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[10].

Precipitation

Authors
Jukka Käyhkö, University of Turku, Finland
Erik Kjellström, Swedish Meteorological and Hydrological Institute (SMHI), Sweden

Water cycle

Linked parameters:
Large-scale atmospheric circulation, Sea ice, Solar radiation, Salinity and saltwater inflows, River run-off, Riverine nutrient loads and atmospheric deposition, Tourism

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 13
EU Maritime Spatial Planning Directive (MSP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Description

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 region[1,2]. 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.

What is already happening?

Mean change: During the 20th century, precipitation was subject to large variations[3], which increases the difficulty in determining statistically significant trends or regime shifts. Generally, precipitation increases in winter. Sweden shows an overall wetting trend in particular since the 1950s[4]. In Finland, the overall increase detected for 1961-2010 is neither regionally consistent nor always statistically significant[5]. The same holds for the Baltic countries[6].

Extremes: Daily amounts of precipitation extremes typically range from 8 to 20 mm, being more numerous in summer[7]. Extreme precipitation intensity has been rising in the period 1960-2018. The maximum annual five consecutive days precipitation index (Rx5d) has shown a significant increase of up to 5 mm per decade over the eastern Baltic Sea catchment[8]. The change has been most pronounced in winter.

What can be expected?

Mean change: Average precipitation amounts are expected to increase in the future. The relative increase will be largest in winter in the North. Most simulations show increasing summer precipitation for the northern parts, while for the intermediate and southern parts of the region, the direction of change is uncertain[9].

Extremes: Warming increases the potential for extreme precipitation due to intensification of the hydrological cycle associated with growth of atmospheric moisture content. Regional climate models indicate an overall rise in the frequency and volume of heavy precipitations in all seasons. The projected increases in northern Europe might be significant throughout all the seasons from 2050 onwards[9,10]. Autumn is projected to see the largest increase of high precipitation days. The number of drought events per year may decrease, while their length may increase[9].

Knowledge gaps

Different methods and data sets used in national studies in the region imply that the knowledge of the precipitation climate is not fully coherent.

Compared to traditional "high-resolution" models, the recent very high-resolution climate model projections, at 1-3 km resolution, have proven to show better agreement with observations in representing precipitation extremes, and sometimes also larger climate change signals, but these are yet to be built for the Baltic Sea region.

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.

Authors
Jukka Käyhkö, University of Turku, Finland

Water cycle

River run-off

Linked parameters:
Air temperature, Salinity and saltwater inflows, Precipitation, Riverine nutrient loads and atmospheric deposition, Benthic habitats, Coastal and migratory fish, Coastal protection

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 13
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Floods directive
EU Biodiversity Strategy

Description

Runoff describes the amount of flowing water, typically given in litres per second per square kilometre ($l\ s^{-1}\ km^{-2}$) to allow comparisons between differently sized rivers. Runoff can also be given in millimeters per year ($mm\ a^{-1}$), allowing comparisons with precipitation and evaporation. Discharge refers to channel flow, typically given as cubic metres per second ($m^3\ s^{-1}$). Floods are extreme run-off events of water submerging usually dry land. In the Baltic Sea region, floods typically occur in the spring-time snow-melt period, or in connection to heavy/long-lasting rain. Floods are closely linked to precipitation, temperature (melting, evaporation), wind, and catchment properties (land use, topography).

What is already happening?

Mean change: No statistically significant change in total annual river runoff has been detected during the last centuries[1,2]. Large decadal and regional variations occur[3]. In the northern Baltic Sea and the Gulf of Finland, larger river runoff is statistically associated with warmer air temperature and increased precipitation, while further south, decreased annual runoff is associated with rising air temperatures[1]. Over the 20th century, winter discharge has increased, while spring floods have decreased[4].

Extremes: According to an example from Sweden, there is no significant trend in daily high flow over the past 100 years[5].

What can be expected?

Mean change: The total runoff to the Baltic Sea has been projected to increase from present day by 2-22% with warming temperatures[6,7]. The increase will take place mostly in the North[3,6,8], with potentially decreasing total runoff in the South[9]. Winter runoff will increase due to intermittent melting[8].

Extremes: Floods are projected to decrease in the North, due to repeated melting and thinner snowpack, but increase south of 60°N due to higher precipitation[10,11]. Large spring floods will decrease by up to 20%[10].

Knowledge gaps

The impacts of observed precipitation changes on stream flow are unclear[12]. 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[7]. Several uncertainties are associated with the impact modelling, including parameter calibration against historical data and model structure uncertainty.

Policy relevance

Seasonal runoff changes will affect sediment and nutrient loads and thereby eutrophication of the Baltic Sea. Changes in the timing of floods will influence risks for riverside settlements. The HELCOM Baltic Sea Action Plan requires nutrient load reduction from the signatory countries. However, plans by EU Member States lack ambition in nutrient reduction implementation[13]. Flood hazard mitigation requires both short-term (rescue) and long-term (planning and construction) measures. Directive 2007/60/EC on the assessment and management of flood risks requires adequate and coordinated measures to reduce flood risk. As new projections continuously become available, climate change is important to include in river runoff and flood policies.

Authors
Karol Kuliński,Institute of Oceanology Polish Academy of Sciences, Poland
Gregor Rehder, Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany
Anna Rutgersson, Uppsala University, Sweden

Carbon and nutrient cycle

Carbonate chemistry

Linked parameters:
Water temperature, Salinity and saltwater inflows, Riverine nutrient loads and atmospheric deposition, Wind, Waves, Microbial community and processes, Benthic habitats, Non-indigenous species, Nutrient concentrations and eutrophication, Ecosystem function, Blue carbon storage capacity

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 12 and 14
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Common Agricultural Policy (CAP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Description

The carbonate system (CO_2 system) characterized by the thermodynamic equilibria between hydrogen ions (reported as pH) and the different CO_2 species (CO_2, H_2CO_3, HCO_3^-, CO_3^{2-})[1,2] is the main determinant of the acid/base balance in seawater and of seawater pH.

Ocean acidification is the decrease of seawater pH, mainly due to the rising CO_2 concentration in the atmosphere and its exchange with the surface seawater[2].

The exchange of CO_2 between the water and the atmosphere is controlled by the air–sea surface difference in partial pressure of CO_2 (pCO_2) and the efficiency of the transfer processes, with wind speed being the dominating parameter[3-5].

What is already happening?

Intra-annual variation of pCO_2 in the Baltic Sea surface waters is controlled by biological processes (organic matter production and remineralization) and by changes in the mixed layer depth and the sea surface temperature[1,2,6]. Eutrophication has enhanced both production and remineralization of organic matter and thus increased the amplitude of seasonal changes in pCO_2 and pH[7,8]. The Baltic Sea is a CO_2 sink in summer and a source in winter[1,6]. However, the annual net CO_2 flux is unknown. The increase in total alkalinity (a measure of the buffer capacity) entirely mitigates ocean acidification in the Gulf of Bothnia and significantly reduces it (to about -0.0012 $year^{-1}$) in the central Baltic Sea[9].

What can be expected?

Future changes in atmospheric pCO_2 and total alkalinity will influence seawater pCO_2 and therefore pH[2,4,7-10]. The projected runoff increase to the northern Baltic Sea may lower alkalinity and pH, due to decreased salinity[7]. However, higher atmospheric pCO_2 will enhance weathering on land and release alkalinity from the catchment, while eutrophication may increase internal alkalinity generation, leaving the net effect unknown[7,8]. Even if alkalinity in the Baltic Sea should increase, a doubling of atmospheric pCO_2 will still result in lower pH[7].

Knowledge gaps

Due to the high spatial and temporal variability in seawater pCO_2, it is currently unclear whether the Baltic Sea as a whole is a net sink of CO_2 or a net source[1,2,6].

Since the origin of the currently observed alkalinity increase in the Baltic Sea is unclear, it is uncertain whether this increase will continue as strongly in the future[9].

The ecosystem productivity in the period after the spring bloom (from mid-April until mid-June) is not quantitatively understood, due to an observed continuation of pCO_2 decrease even after the surface nitrate pool is depleted[1,2].

Policy relevance

The rising atmospheric CO_2 concentration is one of the main drivers shaping the structure of the marine CO_2 system and the dominant cause of ocean acidification, which may influence marine organisms, especially those building their exoskeletons out of calcium carbonate[1,2,9]. The implementation of the Baltic Sea Action Plan resulting in comparatively low nutrient loads and favourable oxygen conditions may minimize wintertime pH reduction[7].

Riverine nutrient loads and atmospheric deposition

Authors
Oleg Savchuk, Baltic Sea Centre, Stockholm University, Sweden
Michelle McCrackin, Baltic Sea Centre, Stockholm University, Sweden
Mikhail Sofiev, Finnish Meteorological Institute (FMI), Finland

Carbon and nutrient cycle

Linked parameters:
Air temperature, Precipitation, River run-off, Carbonate chemistry, Microbial community and processes, Nutrient concentrations and eutrophication, Ecosystem function, Shipping

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 2 and 14
EU Green Deal
EU Water Framework Directive (WFD)
EU National Emissions Ceilings Directive (NECD)
EU Common Agricultural Policy (CAP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Description

External nutrient inputs from land and atmosphere are the major long-term drivers of Baltic Sea eutrophication[1,2]. Land loads and atmospheric deposition are determined by both natural (precipitation, river runoff, temperature) and anthropogenic (demographic, agricultural, and industrial development, wastewater treatment, international shipping) factors. These factors change both over time (changes of seasonality, long-term trends, and lags due to the watershed processes) and space (north-south gradients in climate and land use, east-west gradients in socio-economic features and climate)[3]. Atmospheric deposition is additionally determined by long-range transport from Central, Western and Eastern Europe and, for the Gulf of Finland, from Russia[4,5].

What is already happening?

Substantial reductions of riverine nutrient loads have been achieved since the 1980s[6-9]. Since there are no statistically significant trends in annual river discharges[10], these reductions are attributed to socio-economic development, including protective measures, rather than to climate-related effects[8,11]. The total nitrogen deposition to the Baltic Sea has also been substantially decreasing since the 1980s, due to overall reduction of European emissions[12]. However, the reduction of nitrogen emission and deposition has slowed down since the beginning of the 21st century[13,14]. Atmospheric phosphorus deposition amounts and trends remain highly uncertain[4,15,16].

What can be expected?

Projections suggest that river discharge will increase in the northern Baltic Sea region, while the discharge will decrease in the southern region[10], thus potentially increasing and decreasing waterborne nutrient inputs, respectively. Leaking of excessive phosphorus, accumulated in agricultural soils, will delay the effects of mitigation measures[17]. Simulations with a range of scenarios suggest that land-based nutrient management will have greater effect on nutrient loads than greenhouse gas emissions[18-22]. Atmospheric deposition can be affected by changes in emissions[5,23], for example by increased ammonia evaporation due to rising temperature[24,25].

Knowledge gaps

Besides common uncertainties inherent to regionalization of climate scenarios for precipitation and river runoff[10], an important source of uncertainty is poor quantitative knowledge on long-term response of terrestrial biogeochemical processes, particularly changes in the soil nutrient pools, to the climate changes[26]. Phosphorus sources and transports[4,16,17] as well as ammonia emission and its dynamics[12,24,25] are among the least known processes controlling the atmospheric nutrient deposition. How the anthropogenic drivers of land loads (land use, agricultural practices, wastewater treatment, net anthropogenic nutrient inputs, etc.) will change in response to both climate change and socio-economic development is highly uncertain[27].

Policy relevance

Reduction of nutrient inputs is considered the most important measure for mitigating Baltic Sea eutrophication, both in coastal and offshore waters[11]. 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 (NH_3) emissions, which unlike the nitrogen oxide (NOx) emissions have been largely disregarded, will require large reduction efforts and policy and public support[25].

Sea level

Authors
Christian Dieterich, Swedish Meteorological and Hydrological Institute (SMHI), Sweden
Jürgen Holfort, Federal Maritime and Hydrographic Agency (BSH), Germany
H.E. Markus Meier, Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany, and Swedish Meteorological and Hydrological Institute (SMHI), Sweden
Jani Särkkä, Finnish Meteorological Institute (FMI), Finland
Ralf Weisse, Helmholtz Center for Material and Coastal Research (HZG), Germany
Eduardo Zorita, Helmholtz Center for Material and Coastal Research, (HZG), Germany

Sea level and wind

Linked parameters:
Sea ice, Salinity and saltwater inflows, Wind, Waves, Sediment transportation, Benthic habitats, Waterbirds, Marine mammals, Coastal protection, Tourism, Fisheries, Blue carbon storage capacity

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 13
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Description

The relative sea level in the Baltic Sea rises when melt water is added to the global ocean, when the water expands by warming, or the land sinks[1]. The Baltic Sea level varies between years and seasons[2] and is generally highest in winter[3], especially in mild winters with above average winds[4,5]. Periods of strong westerlies temporarily fill the Baltic Sea with extra water from the North Sea[6]. Increased mean sea level leads to higher storm surges. Storms trigger sea level oscillations[7,8] across the Baltic Sea, meteotsunamis[9,10] (sea level extremes travelling in phase with atmospheric low pressure systems), and wave set-up where breaking waves increase the sea level locally by up to half a metre[11].

What is already happening?

Mean change: Global mean sea level rose 1-2 mm yr^{-1} during the 20th century[12-14]. Presently, rates of 3-4 mm yr^{-1} are estimated over shorter periods[12-15]. For instance in Stockholm, absolute sea level rose by about 20 cm from 1886 to 2009[16]. Land uplift in the northern Baltic is still faster than absolute sea level rise so that, relative to land, sea level there is still falling[14,17-19].

Extremes: Storm surges are a threat to low-lying Baltic Sea coastlines[9,20,21]. No long-term increasing trend has been found for the 20th century for extreme sea levels in the Baltic Sea relative to mean changes[14,22,23].

What can be expected?

Mean change: Global sea level rise will accelerate[12,13,24]. Current projections estimate Baltic sea level rise to about 87% of the global rate[25,26]. Estimates for global mean sea level rise by 2100 are 43 cm (RCP2.6) to 84 cm (RCP8.5)[13]. The likely ranges for these estimates are 29 to 56 cm (RCP2.6) and 61 to 110 cm (RCP8.5)[13].

Extremes: How extremes will change is uncertain, as they depend on the path of future low pressure systems[6,27]. In the southern Baltic Sea, extremes that are rare today will become more common due to mean sea level rise[28,29].

Knowledge gaps

Research is needed on natural variability in drivers of storm surges in the Baltic Sea[21,30-32]. How much the Baltic sea level rises compared to the global mean[25] includes large uncertainties from Antarctic ice sheet melting and climate change in the Atlantic Ocean and the Baltic Sea. Sea level will rise proportionally more on the shallow shelf regions around the continents than in the deeper, open ocean[33], but the extent of this effect has not been evaluated for the Baltic Sea. Storm surges and other hazards can turn into disasters if they coincide[34]. Little is known about the interaction of storm surges and other extreme events.

Policy relevance

Mean sea level rise and extreme events are of great importance, for example for urban planning and commercial ports, and a challenge for flood protection. Ports can adapt to mean sea level rise by building higher quays or relocating. Shipping lanes may need to be dredged less, and ships with a deeper draught can come to port. Coastal flooding can be prevented by protective structures, such as the St Petersburg Flood Prevention Facility Complex, the Stockholm Slussen (Sluice) project, and levees along the German and Polish coasts.

Wind

Authors
Mika Rantanen and Terhi Laurila, Finnish Meteorological Institute (FMI), Finland
Erik Kjellström, Swedish Meteorological and Hydrological Institute (SMHI), Sweden
Anna Rutgersson, Uppsala University, Sweden

Sea level and wind

Linked parameters:
Large-scale atmospheric circulation, Sea ice, Salinity and saltwater inflows, Stratification, Carbonate chemistry, Sea level, Waves, Sediment transportation, Coastal protection, Offshore wind farms, Shipping, Tourism, Fisheries

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Convention on Biological Diversity
EU Green Deal
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity strategy

Description

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.

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[1,2]. For example, mean wind speeds at the Finnish and Swedish coastlines show a slightly negative trend since the 1950s[3,4].

Extremes: Maximum wind speeds at the Finnish coastline show a weakening trend[4], attributed to storm tracks shifting northwards[5,6]. Many studies show contradicting storminess trends in the Baltic region[1].

What can be expected?

Mean change: Projected changes in wind climate are highly uncertain due to large natural variability in the Baltic Sea area[7]. Climate model simulations project a slight but significant wind speed increase in autumn and a decrease in spring[8]. Some studies mention increased future wind speeds in areas no longer covered by sea ice[7,9,10].

Extremes: Projected changes in extreme winds are uncertain due to differences in atmospheric circulation among climate model projections[9]. It is projected that by 2100, severe wind gusts associated with thunderstorms can increase in frequency during summer[11].

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.

Waves

Authors
Ralf Weisse, Helmholtz-Zentrum Geesthacht(HZG), Germany
Christian Dieterich, Swedish Meteorological Institute (SMHI), Sweden

Sea level and wind

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 13
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Maritime Spatial Planning Directive (MSP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Habitats Directive
EU Biodiversity Strategy

Linked parameters:
Sea ice, Sea level, Wind, Sediment transportation, Benthic habitats, Marine mammals, Coastal protection, Offshore wind farms, Shipping, Tourism, Fisheries, Aquaculture, Blue carbon storage capacity

Description

Wind waves are generated by the action of wind on the sea surface. In the Baltic Sea, the highest waves typically occur during long-lasting storms with high wind speeds and long fetch (the distance over which the wind blows).

The wave climate is characterized by parameters such as significant wave height, period, and mean direction. The Baltic Sea wave climate has a pronounced seasonal cycle with higher waves in winter. Breaking waves can substantially increase coastal sea level (wave set-up). Waves are the major driver of nearshore sediment transport. High storm waves are the primary determinants of the extent of erosion.

What is already happening?

Mean change: There are no significant long-term trends in wind speed and direction but considerable decadal variability[1]. Correspondingly, there are no clear indications of long-term trends in wave height[2].

Extremes: From a long-term perspective, no robust signals of changes in Baltic wave climate can be detected[2].

What can be expected?

Mean change: Changes in Baltic Sea wave climate are strongly linked to changes in wind climate and are highly uncertain[3-5].

There is high confidence on reduced ice cover which may increase fetch, and perhaps change the wave climate[6].

By 2100, changes in significant wave height are projected to be around 5% higher than today, in particular in the north and east of the Baltic Sea[5]. However, such changes are superimposed by substantial multi-decadal and inter-simulation variability and are not conclusive because only one climate model was considered[5].

Extremes: Changes in extreme wave heights result from changes in high wind speeds, which are highly uncertain[1].

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 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

Authors
Wenyan Zhang, Helmholtz-Zentrum Geesthacht (HZG), Germany
Joonas Virtasalo, Geological Survey of Finland, Finland

Sea level and wind

Linked parameters:
Sea ice, Sea level, Wind, Waves, Coastal protection, Tourism

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 13
EU Maritime Spatial Planning Directive (MSP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

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[1]. Dominance of mobile sediments makes the southern and eastern coasts vulnerable to wind-wave induced transport[2]. 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[3]. 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[5,9]. Man-made engineering structures add to the uncertainty in the prediction of sediment transport and coastal erosion patterns[10].

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

Oxygen

Authors
H.E. Markus Meier, Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany and Swedish Meteorological and Hydrological Institute (SMHI), Sweden
Jacob Carstensen, Arhus University, Denmark
Oleg Savchuk, Stockholm University, Baltic Nest Institute, Sweden

Carbon and nutrient cycle

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 2 and 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Habitats Directive
EU Common Agricultural Policy (CAP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Linked parameters:
Water temperature, Salinity and saltwater inflows, Stratification, Microbial community and processes, Benthic habitats, Pelagic and demersal fish, Non-indigenous species, Nutrient concentrations and eutrophication, Ecosystem function, Aquaculture

Description

Dissolved oxygen concentration in the water column is controlled by physical transport (air-sea exchange, advection, and diffusion), water temperature and biological processes such as photosynthesis and demand for oxidation of organic matter and sulfide[1]. Deoxygenation and hypoxia occur where the oxygen demand due to elevated concentrations of organic matter concentration in water and sediment cannot be compensated by ventilation[1-10]. Hypoxic area is defined as the extent of bottom water with oxygen concentrations below a threshold, commonly set at 2 mL O_2 L^{-1} [1]. Hypoxia is characterized by a scarcity of multicellular life[1].

What is already happening?

Despite decreasing nutrient loads after the 1980s[5], recently calculated oxygen consumption rates are higher than earlier observed, counteracting the effect of natural ventilation of deep water[6]. Improved oxygen conditions have been observed in some coastal waters, where inputs of nutrients and organic matter have been abated[11]. However, hypoxia remains common in other coastal areas, with unaltered or even worsening conditions[4,6]. 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[3].

What can be expected?

Projected warming may enhance 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[12-16]. However, the future development of deep-water oxygen conditions 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[15]. 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[12,13,15,16].

Other drivers

Model simulations suggest that elevated historical riverine nutrient loads and atmospheric nutrient deposition since the 1950s have been the most important drivers of oxygen depletion in the Baltic Sea[3,5,7]. The impacts of other drivers such as the observed warming or eustatic sea level rise were comparatively smaller but still made a significant contribution to, e.g., the size of hypoxic area[3,7]. There are no statistically significant trends in stratification and saltwater inflows on centennial timescales since 1850. Thus, variations in oxygen transports have caused interannual to decadal variability in oxygen concentrations of the Baltic Sea deep water but could not explain the long-term trend[3,7].

Knowledge gaps

A recent assessment suggests that, in addition to internal variability, the biggest uncertainties in projections of biogeochemical cycles are caused (not listed in order of importance) by (i) poorly known current and future bioavailable nutrient loads from land and atmosphere (see also [17]), (ii) differences between the projections of global and regional climate models, in particular, with respect to the global mean sea level rise, wind and regional water cycle, (iii) differing model-specific responses of the simulated biogeochemical cycles to long-term changes in external nutrient loads and climate of the Baltic Sea region, (iv) poorly known long-term pathways of future greenhouse gas emissions[10,11], and (v) poorly known sediment properties regarding oxygen demand and nutrient release.

Policy relevance

Oxygen conditions are indispensable prerequisites for the marine ecosystem and are closely related to nutrients. Although nutrient loads have been reduced since the 1980s[5], the targets for the maximum allowable inputs have not yet been completely achieved[12]. In addition, the system's response to changes in nutrient loads is slow, currently preventing the Baltic Sea from attaining good eutrophication status. As global warming will worsen oxygen conditions, full implementation of the load reductions of the Baltic Sea Action Plan (BSAP) is needed. Scenario simulations suggest that this will result in successful, albeit slow, mitigation[15,16]. The results of ongoing scenario simulations have high relevance for the BSAP.

Microbial community and processes

Authors
Klaus Jürgens, Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany
Johan Wikner, Umeå University, Sweden

Biota and ecosystems

Links to main policies:
UN Sustainable Development Goals 2 and 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Common Agricultural Policy (CAP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Bathing water directive
HELCOM Baltic Sea Action Plan
EU Biodiversity Strategy

Linked parameters:
Water temperature, Sea ice, Salinity and saltwater inflows, Carbonate chemistry, Riverine nutrient loads and atmospheric deposition, Oxygen, Nutrient concentrations and eutrophication, Ecosystem function

Description

This overview focuses on bacterioplankton, comprising single-celled prokaryotes, i.e., small organisms that lack a nucleus (Bacteria and Archaea), in the water column, consuming organic carbon as an energy and carbon source. Benthic prokaryotes and protozoa (i.e., unicellular zooplankton and zoobenthos) are also important but not included here. Bacteria are the major transformers of carbon, nitrogen, sulphur, and trace metal cycles in aquatic environments. The supply of organic carbon mainly controls bacterial biomass production. The bacterial community composition changes along the salinity and oxygen gradients of the Baltic Sea[1]. Shifts in, e.g., food sources, temperature, and oxygen concentration result in rapid bacterioplankton community changes[2,3], with potential impact also on overall ecosystem functions, such as respiration, carbon consumption, and biomass production.

What is already happening?

Long time-series of marine bacteria are rare in the Baltic Sea, with mostly no or weak trends. In the southern Baltic Proper, bacterioplankton biomass declined by 3.6% per year and community growth by 0.8% per year between 1988 and 2007, mainly attributed to improved water management and changes in temperature and salinity[4]. Bacterial biomass and growth in the Gulf of Bothnia showed no or only weak trends in 1999-2014[5]; also in deeper water layers[6]. Surface water warming enhanced the risk of infection with human-pathogenic Vibrio spp. and increased Vibrio-suitable areas in the Baltic Sea[7].

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, CO_2-production, and oxygen consumption in the Baltic Sea[8,9]. Counteracting this, increased riverine dissolved organic carbon (DOC) discharge due to precipitation will hamper light and thereby algal productivity, while maintaining bacterial production[10]. 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[7].

Other drivers

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[11]. Environmental toxins and pharmaceuticals may also influence bacterioplankton, either by being food for bacterioplankton[12] or by hampering bacterial growth.

Knowledge gaps

Lack of long time-series of bacterial growth, abundance, and composition make the projection of long-term effects uncertain. Few biogeochemical models coupled to meteorology include microbial activity properly, making net outcomes of large-scale and long-term effects difficult to foresee. Rapid bacterial adaptation to altered conditions, occurring on both population and genetic levels, is often associated with evolutionary changes in functions, adding uncertainty. International harmonization of methodology in microbial ecology is further of importance for building reliable knowledge.

Policy relevance

Microbial mechanisms are fundamental for the carbon balance, oxygen status and CO_2 production, and crucial in understanding the effects of climate change and biogeochemical cycles in general. Efforts to reduce greenhouse gas emissions, stop clearing of forests, and re-forest agricultural land are ongoing, but insufficient. Monitoring of bathing water quality is ongoing but needs improvement. Global actions assessed to be a long-term remedy, for example binding CO_2 by fertilizing algae, would likely lead to adverse effects on Baltic Sea oxygen status. Since no means of direct human control of microbial abundance and activity is currently available, the microbial community is not managed through any policies.

Benthic habitats

Authors
Antonia Nyström Sandman, Aquabiota Water Research, Sweden
Markku Viitasalo, Finnish Environment Institute, Finland
Jesper Philip Aagaard Christensen, Århus University, Denmark
Mats Blomqvist, Hafok AB, Sweden
Christina Halling, Swedish University of Agricultural Sciences, Sweden
Ari Laine, Parks and Wildlife Finland, Finland
Georg Martin, University of Tartu, Estonia

Biota and ecosystems

Links to main policies:
HELCOM Baltic Sea Action Plan
EU Water Framework Directive (WFD)
EU Habitats Directive (HD)
EU Birds Directive (BD)
EU Biodiversity Strategy
UN Convention on Biological Diversity (CBD)
UN Sustainable Development Goals (SDGs)
EU Marine Strategy Framework Directive (MSFD)

Linked parameters:
Water temperature, Sea ice, Salinity and saltwater inflows, River run off, Carbonate chemistry, Sea level, Waves, Oxygen, Pelagic and demersal fish, Coastal and migratory fish, Waterbirds, Non-indigenous species, Marine protected areas, Nutrient concentrations and eutrophication, Ecosystem function, Blue carbon storage capacity

Description

Benthic habitats in the Baltic Sea are characterized by a mixture of species of marine and freshwater origin[1]. 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 loss of biodiversity and ecosystem functions as a result[2].

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[3], Baltic clam *Limecola balthica* increasing, and the non-indigenous polychaete *Marenzelleria* becoming dominant[4]. 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[4,5]. 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[6] and increase in the coastal zone[7], causing loss of communities and ecosystem functions[8-11].

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., bladderwrack, blue mussel and eelgrass[12-20]. Increasing temperature affects species turnover rates and physiology[12,21-24]. In coastal ecosystems, increased precipitation and runoff might cause salinity fluctuations[25], affecting species reproduction and survival[26]. Sea-level rise[27] will change prerequisites for important environments like shallow coastal habitats. In the presently oxic areas, macrozoobenthos productivity will decrease if oxygen conditions deteriorate[28,29]. In areas with increasing riverine load of dissolved organic carbon (DOC), pelagic primary production may decrease, affecting the benthic system[21,25].

Other drivers

Eutrophication has a major impact on the benthic ecosystem, mainly through enhanced primary production causing increased water turbidity and decreasing bottom-water oxygen[30]. Nutrient input is likely to increase with increasing precipitation, especially in the northern Baltic Sea[31], and in combination with impacts of increasing temperature, changes can be anticipated in all trophic levels. However, success of nutrient load reductions may have a larger effect on the benthic ecosystem than climate change alone[28,32]. Also, introductions of non-indigenous species can cause changes in marine biodiversity[33] and ecosystem functions[34-36]. Reduction of predatory fish might affect functionality of benthic habitats through trophic cascades[37-40].

Knowledge gaps

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[41,42]. 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[21,43]. 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 keystone species bladderwrack has in some studies been shown to adapt to climate change[44-46], while others have suggested that the species cannot keep pace with the projected salinity change, with large effects on biodiversity and ecosystem functioning[19,36].

Policy relevance

The Marine Strategy Framework Directive requires assessing the status of benthic habitats[46,47], and the cumulative effects of climate change and other pressures, such as eutrophication, on biodiversity and ecosystem functions should be considered. According to the Habitats Directive, the extent of adverse effects cannot exceed a certain proportion of the habitats, and member states shall establish a coherent network of Natura 2000 areas to secure ecosystem structure and function[49]. If climate change causes community changes, conservation targets need to be updated and the network of MPAs should be adapted to take projected changes into account[50]. Also, climate change needs to be incorporated in marine spatial planning, at appropriate spatial and temporal scales[51].

Coastal and migratory fish

Authors
Örjan Östman, Jens Olsson, Noora Mustamäki and Rahmat Naddafi, Swedish University of Agricultural Sciences (SLU), Sweden
Meri Kallasvuo, Sanna Kuningas and Antti Lappalainen, Natural Resources Institute Finland (Luke), Finland
Lauri Saks, University of Tartu, Estonia

Biota and ecosystems

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Habitats Directive
EU Common Fisheries Policy (CFP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Linked parameters:
Water temperature, Sea ice, Salinity and saltwater inflows, River run-off, Benthic habitats, Waterbirds, Marine mammals, Marine protected areas, Ecosystem function, Fisheries

Description

Fish of freshwater origin dominate most Baltic coastal areas, some preferring warm (perch, cyprinids) and others cold waters (salmonids, burbot)[1]. These species often migrate back to their natal spawning ground for spawning, resulting in many local populations that adapt to local conditions. Small scale environmental variations, local fishing pressure, habitat availability, and food web interactions influence their reproduction, recruitment, growth, and mortality.

What is already happening?

Higher water temperature has improved the reproduction of many spring and summer spawners[2-9].

In contrast, the reproduction of autumn-spawners, e.g., vendace and whitefish, is disfavoured by warm winters and their distribution decreases with less ice cover and higher winter temperatures[10-13].

Species preferring warm waters have become more common relative to winter-spawning species[14].

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[15-19].

What can be expected?

Earlier spawning, faster egg, and larval development, increased larval survival of spring spawning freshwater coastal fish species[6-9,20-22] (*).

Earlier migration from nursery habitats[6] may influence food web interactions with negative effects on piscivorous species[23] (*).

Reproduction of autumn-spawning migratory fish is expected to decrease with increasing temperatures, and spawning areas reduced if ice cover decreases further[11-13].

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[3,10,16,17,21,22].

Possible brownification of coastal waters may decrease body growth[24].

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 cormorant and seal populations consume substantial amounts of coastal fish[25], but the impact on fish populations is disputed[26].

Migratory anadromous fish are affected by a similar set of pressures as coastal fish, and in rivers also by altered hydrological regimes, migration barriers caused by dams, and increased sedimentation due to land-use changes in the drainage area[19].

Knowledge gaps

Indirect and interactive effects of different natural and anthropogenic pressures 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.

Policy relevance

Coastal and migratory fish are key elements for Baltic Sea coastal food web structure and function, and fundamental for small scale coastal commercial and recreational fisheries. Current measures to protect and restore coastal and migratory fish populations hardly ever target and consider climate change effects. Targeted short-term actions, e.g., temporary or spatial closures, could help affected fish populations to recover from extreme weather events. Future management should include climate change effects in status assessments and management plans, targets, and measures to acknowledge and mitigate climate related effects.

*) Expected to be caused by warmer temperatures.

Pelagic and demersal fish

Authors
Örjan Östman, Jens Olsson, Noora Mustamäki and Rahmat Naddafi, Swedish University of Agricultural Sciences (SLU), Sweden
Meri Kallasvuo, Sanna Kuningas and Antti Lappalainen, Natural Resources Institute Finland (Luke), Finland

Biota and ecosystems

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Habitats Directive
EU Birds Directive
EU Common Fisheries Policy (CFP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Linked parameters:
Water temperature, Sea ice, Salinity and saltwater inflows, Stratification, Oxygen, Benthic habitats, Waterbirds, Marine mammals, Marine protected areas, Ecosystem function, Fisheries

Description

Fish of marine origin, such as cod, herring, sprat, and flatfishes (flounder, plaice, turbot, and dab), dominate pelagic and demersal habitats of the Baltic Sea[1]. These species occur in large, often internationally managed, stocks.

Currently, sticklebacks 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 temperatures and hypoxic conditions have impaired reproduction, reduced feeding areas as well as quality of food, resulting in decreasing distributions of flatfish, herring and cod, and reduced growth and body condition of cod[2-10].

Increasing temperature favours stickleback[11,12].

Periods with low salinity are connected to lower recruitment of several flatfishes, herring, and cod[13-18], and lower abundance and lipid content of zooplankton prey for herring and sprat[19-22], resulting in lower body growth, condition, and abundance[19-23].

Recruitment of sprat is higher in warmer waters after winters with low ice cover but opposite for herring[24,25].

What can be expected?

Increasing water temperature causes earlier spawning, shorter development, and increased recruitment of sprat[24,26,27],

and increasing larval growth of herring, sprat, and flatfish, and body growth of adult sticklebacks[11,26,28,29]. Herring and cod recruits may miss optimal temperature windows resulting in lowered recruitment[25,26,28,30,31].

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 flatfishes[5,32].

If salinity decreases, this may also reduce recruitment, abundance, and distribution of flatfish, sprat, and cod[2,6,8,15,28,33].

Other drivers

Impacts of multiple drivers on offshore fish communities are perceivable[34,35]. High nutrient discharges have resulted in enhanced hypoxic conditions affecting many fish species negatively[5-10], but also benefitting others[36,37].

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 stratification[31].

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 (competition/predation/food quality) among populations are evident.

Vitamin deficiency (e.g., thiamine) may impact fish species.

Knowledge gaps

Indirect and interactive effects of climate parameters and other pressures on fish need to be better studied[38-41]. 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 conditions 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.

Waterbirds

Authors
Volker Dierschke, Gavia EcoResearch, Germany
Morten Frederiksen, Århus University, Denmark
Elie Gaget, Department of Biology, University of Turku, Finland
Diego Pavón-Jordán, Department of Terrestrial Ecology, Norwegian Institute for Nature Research (NINA), Norway

Biota and ecosystems

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Maritime Spatial Planning Directive (MSP)
EU Birds Directive, EU Habitats Directive
EU Common Fisheries Policy (CFP), EU Common Agricultural Policy (CAP)
EU Strategy for the Baltic Sea Region (EUSBSR), EU Biodiversity Strategy
AEWA Agreement
Ramsar Convention

Linked parameters:
Air temperature, Water temperature, Sea ice, Sea level, Benthic habitats, Pelagic and demersal fish, Coastal and migratory fish, Marine protected areas, Coastal protection, Offshore wind farms, Aquaculture, Marine and coastal ecosystem services

Description

In total, around 100 waterbird species use the marine area and the coastal habitats of the Baltic Sea for breeding, staging during migration, moulting, and/or wintering. They have different roles in the food web, being predators of various fish and invertebrates and foraging in different habitats as well as providers of multiple ecosystem services[1].

What is already happening?

Many waterbird species have shifted their wintering range northwards[2-10].

Some waterbird species migrate earlier in spring[11,12].

Effects of warming water temperature are inconsistent, because both positive and negative effects have been found regarding foraging conditions and food quality, including invertebrate prey and prey fish species[13-15].

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 Africa[16].

What can be expected?

The northward distributional shifts are expected to continue[9,10].

Effects on waterbird food will be manifold, but consequences are difficult to predict[16].

Rising sea level and erosion are expected to influence the availability of breeding habitats[17,18] and rising sea level may reduce breeding success due to flooding of the breeding and wintering foraging habitats.

Other drivers

In the Baltic Sea, waterbird populations are increasingly impacted by human activities during the breeding season, such as recreation[19,20] and introduced predators (e.g., American mink[21-23]) and the wintering season (hunting[24,25], fishing[26,27], ship traffic[28,29], and offshore wind farms[30,31]).

Eutrophication and fishing strongly influence foraging preconditions for waterbirds[3,32,33].

Knowledge gaps

Food web complexity and interacting natural and anthropogenic effects make it difficult to isolate the effects of climate change on waterbird abundance. For some well-studied species, these effects are demonstrated, but in most cases there is a lack of understanding especially of how phenological mismatches will affect breeding and wintering waterbirds across functional groups and life histories.

Policy relevance

Waterbirds are an important part of the marine food web in the Baltic Sea. Changes in the phenology and distribution of waterbirds may require adapting environmental conservation policies, notably by extending and adjusting the networks of protected areas and by supporting their management[17,34] with robustly designed monitoring of sites and populations[9]. Hunting regulations need to be adjusted in space and time to account for distributional and phenological shifts, i.e., regulations need adjustment where climate change has caused increased waterbird occurrence with therefore higher importance of the respective locations.

Marine mammals

Authors
Anders Galatius, Department of Bioscience, Århus University, Denmark
Markus Ahola, Swedish Museum of Natural History, Stockholm, Sweden
Ida Carlén, Coalition Clean Baltic
Antti Halkka, University of Helsinki, Faculty of Biological and Environmental Sciences, Helsinki, Finland
Mart Jüssi, ProMare, Estonia

Biota and ecosystems

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Maritime Spatial Planning Directive (MSP)
EU Habitats Directive
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy
ASCOBANS Jastarnia Plan

Linked parameters:
Sea ice, Sea level, Waves, Pelagic and demersal fish, Coastal and migratory fish, Marine protected areas, Offshore wind farms, Ecosystem function, Shipping, Fisheries, Aquaculture, Marine and coastal ecosystem services

Description

Three seal species and one cetacean live in the Baltic Sea: ringed seal (*Pusa 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.).

What is already happening?

Both the ice cover and duration of the ice season have already been markedly reduced[1-8]. The changes are most prominent in the southern areas where the duration of ice cover during breeding season of ringed and grey seals has increasingly often been either too short or completely lacking[8]. This diminishes breeding success of ringed seals.

To a lesser extent, the breeding success of grey seals is diminished, particularly in the southern areas.

See 'Sea ice and extreme events' for further quantification.

What can be expected?

Projected reduction of sea ice[4,9-11] for ringed seal and of snow for pupping lairs will impact ringed and grey seal breeding. Disappearance of ringed seals from southern areas is possible and transfer of grey seal breeding to land sites probable.

Sea level rise[12,13] causing flooding of haul-outs in the southern Baltic may force out breeding seals. This will likely cause reduction of harbour and grey seal occurrence to foraging individuals.

Changes in temperature and stratification, prey distribution, quality and quantity will affect all marine mammals, but aggregated effects on their abundance and distribution are unpredictable.

Other drivers

Ice-breaking and winter shipping may worsen effects of reduced ice on seal breeding[14,15].

Bycatch affects marine mammals[16-18].

Anthropogenic disturbance affects seal distribution and recruitment[19,20]

Epidemics can reduce seal abundance and possibly distribution[21].

Ecosystem changes and overfishing influence prey availability[22,23]

Pollutants impair marine mammals' immune function and fertility[24,25]

Underwater noise may for all species cause injury and displacement from habitats and disturb natural behavior, and for harbour porpoise interfere with echolocation[16,26].

Knowledge gaps

Seal and porpoise foraging distribution and the relation of the former to haul-out sites are not well known.

While the reduced breeding success of grey seals on land relative to ice has been studied[27], the absolute dependency on ice for successful breeding of ringed seals has not been sufficiently assessed.

Land-breeding of grey seals is not surveyed in most Baltic countries.

Breeding success of ringed seals during favourable ice conditions, even under current conditions, is poorly known. Ringed seals are adapted to ice-breeding. Land breeding attempts are known from extremely poor ice years, but successful land breeding has not been documented for the species.

The aggregate effects of climate-related ecosystem changes on marine mammals have not been modelled.

Policy relevance

Marine mammals are top predators in the Baltic Sea and important as sentinels of ecosystem health[28] and as top-down regulators of the ecosystem. Direct effects of climate change are mostly impossible to address locally. Artificial lairs may mitigate breeding failure and haul-outs could potentially be artificially sustained above water.

Seasonal shipping restrictions may reduce impacts on seal breeding. There are currently no actions to directly mitigate climate change effects on marine mammals, but measures are in place that mitigate human disturbance, pollution and bycatch, and hunting is limited or prohibited.

Further mitigation of pressures will improve climate change resilience of the populations. Consideration of effects of climate change on the populations should be integrated in national management plans.

Non-indigenous species

Authors
Rahmat Naddafi, Swedish University of Agricultural Sciences (SLU), Sweden
Katarzyna Spich, National Marine Fisheries Research Institute (NMFRI), Poland
Isa Wallin, Swedish University of Agricultural Sciences (SLU), Sweden
Örjan Östman, Swedish University of Agricultural Sciences (SLU), Sweden
Maiju Lehtiniemi, Finnish Environment Institute (SYKE), Finland
Ari Laine, Parks & Wildlife Finland (Metsähallitus), Finland

Biota and ecosystems

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 2 and 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Regulation on invasive alien species
EU Biodiversity Strategy

Linked parameters:
Water temperature, Salinity and saltwater inflows, Carbonate chemistry, Oxygen, Benthic habitats, Marine protected areas, Nutrient concentrations and eutrophication, Ecosystem function, Shipping, Aquaculture

Description

Non-indigenous species, NIS, are not native to the geographic region of interest, but transferred there by human activities. Ship ballast water and hull fouling are the main vectors for their transfer[1-4]. NIS are more often found in the coastal zone than the open sea[5-8] and ports are hot spots for their introduction[9-12]. Some 170 NIS are recorded from the Baltic Sea[13,14], with more than 70 permanently established. Most NIS show unique responses to changes in the environment, hence changes caused by climate change will be species-specific and further modified by complex interactions with native species.

What is already happening?

So far, no invasion can be confidently attributed to climate change. Environmental changes caused by climate change may increase stress on native species[15-18] and favour some NIS, increasing their ecological impact[19-21].

Climate driven shifts in species boundaries towards higher latitudes affect potential of new introductions to the Baltic Sea. Changes in salinity regime affect distribution and establishment of NIS depending on their origin and tolerance to salinity[22].

What can be expected?

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[21-35].

Changes may first be seen in estuaries, where the contribution of NIS is already high[36,37].

If oxygen deficiency increases in warmer coastal waters, it may constrain the growth of the round goby[38], but more tolerant species, like the polychaete worm Marenzelleria spp., may increase[39] and change sediment nutrient fluxes and resuspend contaminated sediments[40].

Warmer winters will facilitate survival for introduced warm-water species[41,42].

Other drivers

As the vast majority of NIS arrive with ships, the main driver of biological invasion is the occasional, unintended, and unpredictable introduction of organism into Baltic Sea ecosystem. Also, aquaculture has a significant impact on the arrival of NIS[14]. 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.

Knowledge gaps

Most NIS are ecologically unique, and it is therefore important to predict how invasive 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. Planning of management measures is challenged by the high variability in species characteristics and the unpredictable nature of new introductions.

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 ship-hulls (commercial as well as recreational).

Marine protected areas

Authors
Ari Laine, Metsähallitus Parks & Wildlife Finland, Finland
Örjan Östman, Swedish University of Agricultural Sciences (SLU), Sweden
Dieter Boedeker, German Federal Agency for Nature Conservation (BfN), Germany
Gesine Lange, German Federal Agency for Nature Conservation (BfN), Germany

Biota and ecosystems

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Maritime Spatial Planning Directive (MSP)
EU Habitats Directive
EU Birds Directive
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Linked parameters:
Benthic habitats, Pelagic and demersal fish, Coastal and migratory fish, Waterbirds, Marine mammals, Non-indigenous species, Coastal protection, Offshore wind farms, Shipping, Tourism, Fisheries, Aquaculture, Blue carbon storage capacity, Marine and coastal ecosystem services

Description

Marine protected areas (MPAs) are intended to conserve ecologically significant parts of the marine and coastal environment, including biological and genetic diversity and ecological functions. Biodiversity, including genetic diversity, is needed for species' adaptation and long-term survival under changing environmental conditions[1]. 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[2]. In 2021, HELCOM MPAs covered 13.28% of the Baltic Sea[3,4].

The effect of climate change can be evaluated by assessing consequences to MPA conservation values and function based on benthic habitats, 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[5]. 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)[5]. Milder winters with shorter ice period and reduced 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 *(sea "waterbirds")*. Habitat change through higher temperatures and oxygen depletion (related to eutrophication) may harm fish stocks and benthic communities, also impairing 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[6,7].

Distributional changes of biological communities caused by climate change may impair the function of MPAs and, together with other anthropogenic pressures, prevent MPAs from meeting their objectives[8-14].

Other drivers

Cumulative pressures caused by a variety of human activities both inside and outside MPAs 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.

Knowledge gaps

There is no commonly agreed method to assess the ecological and management effectiveness of MPAs, which impedes evaluations and optimisation 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[15,16].

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[17]. 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 minimum buffer for climate change resilience. However, an expansion of the HELCOM MPA network, with climate refuges in which food web perspectives and genetic diversity are considered[1], is needed.

Nutrient concentrations and eutrophication

Authors
Bärbel Müller-Karulis, Stockholm University, Baltic Nest Institute, Sweden
Bo Gustafsson, Stockholm University, Baltic Nest Institute, Sweden
Oleg Savchuk, Stockholm University, Baltic Nest Institute, Sweden
Jacob Carstensen, Århus University, Denmark

Biota and ecosystems

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 2, 12 and 14
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Common Agricultural Policy (CAP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Linked parameters:
Water temperature, Stratification, Precipitation, Riverine nutrient loads and atmospheric deposition, Carbonate chemistry, Oxygen, Benthic habitats, Pelagic and demersal fish, Coastal and migratory fish, Non-indigenous species, Ecosystem function, Aquaculture, Blue carbon storage capacity, Marine and coastal ecosystem services

Description

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[1,2].

Bottom oxygen conditions regulate denitrification rates and the distribution of phosphorus between sediment and the water. Higher nitrogen loss and phosphorus release from sediments occur when hypoxia expands[3,4].

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[4]. Nitrogen concentrations have decreased in most Baltic Sea basins since 1990, but phosphorus pools have fluctuated without trend[5].

Eutrophication has made shallow areas with restricted water exchange more prone to hypoxic events[6].

Nutrients liberated from sediments during the hypoxic events fuel summer phytoplankton blooms[7]. Changes in stratification and cloud cover[8] currently prolong the phytoplankton growth season, with earlier spring onset and extended autumn blooms[8], without clear effect on nutrient concentrations[8].

What can be expected?

The development of nutrient loads will dominate future nutrient concentrations[9,10], with warming expected to reduce near-bottom oxygen by increasing internal nutrient cycling and by strengthening thermal stratification[9-11].

A decline in the DIP pool is projected[12] (*). DIP surface concentrations in the Baltic Proper will decrease with BSAP load scenarios and slightly increase with current load scenarios while surface DIN concentrations remain unchanged under both scenarios[9].

In the Gulf of Finland and Bothnian Sea, it is expected that DIN levels will increase with both load scenarios and DIP changes will be similar to the Baltic Proper[9].

nitrogen-fixing cyanobacteria blooms are expected to expand[13-15] (**).

Other drivers

Future nutrient loads will affect nutrient concentrations more than climate change[9,10].

In the more nutrient-poor Bothnian Sea and Bothnian Bay, future river loads of dissolved organic carbon will also play an important role as they stimulate bacteria to out-compete phytoplankton for nutrients, which can lower phytoplankton biomass[16].

Knowledge gaps

The magnitude of future nutrient loads, the bioavailability of their organic fraction, as well as nutrient retention in the coastal zone are uncertain, as are future nutrient inputs at the Skagerrak boundary[17]. Freshening of the water would have the potential to increase phosphorus binding in sediments[18], but both the magnitude of future salinity change, and the sediment response are uncertain[17]. Feedbacks between climate change, phytoplankton community structure and sedimentation are poorly known[19] and more quantitative knowledge about the factors controlling nitrogen pathways is needed, especially for coastal areas[20]. Dissolved organic forms of nitrogen and phosphorus are important biogeochemical components with poorly described dynamics in models.

Policy relevance

High nutrient loads cause eutrophication, which is a major problem in the Baltic Sea. Nutrient input is primarily coming from agriculture and fertilizer use on land. Eutrophication is central in the HELCOM Baltic Sea Action Plan[21], the EU Marine Strategy Framework Directive[22] and the EU Water Framework Directive[23], and all these policies aim to reduce eutrophication in the Baltic Sea even more than the already achieved reductions.

*) When climate change effects are taken into account, the Baltic Sea Action Plan (BSAP) and current load scenarios project, respectively, a 50% and 25% decline in the Baltic DIP pool until 2070-2100[12].
**) Without nutrient load reductions, nitrogen-fixing cyanobacteria blooms are expected to expand.

Ecosystem function

Authors
Örjan Östman, Rahmat Naddafi, Jens Olsson,
with input by Agnes ML Karlsson and Magnus Huss,
Swedish University of Agricultural Sciences (SLU), Sweden

Biota and ecosystems

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Maritime Spatial Planning Directive (MSP)
EU Habitats Directive
EU Birds Directive
EU Common Fisheries Policy (CFP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Linked parameters:
Water temperature, Sea ice, Solar radiation, Salinity and saltwater inflows, Stratification, Carbonate chemistry, Riverine nutrient loads and atmospheric deposition, Oxygen, Microbial community and processes, Benthic habitats, Pelagic and demersal fish, Coastal and migratory fish, Waterbirds, Marine mammals, Non-indigenous species, Nutrient concentrations and eutrophication, Coastal protection

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[1-7] that 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[1-4,8-10].

Changes in ice cover, cloudiness, and wind condition in spring may have resulted in changed timing of algal blooms, affecting benthic productivity[1,4].

Changes in hydroclimatic conditions in combination with fishing and eutrophication have resulted in a shift from larger to smaller zooplankton[8,9], 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[5-7,11-13].

What can be expected?

Warmer water may increase pelagic and benthic primary production[1,2,8,9,14].

Unless nutrient loads are reduced, oxygen levels in the water and close to the seabed will decrease[15]. Responses at higher trophic levels will differ among organism groups[8,16-19].

If salinity decreases, this will likely affect the species composition of zooplankton and fish, and the associated functions, e.g., predation rates[9,17,20,21].

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 benthic and pelagic food webs[22,23].

Other drivers

Fishing is a strong pressure on some fish species and results in reduced natural control of their prey[5-7,11-13].

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[8,9,15,24].

Seals and cormorants have increased in the Baltic Sea, but food web effects are poorly known and uncertain[6]. 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.

Knowledge gaps

Several parameters are intercorrelated and there are potentially indirect and interactive effects of for example oxygen, salinity, and temperature on ecosystem functioning[6,8,9,18,19,24].

The magnitude and interactive effects of climate change relative to other human pressures are hence important to estimate[6].

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 heat-waves. It would be important to analyse monitoring data before, during, and after extreme events, such as the heat waves or low ice cover[25,26].

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)[2,3,9,14,15]. Long-term management plans and measures should consider projected changes in primary production and trophic structure of Baltic Sea ecosystems6.

Indirect parameters:

Human use

Authors
Jukka Käyhkö, University of Turku, Finland

Human activities

Offshore wind farms

Linked parameters:
Sea ice, Wind, Waves, Sediment transportation, Coastal and migratory fish, Waterbirds, Marine mammals, Marine Protected Areas, Shipping, Tourism, Fisheries, Blue carbon storage capacity

Links to main policies:
UN Sustainable Development Goals 13 and 14
EU Maritime Spatial Planning Directive (MSP)
EU Strategy for the Baltic Sea Region (EUSBSR)
HELCOM Baltic Sea Action Plan
Renewable Energy Directive (2018/2001/EU)
EU Strategy to harness the potential of offshore renewable energy for a climate neutral future (COM(2020) 741)
EU Biodiversity Strategy

Description

Wind farms are the most significant offshore structures in the Baltic Sea, and, in 2021, account for 10% of European offshore wind energy with the current 2 GW of installed capacity[1]. The ambitious scenario for deployed offshore wind power capacity by 2050 has been estimated at 32 GW[2]. The environmental impact of wind farms should be considered case specifically with great caution. They affect many oceanographic processes including downstream turbulence, wave energy, local scour, inflowing currents, and surface upwelling[3]. The submerged structures may locally alter the structural and functional biodiversity of the benthic system[4]. Turbines affect marine mammals through underwater noise during construction and birds and bats through physical disturbance during operation[5-9].

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 (1,074 MW), Denmark (872 MW), Sweden (192 MW) and Finland (68 MW)[1]. Climate change (e.g. changes in ice conditions, wind fields, waves) does not have any major influence on the deployment of offshore structures[10]. 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[11].

What can be expected?

The European Commission estimates that Europe will need 240–450 GW of offshore wind by 2050, equalling up to 30% of Europe's estimated electricity demand at the time[12]. 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 km^2) to 3.6 GW (720 km^2) 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[13,14].

Other drivers

Climate change mitigation is the key driver for offshore wind farm industry. However, primarily drivers other than climate change modify the deployment of these offshore structures. The key parameters regarding the location are water depth (< 50 m), wind conditions (> 7 ms^{-1}) and planning issues[2]. Other drivers include, e.g., investments, industrial and employment dimensions, regional and international cooperation, legal framework, supply chains, technological innovations[6], and exclusions due to military radar issues[13].

Knowledge gaps

There is insufficient knowledge on the impact of scale of offshore structures on marine biota. Numerical modelling is not able to predict the effects of large-scale construction, potential cumulative effects of multiple farms, or far-field effects at the coast. Further expansion of offshore wind energy should only take place gradually with adequate environmental assessments. In addition, the effects of the expansion of offshore wind energy on biodiversity must be further studied through comprehensive, continuous, and close-meshed research and monitoring. Observational studies are also necessary to validate the models, and extensive site-specific data collection is necessary to compare any changes to the natural ocean state[3].

Policy relevance

Offshore wind is one of the cornerstones of EU's energy and climate targets. The European Green Deal recognizes the offshore wind potential in contributing to a modern, resource efficient and competitive economy. The Commission has published an EU strategy on offshore renewable energy, inviting stakeholders to discuss and take forward the proposed policy actions[11]. However, the EU and national governments have also committed to protecting ecosystems, which may be at risk due to increasing offshore structures. Hence, a broad political discussion is called for to balance the need for renewable energy with its environmental impacts.

Authors
Jukka Käyhkö, University of Turku, Finland

Human activities

Coastal protection

Linked parameters:
Sea ice, River run-off, Sea level, Wind, Waves, Sediment transportation, Waterbirds, Marine Protected Areas, Ecosystem function, Tourism

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 13 and 14
EU Maritime Spatial Planning Directive (MSP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Floods Directive
EU Biodiversity Strategy

Description

Baltic Sea coasts are under multi-stressor impact due to climate change and various human activities[1,2]. The impact varies regionally depending on the material of the coast, and the processes in operation[1]. Over decades, various coastal protection structures have been established especially along the soft sedimentary shores at the southern coastline of the Baltic Sea, including groins, bulkheads, seawalls, revetments, breakwaters, sills, and sand fences[3]. These structures modify natural processes and introduce a more static habitat into a formerly dynamic one, raising concerns about their long-term sustainability and ecosystem benefits[4], while acknowledging the need for coastal flood protection.

What is already happening?

The soft sedimentary coasts in the south are facing the largest changes[1] and exhibit also the most abundant coastal protection structures. However, there is a growing understanding that "soft interventions" rather than "hard" structures may be a more satisfactory way forward. Ecosystem services provided by, e.g., intertidal wetlands can play a critical role in reducing the vulnerability of coastal communities to rising seas and coastal hazards[5]. There are examples of abandoning traditional "hard" coastal protection measures at the Baltic Sea coastline, such as sand nourishment, to enable a recovery of natural dynamics[6,7].

What can be expected?

Coastal protection strategies have to increasingly take into account the effects of climate change[8]. Along the low coasts of the southern Baltic Sea, sea level rise is expected to increase cliff and beach erosion and to increase the supply of sediment to the coastal zone[9]. These effects of climate change are expected to increase societal costs for coastal protection, losses of sediment for coastal rebuilding, losses of valuable natural habitats, and of economic value and property[10]. Therefore, there is a need for a wider use of innovative approaches such as the Systems Approach Framework (SAF) as a tool for the transition to sustainable development in coastal zone systems[11,12].

Other drivers

Direct human influence often has an impact on coastal processes via changes in land use and land cover, coastal and offshore infrastructure constructions, dumping of material and dredging. Regional demographic development and socio-economy influence the coastal ecosystem, as diverse societal and economic claims need to be integrated into regional spatial planning policies alongside climate change adaptation[8].

Knowledge gaps

Changes in land use, land cover and infrastructure construction are of crucial importance as they operate reciprocally with sedimentary processes causing unexpected morphodynamic consequences. A regional sediment budget for the southern and eastern Baltic Sea is still to be constructed. This requires interdisciplinary and international collaboration[1]. In many parts of the southern Baltic coastline, the key question regarding the existing coastline protection structures is their sustainability and efficiency under changing climate and consequently, their potential replacement, adjustment, or removal procedures[4].

Policy relevance

Coastal processes and their sustainable management under climate change have extremely high policy relevance globally, and in the Baltic Sea. Coastal protection measures should be nationally or regionally incorporated into integrated coastal zone management plans including physical and ecological parameters, cost-benefit analyses, and administrative and legal structures[13]. Due to the complexity of coastal systems and the lack of precise economic valuations, both land and marine spatial planning usually neglect natural coastal protection and other important ecosystem services[2], calling for a policy change.

Shipping

Authors
Anna Rutgersson, Uppsala University, Sweden
Stuart Ross, European Community Shipowners' Associations
Jonas Pålsson, Swedish Agency for Marine and Water Management, Sweden

Human activities

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 14
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Maritime Spatial Planning Directive (MSP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy
MARPOL Annex VI

Linked parameters:
Sea ice, Riverine nutrient loads and atmospheric deposition, Wind, Waves, Marine mammals, Non-indigenous species, Marine protected areas, Offshore wind farms, Fisheries

Description

The Baltic Sea has been an important route for maritime trade since prehistory and is now one of the busiest maritime areas in the world. In 2017, there were 40,391 passages into the Baltic Sea[1]. In 2018, approximately 8,300 vessels operated within the area[2]. Shipping is a carbon-efficient transport medium, but still has adverse effects on air quality, eutrophication, and other aspects of the marine environment[3].

What is already happening?

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[4,5], facilitating shipping in usually ice-covered areas. Changes in wind field have so far been small and depend on the time period and area studied[6]. Extreme waves have not changed significantly in strength or intensity[6]. Changes in wind and waves could potentially influence safety and fuel consumption.

What can be expected?

Modelling predicts an annual shipping increase of 2.5% for cargo and 3.9% for passenger traffic in Europe[7]. 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.

Ports and shipping lanes may need to move location or increase or decrease dredging due to sea level rise and increased sedimentation from coastal erosion and river runoff.

Other drivers

Market changes and new regulations will likely modify future shipping much more than direct climate effects. Particularly, regulations to reduce emissions of CO_2, NOx, SOx, and particles will influence ship design and fuel use. The changing climate may influence the transportation pattern of traded goods, as some commodities may start to be produced in new locations around the world. Hence, trade flows will shift.

Knowledge gaps

There is a knowledge gap in how new regulations driven by climate change mitigation efforts will affect the fleet composition, fuel selection, and additional technological development. Thus, the response of future Baltic Sea shipping to changes in climate cannot be fully quantified.

Policy relevance

Shipping is a CO_2 effective way to move goods, but still has a substantial carbon footprint. Member States to the IMO have committed to reduce the total annual greenhouse gas emissions from international shipping by 50% by 2050 (from 2008), and phase them out entirely by 2100[8]. Amendments to the IMO environmental regulations concerning mandatory goal-based technical and operational measures to reduce carbon emissions were adopted in 2021.

Increased shipping in previously iced covered areas may increase environmental pressures, but new regulations on noise and emissions may exclude vessels from sensitive marine 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.

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Secondary parameters: Human use

Tourism

Authors
Kari Hyytiäinen, Department of Economics and Management, University of Helsinki, Finland
Jarkko Saarinen, Geography Research Unit, University of Oulu, Finland
Janika Laht, Climate Department, Ministry of the Environment, Estonia

Human activities

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goal 14
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Bathing water Directive
EU Maritime Spatial Planning Directive (MSP)
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Recommendation on Integrated Coastal Zone Management
EU Biodiversity Strategy

Linked parameters:
Air temperature, Water temperature, Sea ice, Solar radiation, Precipitation, Sea level, Wind, Waves, Sediment transportation, Marine Protected Areas, Coastal protection, Offshore wind farms, Marine and coastal ecosystem services

Description

The Baltic Sea is an important region for coastal and maritime tourism. The region's tourism industry employs approximately 640,000 people and registers over 227 million overnight stays annually[1]. The coastal areas of the Baltic Sea provide opportunities for a wide range of 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[2]. In 2019, the Port of Helsinki was the busiest international passenger port in Europe with a total of 12.2 million passengers[3].

What is already happening?

Changing climate may either increase or reduce the provision of ecosystem services and resources relevant to tourism[4]. 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[5], making bathing less attractive. Introduction of non-indigenous species alter opportunities for fishing and recreation[6]. 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.

What can be expected?

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[7]. 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.

Other drivers

The tourism industry is vulnerable to external changes and pressures, including global and regional economic and political processes[8]. 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 the number of visits globally, regionally, and locally depending on geographical areas and customer segments that suffer the consequences. For example, the COVID-19 outbreak in 2020 led to a quick collapse of international travel.

Knowledge gaps

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

Baltic Sea coastal and cruise tourism is important for the socioeconomy of the region. The competitiveness of this tourism depends largely on the environmental state of the Baltic Sea and the resilience of the tourism industry to natural, social, and economic changes. To improve the future prospects of blue tourism, it is important to control pollution loads, including nutrients, litter, and oil spills. Other relevant developments include multi-stakeholder governance of coastal and marine tourism and coordinated collection of economic, ecological, cultural, and social sustainability indicators[8]. Monitoring is required both for the internal development of the sector, which consists of a large number of enterprises of different sizes, and for planning public mitigation and adaptation policies.

Fisheries

Authors
Meri Kallasvuo, Sanna Kuningas, Antti Lappalainen, Natural Resources Institute Finland (Luke), Finland
Örjan Östman, Jens Olsson, Rahmat Naddafi, Lena Bergström, Swedish University of Agricultural Sciences (SLU), Sweden
Oksana Glibko, St. Petersburg State Geological Unitary Enterprise "Specialized Firm Mineral", Russia
Antanas Kontautas, Marine research institute, Klaipėda University, Lithuania

Human activities

Linked parameters:
Sea ice, Sea level, Wind, Waves, Pelagic and demersal fish, Coastal and migratory fish, Marine mammals, Marine protected areas, Offshore wind farms, Ecosystem function, Shipping, Aquaculture, Marine and coastal ecosystem services

Links to main policies:
HELCOM Baltic Sea Action Plan (BSAP)
UN Sustainable Development Goals 2 and 14
UN Convention on Biological Diversity (CBD)
EU Maritime Spatial Planning Directive (MSP)
EU Common Fisheries Policy (CFP)
EU Biodiversity Strategy

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 flatfishes. 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[1]. Recreational fishing is common in coastal areas[2]. For certain coastal species, the recreational catch is comparable or even higher than the commercial catch[3,4].

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 period of ice cover[5]. Coastal recreational ice fishing opportunities have been reduced[2]. 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[5]. The species composition targeted especially by the coastal and demersal fisheries is changing due to eutrophication and climate change[6,7]. Also, increased effort is needed for fishing-gear maintenance, due to accumulating biofilm and filamentous algae[5].

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[8,9]. The coastal and recreational fisheries will increasingly target species that prefer warmer and more nutrient-rich waters[10]. 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

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 the dispersal of non-indigenous species, will also affect the quantity and quality of fish, and the demand for the catch.

Knowledge gaps

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.

Policy relevance

Fisheries have 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[11]. 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.

Aquaculture

Authors
Anders Kiessling and Martyn Futter, Swedish University of Agricultural Sciences (SLU), Sweden
Georg Martin, UT, University of Tartu, Estonia
Lauri Niskanen, Markus Kankainen and Jouni Vielma, Natural Resources Institute Finland (Luke), Finland
Martin Karlsson and Martin Reutgård, Ecopelag
Knut-Olof Lerche, Raisio

Human activities

Linked parameters:
Water temperature, Sea ice, Salinity and saltwater inflows, Waves, Oxygen, Pelagic and demersal fish, Coastal and migratory fish, Waterbirds, Marine mammals, Non-indigenous species, Marine protected areas, Nutrient concentrations and eutrophication, Fisheries, Blue carbon storage capacity, Marine and coastal ecosystem services

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 2, 6, 12, and 14
UN Convention on Biological Diversity
EU Green Deal
EU Water Framework Directive (WFD)
EU Maritime Spatial Planning Directive (MSP)
EU Habitats Directive
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

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[1]. Farms are 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 Tagalaht bays. Extractive farming where blue mussels and macro-algae are harvested as a way to recover excessive marine 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[2] reducing physical fitness, impairing growth, and increasing mortality[3]. 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[4,5].

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, without risk of interference with shipping and recreation[6].

Other drivers

Policies promoting circular production and rural development will be positive drivers for aquaculture, however, industrial sized land-based systems are not likely to be implemented in remote locations within the archipelago, due to infrastructure dependencies. Marine spatial planning priorities, consumer acceptance of farmed fish, as a complement to wild fish, as well as governmental acceptance of blue catch crops, are all important for future Baltic Sea aquaculture. Synergies between renewable energy and food production based on co-location of aquaculture with offshore energy should especially promote extractive aquaculture. Demands for resilient, resistant, local food production and the possibility of local and circular-based feed sources, should further promote all types of aquaculture.

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 techniques 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 counteracting marine eutrophication. Political obstacles and public perceptions are probably more difficult challenges to Baltic Sea aquaculture than the changing climate. Aquaculture using sterile fish, which express neither phenotypic nor behavioural spawning characteristics, is needed to protect Baltic Sea biodiversity. Policy support for science-based solutions incorporating technological innovation and best practices is needed, as are marine spatial planning processes that avoid environmentally sensitive sites but still allow aquaculture to develop to meet European and regional policy targets, such as the EU Blue Growth Strategy.

Blue Carbon storage capacity

Authors
Dorte Krause-Jensen, Århus University, Denmark

Services

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 13 and 14
UN Convention on Biological Diversity
EU Green Deal
EU Marine Strategy Framework Directive (MSFD)
EU Water Framework Directive (WFD)
EU Maritime Spatial Planning Directive (MSP)
EU Habitats Directive
EU Strategy for the Baltic Sea Region (EUSBSR)
EU Biodiversity Strategy

Linked parameters:
Water temperature, Sea ice, Salinity and saltwater inflows, Carbonate chemistry, Sea level, Waves, Benthic habitats, Marine protected areas, Nutrient concentrations and eutrophication, Offshore wind farms, Aquaculture, Marine and coastal ecosystem services

Description

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 here[1,2]. These "BC ecosystems" are under pressure and have experienced major global losses in area[3,4] and, hence, losses of carbon sink capacity[5,6]. Management strategies to protect and restore them therefore contribute to mitigating climate change[2]. This is a win-win strategy as the BC ecosystems also constitute natural coastal protection and support biodiversity and other ecosystem services[2,4,7,8]. In the Baltic Sea, vegetated coastal ecosystems encompass tidal marsh/coastal meadows, eelgrass/seagrass meadows, and macroalgal beds.

What is already happening?

While Blue Carbon ecosystems offer mitigation and adaptation to climate change, they are also susceptible to multiple aspects of climate change such as warming, increased frequency of heatwaves, reduced sea ice cover, changing salinity and sea level rise[7,9,10]. Relatively few such studies are yet available for BC ecosystems in the Baltic Sea but there are examples of negative effects of, e.g., warming on Baltic marine vegetation[11,12]. Interactions between climate change and other human-induced pressures, which are prominent in the Baltic Sea[13], tend to aggravate such negative effects of climate change on BC ecosystems in the region[11,14].

What can be expected?

Climate-change related effects on Blue Carbon ecosystems in the Baltic Sea and elsewhere are expected to increase in the future, with associated impacts on their mitigation and adaptation capacity. There are, e.g., projections of negative effects of climate change on Baltic eelgrass meadows and macroalgal beds[14,15], and flooding over tidal marshes as the sea level rises[16]. However, the extent of negative effects of climate change on BC habitats will depend on management of both climate change and other pressures[11,13]. A recent review highlights the potential for substantial recovery by 2050 in the abundance, structure, and function of marine life, including coastal vegetated ecosystems, if major pressures, including climate change, are mitigated[17].(*)

Other drivers

Vegetated coastal ecosystems in the Baltic Sea and elsewhere are affected by a wide range of human-induced pressures in addition to climate change, including eutrophication, e.g., reducing water clarity, land-use changes and fisheries[13,17]. For example, warming in interaction with eutrophication and trawling, poses key threats to Baltic eelgrass meadows[11], and release of the local pressures can increase resilience of the meadows against realized and further warming[11,14]. Likewise, land-use management can help relieve the risk of coastal squeezing of tidal marshes in the face of climate change, while also supporting coastal protection[16,18,19]. The future of BC ecosystems and their climate change mitigation capacity therefore depends on sustainable, holistic management of combined pressures.

Knowledge gaps

Knowledge gaps at the Baltic Sea scale include quantification of the role of vegetated habitats in the marine carbon cycle of the region, i.e., mapping their area and related carbon fluxes (primary production, sequestration rates, export fluxes and fate) and identifying carbon sink areas beyond these habitats. Moreover, there is a need to quantify realized changes in vegetated areas and to estimate the potential to expand vegetated areas through restoration and protection as a nature-based solution (NBS) for mitigating climate change. Identification of target areas for restoration and protection of Blue Carbon ecosystems and carbon sinks, will maximize the benefit of NBS. A recent review provides further guidance on Blue Carbon science and management[20] and the recently concluded Nordic Blue Carbon project provides an update on eelgrass and macroalgae in the Nordic Blue Carbon context[21].

Policy relevance

Restoration and conservation of coastal vegetated ecosystems are direct sustainable management measures to mitigate climate change, while also stimulating biodiversity and additional ecosystem functions. Blue Carbon-strategies are, therefore, important nature-based solutions to two concurring global challenges: climate change and biodiversity loss, which are increasingly addressed in international policy, for example Blue Carbon Initiative[22], IUCN[23], the Ocean Panel[11], the Nordic Council of Ministers[24] and EU initiatives on nature-based solutions (NBS[25] also involving the Baltic Sea[26]. There are local-scale initiatives in the Baltic Sea to protect and restore eelgrass, implement coastal realignment programs with tidal marshes and recreate reefs. However, coordinated Baltic-scale Blue Carbon-strategies represent a yet untapped potential.

*) Several studies confirm climate-related effects on marine vegetation and associated carbon sink capacity, with the extent and direction of change differing between regions e.g., depending on latitude and interaction with other pressures.

Marine and coastal ecosystem services

Authors
Artūras Razinkovas-Baziukas, Marine Research Institute, Klaipeda University, Lithuania

Services

Links to main policies:
HELCOM Baltic Sea Action Plan
UN Sustainable Development Goals 2, 6, 8, 12, and 14
UN Convention on Biological Diversity
EU Green Deal
EU Water Framework Directive (WFD)
EU Maritime Spatial Planning Directive (MSP)
EU Biodiversity Strategy
EU Habitats Directive
EU Strategy for the Baltic Sea Region (EUSBSR)

Linked parameters:
Sea ice, Waterbirds, Marine mammals, Marine protected areas, Nutrient concentrations and eutrophication, Ecosystem function, Tourism, Fisheries, Aquaculture, Blue carbon storage capacity

Description

Ecosystem services (ES) are commonly assessed as supply (mostly related to the 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 components[1], which in turn, are altered by climatic changes. The assessment of ES demand is based mostly on the global societal changes like alteration of lifestyles or climate change induced alterations in ES supply at global scales (e.g., further increase of summer temperatures in 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 econometric methods).

What is already happening?

The present trends in cultural ecosystem services, mainly tourism and recreation[2-4], are positive but the interplay between the different drivers makes the relation to climate change uncertain. There is a negative trend in aquaculture (a provisioning ecosystem service), as water temperature is suboptimal for rainbow trout, mussel, and algae farming, while impacts on fisheries are mixed[5-7] The trends in the supply of regulation and maintenance ecosystem services based on the key messages on eutrophication, benthic habitats, and ecosystem function varies across different parts of the Baltic[8-12].

What can be expected?

The cultural ecosystem services (mainly relevant to tourism and recreation, including recreational boating) 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 quality[13], 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 filters[14].

Other drivers

Several anthropogenic pressures such as eutrophication, pollution, microplastics, fishing as well as habitat degradation, could offset positive and strengthen negative trends in ecosystem services supply, while protection and restoration efforts could lead to their improvement. Uncertainty in the future pressures increases the uncertainty of projections for ecosystem services.

Knowledge gaps

In the terrestrial domain, there are already many scientifically sound biophysical ES models capable of producing spatial coverage and tools for biodiversity and natural resources management, but the modelling of aquatic ES hitherto is largely underdeveloped[3,15]. Moreover, so far there is little understanding of the relationships and feedbacks between aquatic ecosystems and the services they produce, resulting in the negligible impact on the policy process of economic valuation of coastal and marine ES[4].

Policy relevance

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' 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

Glossary

Glossary of words related to climate change

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
anoxia — 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 interrupt 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
bacterioplankton — single-celled prokaryotes, 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 — vegetated 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
biodiversity — variety of all living things on Earth
biomass production — production of organic matter
brownification — darker water due to more organic substances and iron
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 CO_2, for example the ocean
carbon source — releases more carbon than absorbs and thus increases the atmospheric concentration of CO_2, for example burning of fossil fuels
climate refuges — areas in which temperature increase is expected to be lower than on average, important areas for conservation
climate change — climate change means a change in average or in variation 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
climate change signal — observed long-term trends and projections linked to climate change
climate model — complex mathematical representation of the climate system, used to project future climate conditions and to understand past climates
climate projection — simulation of Earth's climate far into the future, derived using climate models and assumptions of future developments of climate drivers (e.g., greenhouse gases, land use)
CO2 species — composed of chemically identical molecular entities with CO_2, i.e., CO_2, H_2CO_3, HCO^{3-} and CO_3^{2-}
cyanobacterial blooms — blooms in the water formed by microscopic single-celled cyanobacteria (aka blue green algae), common in the Baltic Sea during summer due to high level of eutrophication and warm water
DIN — dissolved inorganic nitrogen
DIP — dissolved inorganic phosphorus
demersal — area near the sea bottom, for example demersal fish live on or near the sea bottom
deoxygenation — the removal of oxygen atoms from an environment, substance, or molecule, i.e., decline of oxygen, the primary cause of deoxygenation in the Baltic Sea is eutrophication, deoxygenation leads to hypoxia with detrimental effects on biota
ecosystem function — physical, chemical, and biological processes that transform energy, nutrients, and organic matter in an ecosystem; capacity of an ecosystem to provide goods and services that are potentially useful to humans
ecosystem functioning — interaction between an ecosystem and its environment, for example biotic activities affect the physical and chemical conditions of their environment
ecosystem services — services and benefits to humans provided by the nature and healthy ecosystems, commonly assessed as supply (mostly related to the biophysical or ecological characteristics of the environment), demand (mostly societal drivers) and flow (actual provision and use)
erosion — geological process by which surface material (e.g., soil, rock) is worn and transported, caused by natural processes such as wind, water, and ice
estuary — partially enclosed coastal area extensively influenced by river freshwater discharge causing brackish water conditions and estuarine circulation
euphotic zone, photic zone — water layer close to the surface with sufficient amount of light for photosynthesis (i.e., transfer of CO_2, water, and sun light into chemical energy mainly by plants and zooplankton)
eutrophication — excessive growth of phytoplankton, algae, and plants, caused by excessive input of nutrients to the marine environment; excessive eutrophication causes reduced light conditions, oxygen depletion, cyanobacterial blooms, and other ecosystem changes

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Glossary

euxinia — anoxia with raised level of free hydrogen sulfide (H_2S) in the water
evolution — the development of new species by mutation of the genome and natural selection
exoskeleton — external skeleton that protects an organism; acidification may impair marine organisms, such as mussels, that build their exoskeleton out of calcium carbonate
extractive farming — aquaculture where for example blue mussels and macro-algae are harvested as a way to recover excessive marine nutrients for terrestrial use
fetch — the distance over which wind blows
foodweb — representation of who eats what in an ecosystem, describes the movement of energy and nutrients through an ecosystem, contains different trophic levels
genetic diversity — variation in the genetic composition among individuals, species or a community, genetic diversity is important for adaption to changing circumstances and is an important part of biodiversity
greenhouse gases (GHGs) — gases that absorb heat in the atmosphere, the main greenhouse gases are water vapor, carbon dioxide ($C0_2$), methane (cH_4), Nitrous oxide (N20), fluorinated gases and ozone
haline — saline, salty
halocline — vertical zone in the water column in which salinity changes rapidly, usually causing strong stratification of the water due to resulting different densities with higher densities for higher salinities, permanently found in large parts of the Baltic Sea and located below the mixed surface water layer
haul-out — land area for resting, breeding, foraging etc. of a seal or other marine mammal
hypoxia — low oxygen level in the environment or tissues of a body of an organism
instrumental period — time period of 1886–2017, routine weather observations at fixed sites started in the beginning of the instrumental period
keystone species — organism that has a substantially large effect on the communities in which it occurs, helps to maintain local biodiversity, for example bladder wrack (*Fucus vesiculosus*) in the Baltic Sea
macrophyte — large aquatic plant
meteotsunami — sea level extreme travelling in phase with atmospheric low-pressure systems
mixed layer — the surface water layer, which is well mixed, oxygenated, and of uniform density
Major Baltic Inflows (MBIs) — large, meteorologically driven saltwater inflows to the Baltic Sea which sporadically renew the deep water with saline, oxygen rich water; this is the only process that effectively ventilates the deep water of the Baltic Sea.
nature-based solutions (NBSs) — actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN description)
non-indigenous species (NIS) — species not native to the geographic region of interest, but transferred there by human activities
North Atlantic Oscillation (NAO) — describes the intensity of the westerly flow. A positive NAO is related to mild, wet winters and increased storminess over northern Europe
nucleus — a separate entity in a cell surrounded by a membrane where the genome is situated, is characteristic of plant and animal cells
ocean acidification — decrease of seawater pH, due mostly to the rising CO_2 concentration in the atmosphere and its exchange with the surface seawater
open-cage farm — aquaculture in open-top cages in coastal waters or lakes
organic matter — carbon-based compounds found in nature, e.g., in plants, animals, their remains and dissolved organic matter in the water
pCO2 — partial pressure of CO_2
pH — measure of acidity or basicity of a solution, acidic solutions (values <7) have lower pH values than basic or alkaline solutions
paleoclimate period — time period before 1886 from which no instrumental climate records are available
pelagic — refers to the water column above the bottom and below the sea surface in open sea regions
phenological mismatches — a mismatch in the timing of the life cycle between different organisms and environmental features, for example hatching of juveniles during sub-optimal conditions
phenology — the study of cyclic and seasonal natural phenomena, especially in relation to climate and plant and animal life
phenotypic or behavioural spawning characteristics — changes in behavior or appearance related to spawning, e.g., muscle tissue of fish becoming lighter and of inferior quality for food consumption during spawning
photosynthesis — conversion of sun light energy to chemical energy by plants, algae, and certain bacteria, binds carbon dioxide and produces oxygen, crucial for maintenance of life on Earth
phytoplankton — photosynthesizing microscopic marine organisms, inhabit the upper water layer, foundation of the aquatic food web
piscivorous fish species — fish that eat other fish
primary production — synthesis of organic compounds from carbon dioxide by plants and other organisms capable of photosynthesis. Oxygen is an important by-product of photosynthesis.
protozoa — unicellular organisms of many species eating other small organisms or bacteria
pycnocline — vertical zone in the water column in which density changes

Glossary (continued)

rapidly caused by corresponding changes of temperature and/or salinity with lower densities to the surface and higher densities to the bottom due to stratification

radiative forcing — difference between solar energy absorbed by the Earth and radiated back to space

range shifts — changes in the distribution limits of a species

refractory compounds — chemical compounds difficult to decompose and use as food

regime shifts — large, persistent change in the structure and function of an ecosystem, e.g., in Central Baltic Sea a previously cod-dominated system changed to domination by small pelagic fish, due to overfishing, eutrophication and climate change

remineralization — breakdown or transformation of organic matter to inorganic chemical compounds

Representative Concentration Pathway (RCP) — used to describe different climate futures depending on the greenhouse gas (GHG) emissions in the coming years. The RCPs indicate a possible range of radiative forcing in the year 2100 compared to 1850.; the RCPs include a "mitigation" scenario which aims to keep global warming below 2°C above pre-industrial temperatures (RCP2.6) and a high emissions "worst case" scenario (RCP8.5) that corresponds to a future without climate mitigation; One intermediate scenario is the RCP4.5 which likely results in global mean temperature rise between 2–3°C degrees by 2100.

recruitment — successful reproduction and survival of offspring

run-off — waterflow on land when the amount of water exceeds the ability of land to absorb water, increased river run-off increases input of nutrients to the Baltic Sea

climate scenario — representation of future climate

scenario simulations — simulations of future climate using numerical climate models driven by different assumptions on the future development of greenhouse gas emissions, land use, and aerosol emissions

sediment budget — balance between sediment added and removed from a coastal system

stratification — vertical ordering of inhomogeneous sea water according to its different densities due to gravitation, different densities in sea water are caused by temperature and/or salinity variationsthermocline — vertical zone in the water column in which temperature changes rapidly usually causing stratification of the water due to resulting different densities with lower densities for higher temperatures, in most parts of the Baltic Sea seasonally found with heated surface water in summer

thermodynamic equilibrium — the state of a system which is reached when it does not change by itself anymore, i.e. the (macroscopic) thermodynamic variables describing the system, the so-called state variables, remain unchanged over time; a set of state variables fully describing a system of sea water is, for example, salinity, temperature and pressure.

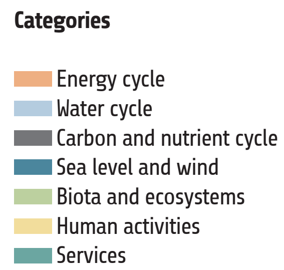
trophic cascade — a change of one species or trophic level of the food web (such as removal or addition of top predators) that triggers substantial changes in ecosystem structure, nutrient flows, and ecosystem functions

trophic level — a group of organisms in a food web of similar size

zooplankton — microscopic marine organisms which are not photosynthesizing, but feed on other organisms

Policy linkages

Linkages between the parameters affected by climate change and various major policies



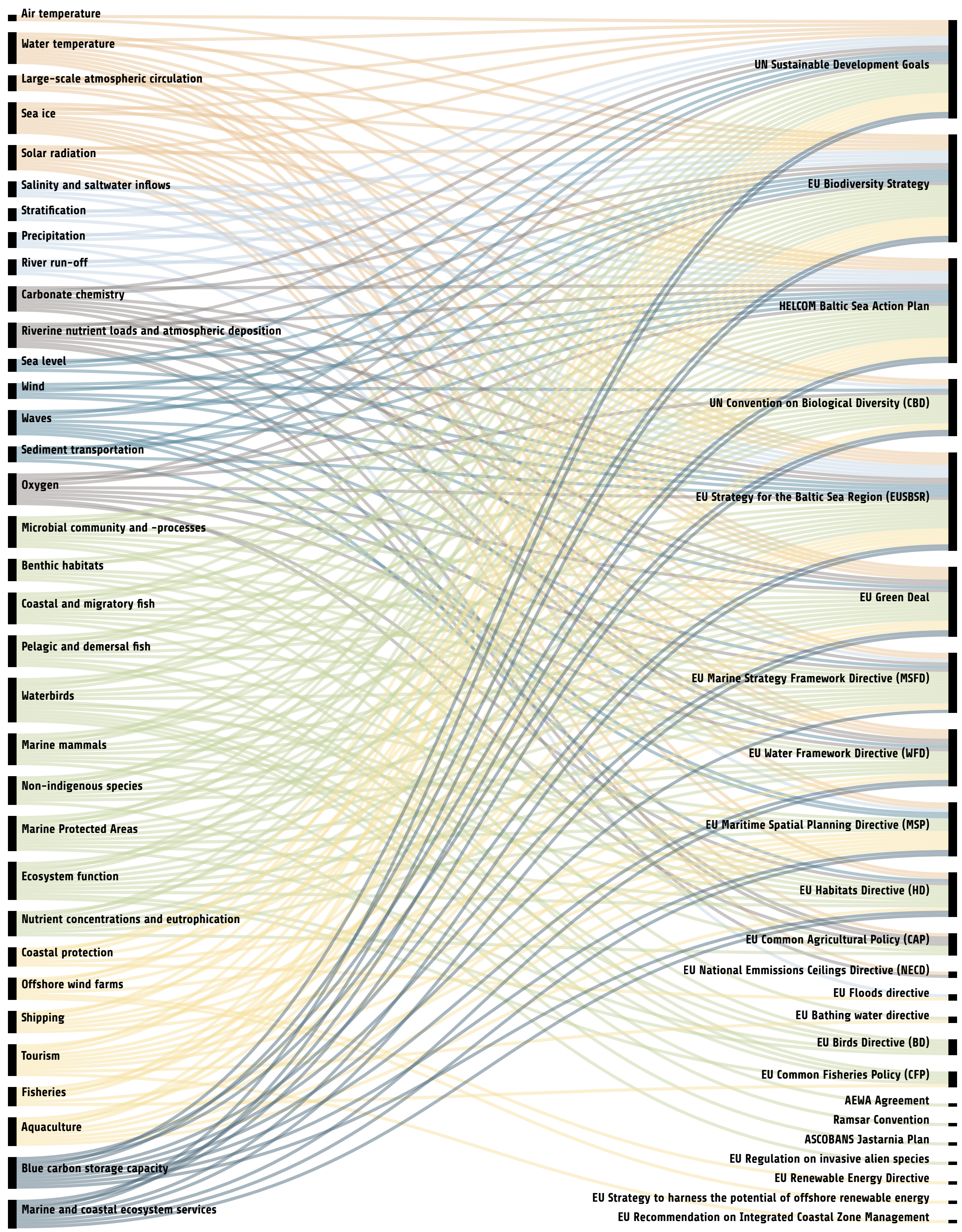


Figure 3. Linkages between the different parameters that were used in the assessment of the effects of climate change in the Baltic Sea and major policies.

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