Figure 2.2. Species in all parts of the food web are affected by changes in the Baltic Sea environment.

2.2. How is climate change affecting the Baltic Sea?

Climate change has global impacts on biodiversity and ecosystem health (IPCC 2023), and effects of climate change are also evident in the Baltic Sea today: the water temperature is rising, the ice extent is decreasing, and annual mean precipitation is increasing over the northern part of the region. Ongoing changes in the climate are having significant impacts on the Baltic Sea ecosystem, and this is expected to continue in the near future (HELCOM and Baltic Earth 2021, see also Box 2.1). All these changes affect the sea, its ecosystems and ecosystem services, as well as human activities that depend on these.

The effects of climate change are complex and could differ between parts of the Baltic Sea region (Meier *et al.* 2022). This complexity is further exacerbated by a system of feedbacks between climatic and non-climatic factors, as well as between different parts of the ecosystem (Figure 2.3). Climate change contributes to the cumulative pressure from multiple environmental and human-induced pressures. The effects of climate change can therefore in some cases be difficult to distinguish from certain human pressures (HELCOM/Baltic Earth 2021).

BOX 2.1.

Work on climate change knowledge in HELCOM

The joint HELCOM/Baltic Earth Expert Network on Climate Change (EN Clime) functions as a coordinating platform to connect leading scientists with expertise on the direct and indirect effects of climate change on the Baltic Sea environment. A key role of the platform is to make this expertise available to policymakers and create a space for closer dialogue. The network aims to ensure that new scientific findings on climate change and its impacts on oceans and seas are visible in HELCOM and find their way into HELCOM decision-making and day to day work. Among other things, the Expert Network produces and delivers scientific products on climate change, such as the climate change fact sheet (HELCOM and Baltic Earth 2021) and supporting material.

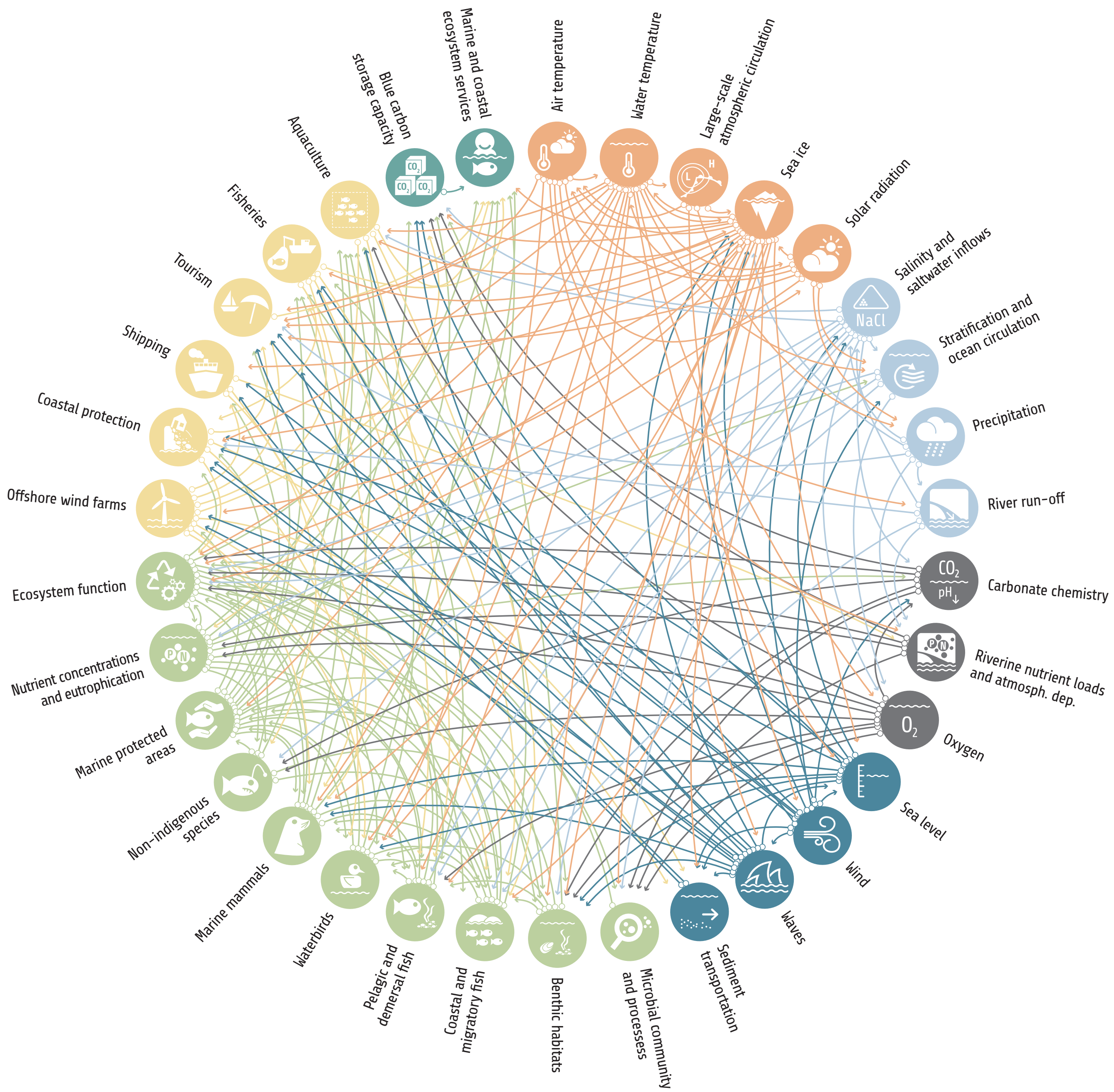

Figure 2.3. The Baltic Sea is facing complex effects and feedbacks between climatic and non-climatic factors, as well as between the effects of climate change on different parts of the ecosystem. Source: HELCOM/Baltic Earth 2021.

The Baltic Sea region is located between two climate zones, the maritime temperate and the continental subarctic climate zones. The opposing effects of moist and relatively mild marine airflows from the North Atlantic Ocean and the Eurasian continent make the climate of the region variable; the prevailing weather regime varies depending on the exact location of the polar front and the strength of the westerlies, and there are considerable seasonal and inter-annual variations (Meier *et al.* 2022).

The future climate projections with the greatest certainty show that the water temperature and sea level will rise, whereas sea ice cover will decrease. Such changes are already occurring in the Baltic Sea environment (Figures 2.3-2.5) and are linked to changes in the Baltic Sea ecosystem in various ways (Figures 2.6-2.7). Model scenarios are still uncertain about future changes in Baltic Sea salinity, although they show a tendency towards reduced salinity. The uncertainties relate to factors such as regional winds, the water cycle and global sea level rise. Increased oxygen deficiency is also expected (Meier *et al.* 2022). The scenario simulations, further, suggest that Baltic Sea water may become more acidic in the future, although these predictions depend on several uncertain factors, such as future emissions of pollutants that contribute to acidification. Changes in oxygen, salinity and acidity are likely to erode the resilience of the Baltic Sea ecosystem and affect the survival or distribution of its species.

How climate-related factors will develop further over time is tightly linked to changes in our society. In order to obtain realistic projections for the Baltic Sea, further work is needed on the scenarios and models that evaluate the relative importance of several drivers together (i.e. multiple or cumulative effects), as opposed to looking at climate change in isolation. This calls for a broad perspective that also considers factors such as changes in emissions, demographic and economic changes, and changes in land use. The evaluation of the effects of climate change on the ecosystem is also dependent on how other environmental drivers and pressures develop (Figure 2.4). Atmospheric and aquatic pollution and eutrophication, overfishing, and changes in land cover are all aspects that interact with climate-related changes to affect the environment (Meier *et al.* 2022).

Figure 2.4. The combination of biodiversity degradation and climate change creates a particularly challenging situation for plant and animals to adapt to changing environmental conditions.
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2.2.1 Trends in temperature in the Baltic Sea

Changes in air temperature is the main driver of changes in water temperature (Dutheil *et al.* 2021). Around the globe, marginal seas have warmed faster than the global ocean since the 1980s, and of these, the Baltic Sea has warmed the most (Belkin 2009). The surface water temperature has increased the fastest (Figure 2.5) and the heat spreads downward with time, eventually warming the whole water column (Meier *et al.* 2022). Monitoring data, satellite data and model-based historical reconstructions indicate an increase in the annual mean sea surface temperature of 0.4–0.6 C° per decade (averaged over the Baltic Sea), or around 1–2 Co since the 1980s. Without excluding internal variability, warming trends have recently accelerated tenfold (Meier *et al.* 2022).

In the future, the northern part of the Baltic Sea is expected to have higher water temperatures, a shallower mixed layer with a sharper thermocline during the summer, less sea-ice cover and greater mixing during the winter than today. Both the frequency and duration of marine heat waves will increase significantly in the Baltic Sea, in particular in the coastal zone, except in regions with frequent upwelling (Meier *et al.* 2022).

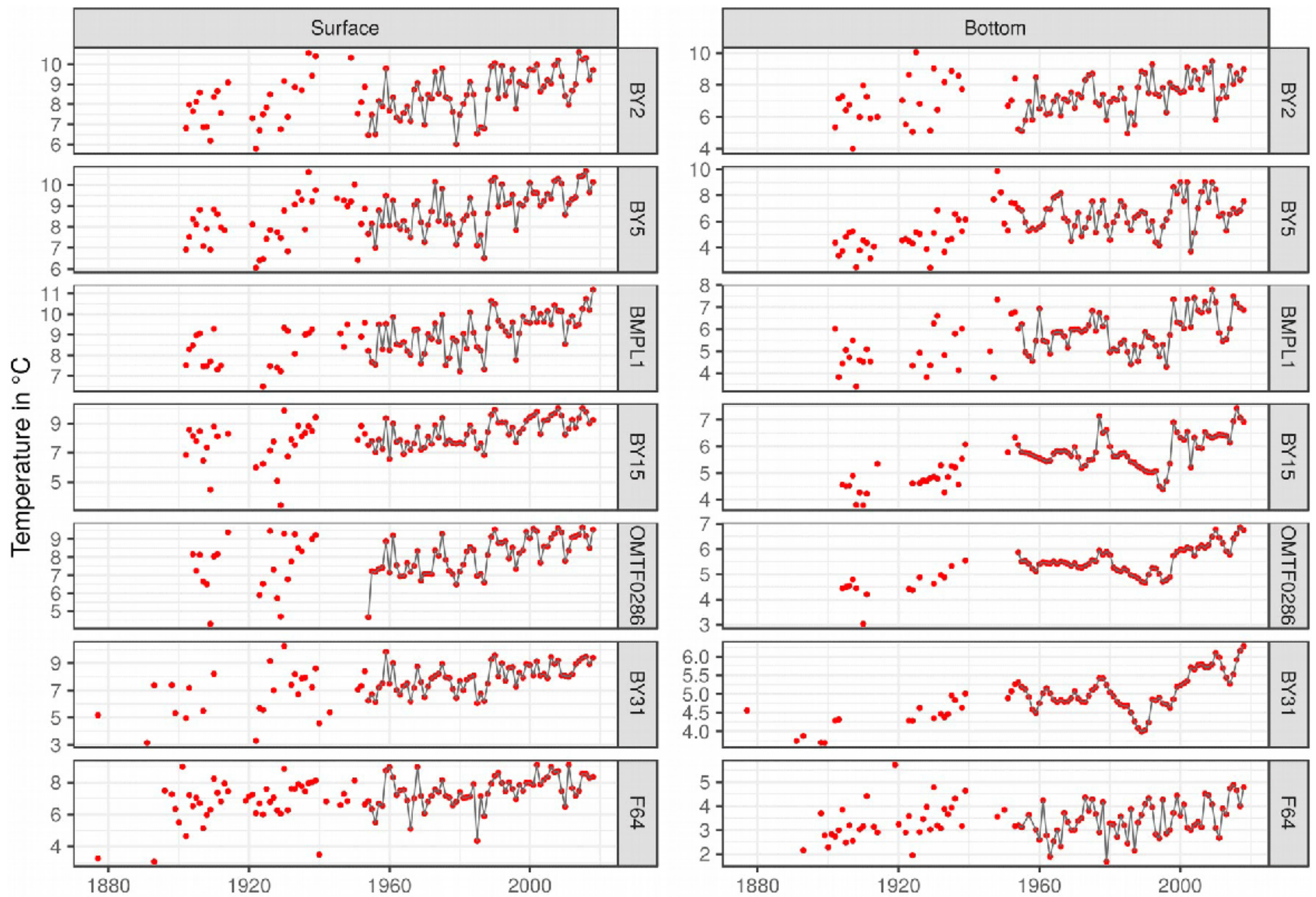

Figure 2.5. Changes in temperature. Annual mean values of daily sea surface temperature (left column) and bottom temperature (right column) at seven monitoring stations in the Baltic Sea during 1877–2018 (red dots). The grey lines indicate the period when every station has data for every year (1954–2018). The data shown has been post-processed to overcome possible seasonal biases due to missing values in the observations. For data sources and more details, see Meier *et al.* (2022).

2.2.2 Trends in ice cover in the Baltic Sea

The maximum extent of sea ice in the winter is an important key indicator of climate change in the Baltic Sea region. On average, around 40 % of the total Baltic Sea area is covered by ice in the winter (including the Kattegat and Skagerrak), which corresponds to about 170,000 square kilometres (Finnish Meteorological Institute 2023). Mild ice winters are defined as having a maximum ice cover of less than 130,000 square kilometres. The frequency of mild ice winters has increased from 7 years within the 30-year period 1950-1979 to 16 years within the 30-year period 1993-2022, whereas the frequency of severe ice winters (at least 270,000 square kilometres of ice) has decreased from 6 years to 1 year during the same periods (Figure 2.6). An extremely mild winter occurred in 2015, during which the Bothnian Bay was not fully covered by ice and the maximum extent in the Baltic Sea was 51,000 square kilometres. In the winter of 2020, the maximum ice extent was only 37,000 km^2, the lowest value since the start of the time series in 1720 (Finnish Meteorological Institute 2023) (Figure 2.7).

The trend of decreasing sea ice extent in the Baltic Sea exceeds natural variability so much that it can only be attributed to global climate change (Meier *et al.* 2022). Baltic Sea ice extent and thickness are projected to continue to shrink significantly. The best estimate of the decrease in maximum ice extent over the 21st century is 640km2/year for a medium emissions scenario (RCP4.5). For a high emissions scenario (RCP8.5), the decrease is estimated to be 1,090km2/year with largely ice-free winters by the end of the century (Luomaranta *et al.* 2015).

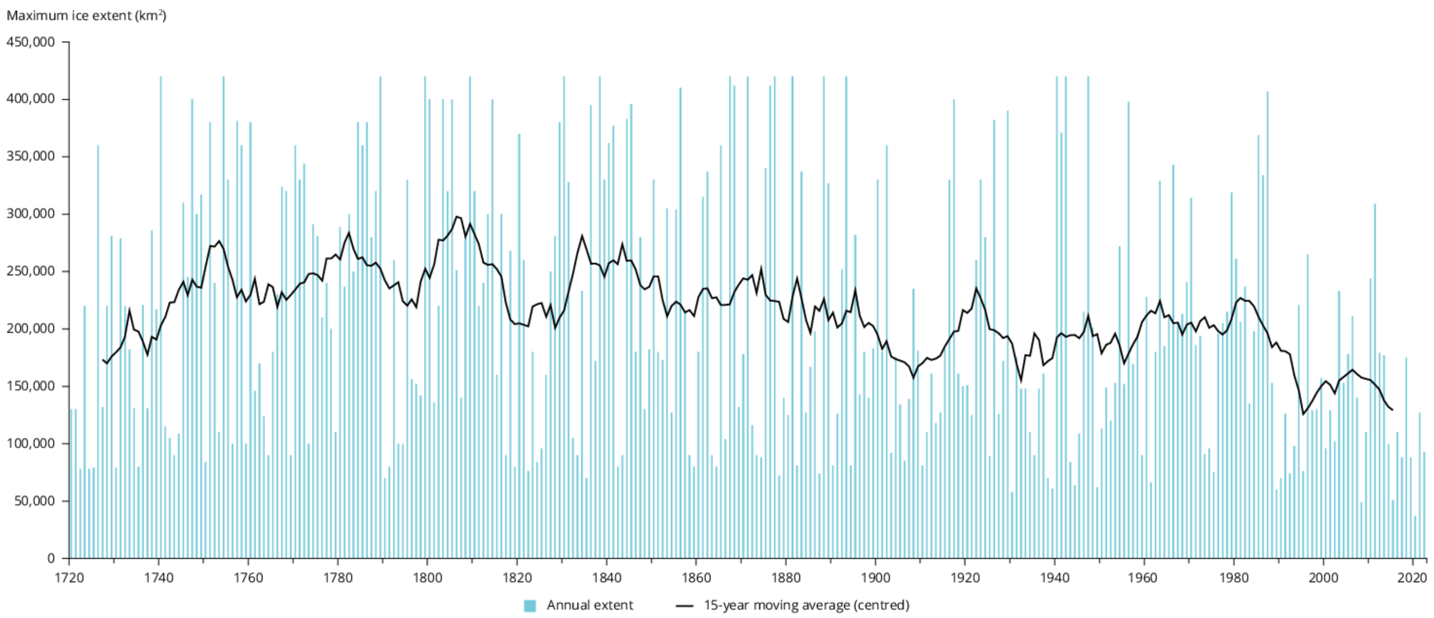

Figure 2.6. Changes in the maximum extent of ice cover in the Baltic Sea in the winter. The line shows a 15-year moving average. Source: EEA 2022.

Figure 2.7. Ice conditions in the winter is an important indicator of climate change in the Baltic Sea

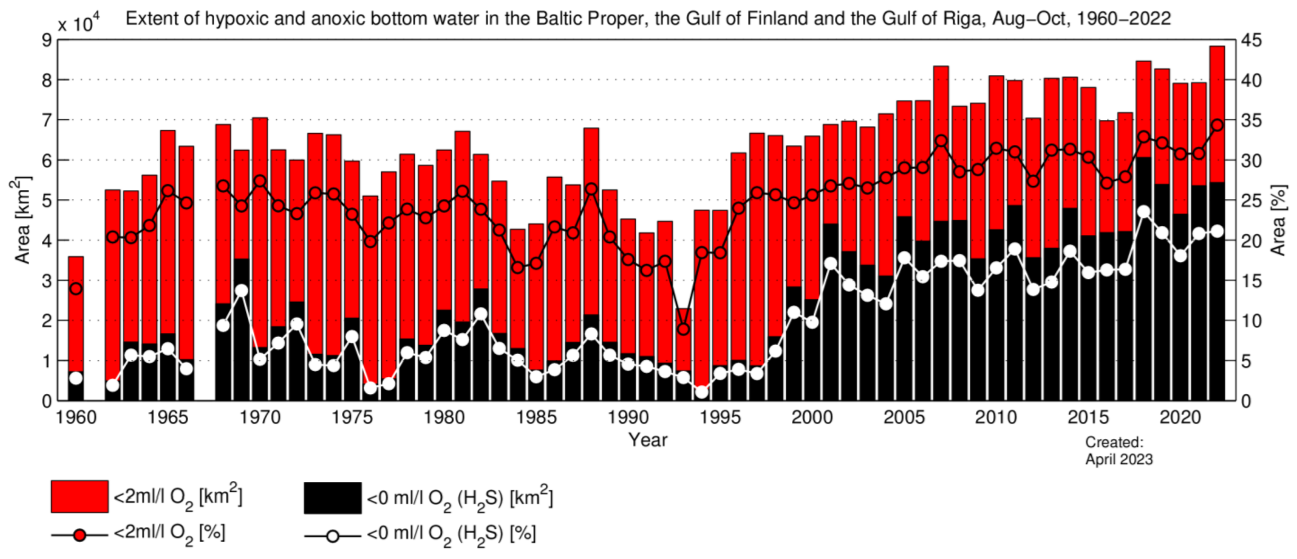

Figure 2.8. The extent of areas with hypoxic (<2 mL O_2 L^{-1}) and anoxic (<0 mL O_2 L^{-1}) bottom water in the Baltic Proper, the Gulf of Finland, and the Gulf of Riga during regular cruises in August–October during 1960–2020. Source: Hansson and Viktorsson 2023.

2.2.3 Effects of climate change on biogeochemical cycling and oxygen conditions

The impact of climate change on biogeochemical cycling is predicted to be considerable, but smaller than the impacts of nutrient inputs, even when recent nutrient reductions are considered.

Even in a future climate, implementing the nutrient reduction targets of the Baltic Sea Action Plan for the entire catchment area is expected to result in a significantly improved environmental status of the Baltic Sea, including a reduced hypoxic area (Figure 2.8). This would also increase the resilience of the Baltic Sea against climate change (Meier *et al.* 2022).

The areal cover of sea bottoms with no oxygen or poor oxygen conditions is considerably higher today compared to when the first oxygen measurements in the Baltic Sea were taken. In 2016, the maximum extent of areas with poor oxygen conditions (hypoxia) in the Baltic Sea was about 70,000 square kilometres, whereas it was presumably very small or even absent 150 years ago (Gustafsson *et al.* 2012, Carstensen *et al.* 2014a, b, Meier *et al.* 2019). Hypoxia is mainly caused by increased nutrient inputs from the land and atmospheric deposition, leading to eutrophication (Chapter 4). Other drivers, such as warming or sea level rise, have a smaller, though still important, impact (Carstensen *et al.* 2014a, Meier *et al.* 2019). On annual to decadal timescales, variations in the halocline also have a considerable influence (Conley *et al.* 2002, Väli *et al.* 2013).

2.3. Human uses of the Baltic Sea

The Baltic Sea countries benefit considerably from their utilization of the Baltic Sea, both economically and socially. Nine countries share the borders of the Baltic Sea, namely Denmark, Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Poland and Germany. Another five countries are partly located within its drainage area (Figure 2.9). In total, around 85 million people live within the drainage area of the Baltic Sea. The benefits we receive from the Baltic Sea include jobs, income and natural resources, as well as various contributions to personal well-being. We all depend on biodiversity in our daily lives in ways that are not always directly apparent or appreciated.

Figure 2.9. The Baltic Sea and its drainage area.