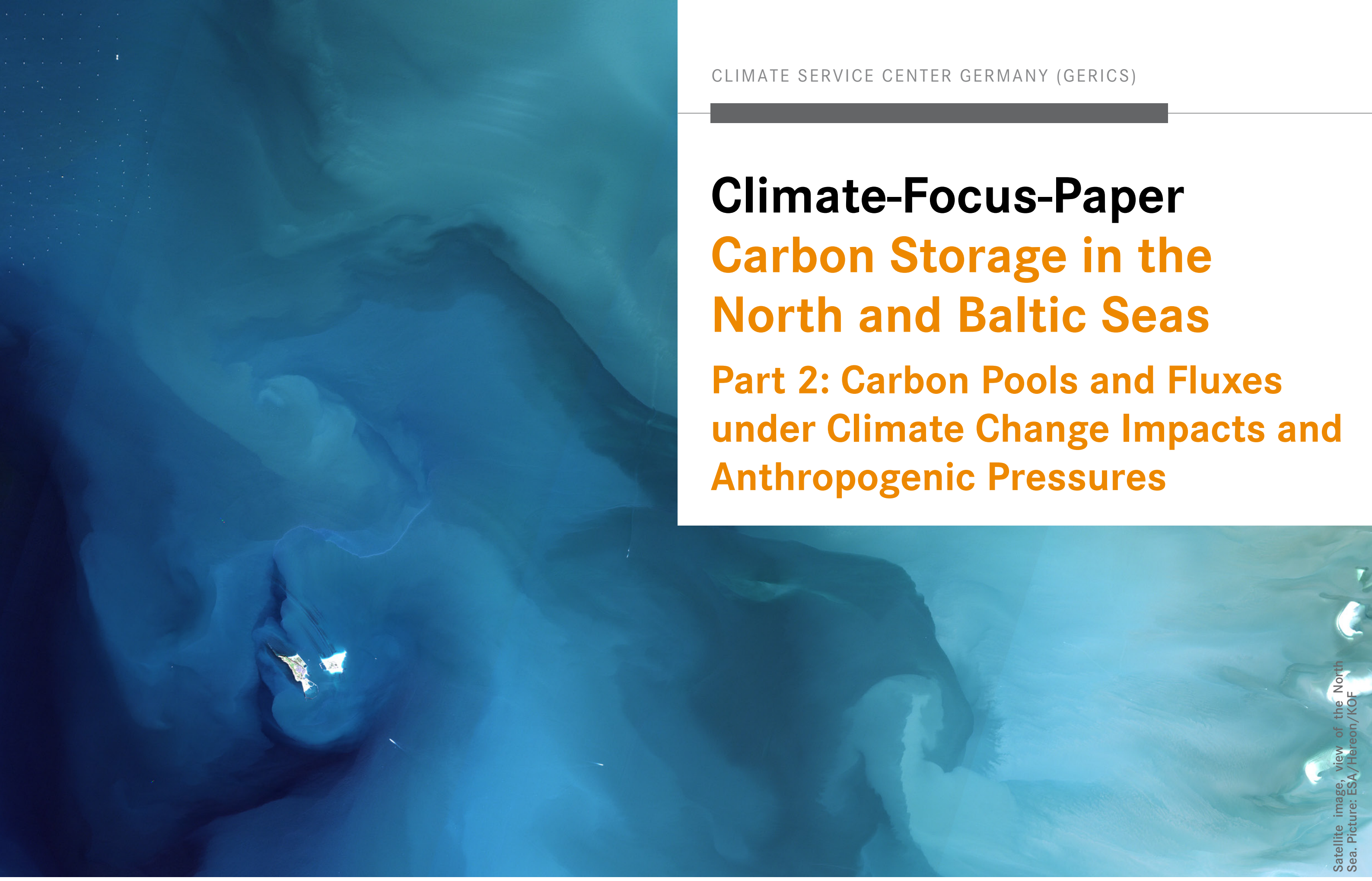
CLIMATE SERVICE CENTER GERMANY (GERICS)

Climate-Focus-Paper
Carbon Storage in the North and Baltic Seas
Part 2: Carbon Pools and Fluxes under Climate Change Impacts and Anthropogenic Pressures



Satellite image; view of the North Sea. Picture: ESA/Hereon/KOF

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- → The main driver of altered carbon pools in the water columns of the North Sea and Baltic Sea is the rising CO_2 concentration in the atmosphere, which forces atmospheric CO_2 into the water. However, increasing sea surface temperatures reduce the uptake capacity of atmospheric CO_2.
- → It is anticipated that the salinity of the North Sea will decline during the 21st century, which will result in a reduction of the capacity to absorb atmospheric CO_2; conversely, it is unlikely that the salinity of the Baltic Sea will undergo significant alterations.
- → Sea level rise may enhance or reduce the ability of the ocean to absorb atmospheric CO_2. For instance, carbon storage in seagrass beds could be diminished, whereas a stronger weathering of carbonate-containing rocks could strengthen the CO_2 uptake.
- → The extension of the summer growth phase of phytoplankton due to lower wind speeds in the future will increase the uptake of CO_2 from the atmosphere. However, a predicted increase in storm activity particularly in winter may lead to greater erosion of coastal habitats and a decline in carbon sequestration in e.g. seagrass beds.
- → Increasing water turbidity in both seas, caused by an increase in the concentration of suspended matter, could lead to a decrease in phytoplankton production and CO_2 uptake from the atmosphere.
- → Anthropogenic riverine nutrient inputs have been reduced in both seas in recent decades. Model simulations with strong nutrient reductions show an overall increase in dissolved inorganic carbon (DIC) in the Baltic Sea in the short term, while in the long term, the reduction of hypoxic areas will increase the capacity to absorb atmospheric CO_2. No major changes of the carbon pools are expected for the North Sea.
- → Increasing freshwater input into the Baltic Sea is predicted for the northern regions, reducing its capacity to absorb atmospheric CO_2.
- → Bottom trawling generally reduces the ocean's capacity to absorb atmospheric CO_2. The disturbance of sediments can release organic carbon and additional nutrients into the water column. However, during nutrient limitation periods in the North Sea, the released nutrients can be used for additional primary production leading to the absorption of atmospheric CO_2.
- → It is expected that natural processes over which humans have no direct control will dominate the uptake capacity of atmospheric CO_2 over manageable anthropogenic influences.
- → The North Sea is currently a sink for atmospheric CO_2. However, as CO_2 emissions and water temperatures rise, the North Sea will become less effective at absorbing CO_2 from the atmosphere or even becoming a source of atmospheric CO_2. For the Baltic Sea, it is not possible to identify a general future trend in its development as a net sink or source of atmospheric CO_2 due to high uncertainties and large regional differences.

CARBO STORE
Carbon Storage in German Coastal Seas

GERICS
Climate Service Center
Germany

Bundesministerium
für Bildung
und Forschung

Introduction

The oceans play a significant role in mitigating climate change due to their ability to absorb large amounts of CO_2 from the atmosphere. They are therefore a very important carbon sink.

In order to better understand the processes of marine carbon storage, the *CARBOSTORE* project (Carbon Storage in German Coastal Seas) conducts research on carbon pools in the North and Baltic Seas and provides background information and project results in two Climate Focus Papers (CFP).

The first Climate Focus Paper provides an overview of carbon pools and fluxes in the North and Baltic Seas: it quantifies the larger carbon pools and offers a brief outlook on potential future developments of carbon pools and fluxes. Carbon enters the ocean in numerous ways, including from the atmosphere, rivers, and groundwater, and in different forms, including organic, inorganic, dissolved, and particulate. In the marine environment, carbon can be transformed into organic compounds through photosynthesis or remain in the water column as dissolved inorganic and organic carbon (DIC, DOC). It can also be stored in the sediments as particulate organic and inorganic carbon (POC, PIC). A carbon pool is defined as a class of carbon compounds (e.g. dissolved inorganic carbon) in the water column (pelagic zone) or the sediment (benthic zone) within a defined area (e.g. the North Sea). It has been shown that in the North Sea and the Baltic Sea, the largest pool of carbon is dissolved inorganic carbon in the water column[1,2]. Within the North Sea, this pool is enriched by an effective uptake of atmospheric CO_2. The circulation of the North Sea effectively transports absorbed carbon out of the North Sea. It is transported to deeper ocean layers in the North Atlantic and is stored there for centuries. In contrast, the Baltic Sea has a close to net zero uptake of atmospheric CO_2. Moreover, large accumulation centers of organic carbon (referred to as deposit centers, where large quantities of carbon have been accumulated over the centuries) can be found in the sediments of the Skagerrak and the Norwegian Trench. The carbon there has been transported from large parts of the North and Baltic Seas.

This second CFP focuses on environmental parameters and anthropogenic pressures that may alter the carbon pools. It also takes a closer look at the possible effects of climate change on future carbon storage in the North and Baltic Seas. The selection of climate-related and anthropogenic stressors for the North Sea was based on the review article by Legge et al. (2020)[3] and references therein. In the case of the Baltic Sea, some of the changing environmental conditions and their consequences were derived from the review articles by Meier et al. (2022a and 2022b)[4, 5] and references therein.

Background

Environmental conditions in the North Sea and the Baltic Sea have changed dramatically over the last 50 years. They have already altered the carbon pools in recent decades and will continue to do so in the future. The main driver is the increase in atmospheric CO_2 by anthropogenic emissions. This is forcing CO_2 from the atmosphere into the water. The current partial pressure of atmospheric CO_2 is 420 ppm. Projections range from <400 (SSP1-1.9) to >1000 ppm (SSP5-8.5) by 2100 (SSP - Shared Socioeconomic Pathway)[6]. By absorbing large amounts of atmospheric CO_2, the ocean has been acting as a buffer to increasing atmospheric CO_2 concentrations, preventing even worse warming. However, as the ocean continues to absorb more and more CO_2, this buffer effect diminishes, and the ocean continues to acidify. Without a functioning buffer effect, the current atmospheric CO_2 concentration would be much higher and global warming would progress even faster. Additionally, the acid binding capacity of the water (also known as alkalinity) and the concentration of DIC determine the extent to which seawater acidifies due to CO_2 uptake. Several processes, including the weathering of carbonate rocks in the Baltic Sea and anaerobic processes in the Wadden Sea, can increase alkalinity. This elevated alkalinity allows more CO_2 to be absorbed without negative effects such as acidification and its harmful consequences for the marine environment.

Climate change is causing an increase in atmospheric temperature, which has warmed the surface waters of both sea areas relatively fast in global comparison[7]. As the solubility of carbon dioxide in water decreases with increasing water temperature, the capacity of the oceans to absorb atmospheric CO_2 will decrease[8], leaving more CO_2 in the atmosphere and exacerbating global warming.

Furthermore, climate change may result in environmental changes, including a reduction in salinity due to altered North Atlantic currents, less sea ice in the northern Baltic Sea, a rise in sea level, and changes in wind speeds. These factors will also influence the future development of marine carbon storage (see chapters below).

Other direct and indirect anthropogenic environmental influences affecting the carbon pools of the North Sea and Baltic Sea include disturbance of marine sediments, such as by bottom trawling and the installation of large wind farms, and nutrient inputs from rivers and the atmosphere, leading to eutrophication. Eutrophication has a direct impact on the carbon balance of water bodies: it stimulates primary production which indirectly removes CO_2 from the atmosphere. The corresponding carbon can be stored or remineralised, which in turn may pose a problem for the water body, creating anoxic areas with negative consequences for living organisms and ultimately also for carbon storage[9].

The following chapters provide an overview of important factors that influence and could change carbon storage in the North and Baltic Seas in the future. However, it should be noted that considering environmental factors and anthropogenic disturbances in isolation from each other has its limitations when dealing with such a complex question as the future development of marine carbon storage.

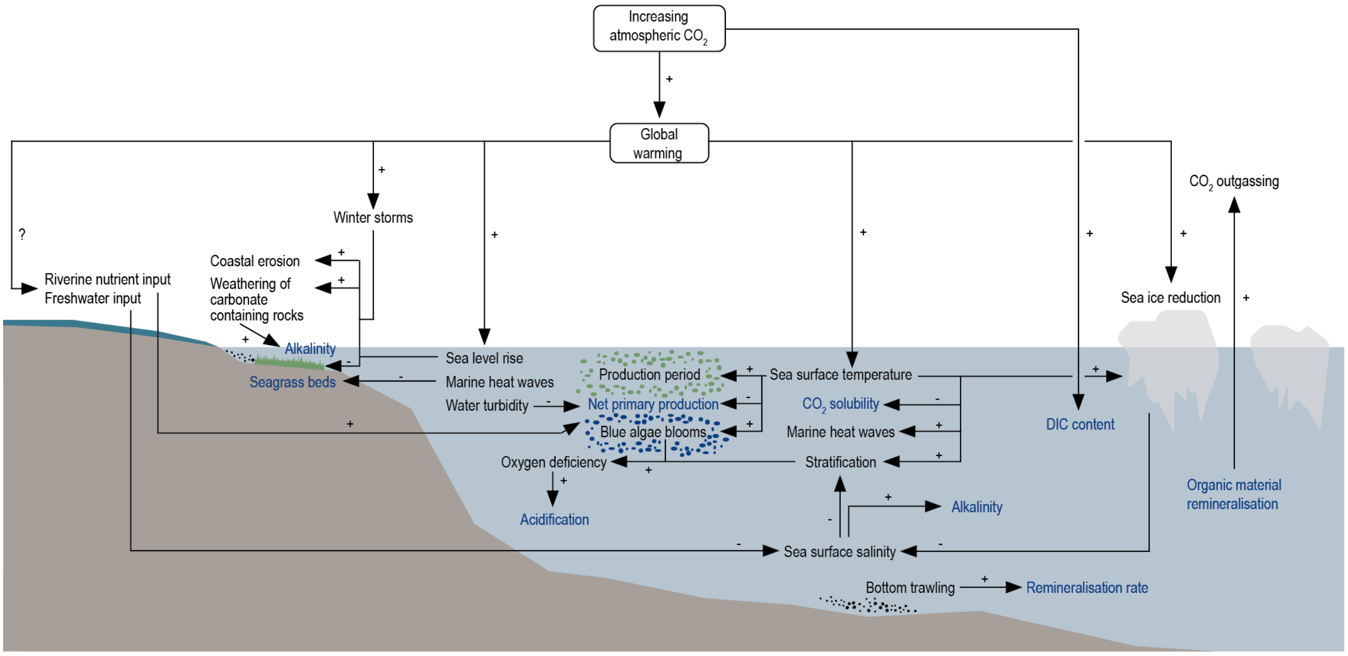

Figure 1: Simplified representation of the changing environmental factors influencing the capacity to absorb atmospheric CO_2 and their interactions. Factors directly affecting atmospheric CO_2 uptake are shown in blue. Arrows and the symbols +, -, ? illustrate how one environmental factor affects another. The symbol + indicates a process in the same direction (e.g. an increase in winter storms leads to increased coastal erosion), the symbol - indicates a process in the opposite direction (e.g. rising sea surface temperatures lead to reduced CO_2 solubility), and the symbol ? indicates an unclear influence.

The North Sea

In the North Sea region, sea surface temperature (SST) is increasing and is expected to continue to increase throughout the 21st century[10]. Salinity is expected to decline due to the predicted decrease in the salinity of the neighbouring North Atlantic[11, 12]. It is anticipated that mean wind speeds in spring, summer, and autumn will decrease[13], although the storm activity over north-west Europe is expected to increase[14]. On the land side, nutrient inputs from sewage treatment and agricultural activities are expected to decrease, although strong precipitation events could increase the supply of fresh water from rivers, thus also increasing the supply of nutrients and organic carbon compounds[15]. However, there is a high degree of uncertainty in this context. All these trends, many of which are climate-related, have an impact on the carbon content of the North Sea and its capacity to absorb atmospheric CO_2.
The main environmental and anthropogenic pressures that affect the North Sea's ability to store carbon are briefly outlined below.

Sea surface temperature

The latest IPCC report shows a range of expected sea surface temperatures between -0.7 to 1.8° C (mean: 0.6° C) for the low emission scenario SSP1-2.6 and 1.2 to 4.6° C (mean: 2.9° C) for the high emission scenario SSP5-8.5 by the end of the 21st century relative to a 1991–2020 average[10].

→ The pelagic carbon budget is affected by rising water temperatures in several ways. However, the dominant effect for the North Sea region is the reduction in CO_2 solubility, leading to a reduction in atmospheric CO_2 uptake[3].

→ An increase in sea surface temperature is also expected to increase the intensity of water column stratification on the shelf[16]. This is because the heat source affects the upper water column, which therefore heats up more than the deeper layers. This leads to a decrease in primary production due to a reduced nutrient supply from the North Atlantic, as more nutrient-depleted surface water is imported from there[11]. A decline in primary production will reduce the absorption of atmospheric CO_2. The increased stratification can cause the expansion of oxygen-deficient areas, or at least induce short-term hypoxia. In these areas, anaerobic remineralisation in the sediments (which means the decomposition of organic material in the absence of oxygen) will become dominant[17]. Consequently, N_2 gas is released from the marine system, which in turn reduces primary production and the uptake of atmospheric CO_2.

→ Rising temperatures increase the biogeochemical turnover in the mostly anaerobic Wadden Sea sediments through enhanced bioturbation and remineralisation[18]. The Wadden Sea is defined in this Climate Focus Paper as the area between the islands and the mainland that is covered by water at high tide. Due to rising water temperatures and increasing bioturbation it can be expected that the Wadden Sea remineralisation processes will intensify, with inorganic components (e.g. DIC and alkalinity) reaching the southern North Sea in greater quantities. To date, this has reinforced the buffering effect of the carbonate system in the southern North Sea, resulting in enhanced CO_2 absorption from the atmosphere without an increase in acidification. This effect is likely to intensify in the future.

→ In June 2023, a severe marine heat wave (MHW) occurred in the eastern North Atlantic and North Sea[19]. Such events will happen more often in the future. This is derived from projections to mid-century under a high CO_2 emissions scenario RCP8.5 (Representative Concentration Pathway). The consequence of such heat waves is stronger stratification and lower primary production[20], and thus a reduction in the absorption capacity of atmospheric CO_2.

→ Changes in the composition of benthic and pelagic plankton species due to warming and acidification could alter the proportion of calcite shell-formers, thus affecting benthic calcite stocks. However, knowledge of benthic calcite stocks is very limited, making it difficult to predict future changes in this important part of the carbon budget[3].

As previously stated, the lower solubility of CO_2 is likely to have the greatest effect on the carbon content in the North Sea, given that the stratification effect is only applicable during the warm season. Furthermore, the reduced nutrient supply from the North Atlantic is expected to increase again after 2100[21]. The Wadden Sea only has an impact on the southern North Sea.

Salinity

The salinity of the North Sea is predicted to decrease in the 21st century due to the decreasing salinity of the inflowing Atlantic waters[13].

→ In addition to temperature, salinity also determines the structure of the water column: As predicted by Gröger et al. (2013)[11], a lower salinity in the surface water increases stratification and reduces primary production, as mentioned above for temperature.

→ A decrease in salinity is also associated with a decrease in alkalinity. This results in a reduction in the buffering capacity of the carbonate system and a diminished absorption capacity of atmospheric CO_2[3].

In summary, the clear prediction of a reduction in salinity also implies a clear prediction of a reduced capacity to absorb CO_2.

Sea level rise

Recent high-emission climate model projections (SSP5-8.5) indicate a sea level (SLR) rise of 60-70 cm for large parts of the North Sea by 2100[22]. For a marine area such as the North Sea, the SLR also interacts with the tidal dynamics. In their model results, Jordan et al. (2021)[23] observe a critical increase in tidal ranges for the Wadden Sea area above a certain level of SLR. They argue that not only a mid-range SLR can be anticipated, but that considerably higher floods can be expected regularly, which can then also reach previously dry areas, resulting in erosion and the transport of terrestrial carbon into the sea. This additional carbon, mostly organic, is remineralised, increasing the DIC pool and reducing the capacity to absorb atmospheric CO_2, at least near the coast.

Based on a review of the literature on predicted carbon losses due to SLR, Legge et al. (2020)[3] estimate a decrease of approximately 10 Kt of carbon per year in the combined storage of carbon in salt marshes, mud and sand flats, and seagrass meadows due to habitat area losses in the north-west European continental shelf seas, which includes the North Sea. This quantity of carbon would then potentially be incorporated into the DIC pool, reducing the absorption capacity of atmospheric CO_2.

Mean wind speed and storm activities

Mathis and Pohlmann (2014)[13] have demonstrated that the average wind speed will decrease in the 21st century. This applies to all seasons except winter. Model experiments by Harvey et al. (2012)[14] indicate a slight increase in storm activity (storm intensity) over north-western Europe in winter[24].

→ Lower mean wind speeds in the warmer seasons prolong the duration of temperature-dependent stratification of the water column by approximately six days[13], which has the potential to extend the growth phase of phytoplankton as long as nutrients are available. This is accompanied by an increase in the uptake of atmospheric CO_2.

→ An increase in storm activity results in the erosion of sediments in coastal habitats, which in turn leads to a decrease in the carbon bound in biomass, as observed in seagrass meadows[3]. The organic carbon that is released is remineralised, reducing the capacity of the atmosphere to absorb CO_2. Increased storm activity increases the ocean-atmosphere gas exchange[25]. However, after several days or weeks, the DIC content in the water is found to be similar to that observed during a period of less storm activity.

The prolongation of the phytoplankton growth phase appears to be important, as there would probably be no negative side-effects such as increased hypoxic areas over longer periods. This phenomenon can be attributed to the North Sea circulation, which effectively removes the dead organic material and transports it into the adjacent North Atlantic.

Water turbidity

Before the 1950s, the water turbidity of the central and southern North Sea was considerably lower than it has been since then. The increase in water turbidity is due in part to an increase in the concentration of suspended matter. A combination of causes is thought to have contributed to this increase in suspended sediment, including changes in seafloor communities and weather patterns, rising estuarine export, particularly from rivers in the south-east of the UK, and enhanced coastal erosion. A predicted future increase in storm activity could result in higher concentrations of suspended sediment in the water column, leading to a further increase in water turbidity. This could result in decreasing phytoplankton production and CO_2 uptake from the atmosphere[26].

Fresh water and nutrient inputs from rivers and the atmosphere

Anthropogenic nutrient inputs from rivers and the atmosphere affect the carbon storage capacity of the oceans, for example by enhancing primary production. However, an oversupply of nutrients causes eutrophication, which leads to oxygen deficiency or even depletion. Riverine inputs of nutrients such as nitrate and phosphate to the North Sea have been in decline for several decades. Atmospheric nitrogen deposition into the North Sea has also been reduced. This has been achieved through the reduction of phosphorus in today's detergents, and the increasing removal of nitrogen compounds by wastewater treatment. The most recent IPCC report[6] predicts a decrease in run-off for continental rivers under the highest emission scenario, particularly during the summer months (see Figure 8.18 in IPCC, 2021[6]). For all other global emission scenarios, future trends remain uncertain. Winter high run-off events during heavy precipitation are likely to increase[27]. Projections of nutrient loads are even more uncertain than projections of river discharge due to the unknown future land use[12] and agricultural development. Legge et al. (2020)[3] report a possible increase in run-off, which would increase nutrient loads, and a possible decrease in nutrient concentrations, which would decrease nutrient loads. They conclude that the net effect on the total amount of nutrient input to the Northwest European shelf, of which the North Sea belongs to, is uncertain. Schöpp et al. (2003)[28] predict that atmospheric nitrogen deposition over Europe will continue to decrease until at least 2030.

Recent studies have shown that the Elbe-North Sea region is already experiencing the effects of droughts[29, 30] and floods[31, 32]. These studies have revealed that these extremes alter the nutrient and carbon fluxes at the land-ocean interface. Droughts have been identified as low input situations, while floods have been identified as high input situations for nutrients and carbon.

For the North Sea, model results from the CARBOSTORE project[33] show that substantial reductions in nutrient inputs do not significantly alter carbon pools because of the effective flushing of the North Sea by North Atlantic waters (Box 1).

Box 1: Effects of OSPAR and HELCOM nutrient reduction goals on carbon pools in the North and Baltic Seas

Nutrients enter the sea from rivers and the atmosphere and influence the magnitude of carbon pools in the ocean. An oversupply of nutrients can lead to eutrophication and oxygen depletion in the water, which is a serious environmental problem in the Baltic Sea, and, to a lesser extent, in the North Sea. OSPAR countries have addressed eutrophication through the North-East Atlantic Environmental Strategy (NEAES)[34], while HELCOM countries have done so in the Baltic Sea Action Plan (BSAP)[35]. HELCOM members have agreed to set Maximum Allowable Inputs (MAIs) of nutrients to regulate the amount of nitrogen and phosphorus that can be discharged into the Baltic Sea without negative impacts for the marine environment (see Table 1 in HELCOM, 2021[35]), whereas the OSPAR countries have yet to agree on MAIs for the North-East Atlantic.

The CARBOSTORE project investigated the effects of meeting the OSPAR and HELCOM nutrient reduction targets on carbon pools in the North Sea and Baltic Sea. Numerical simulations with nutrient reductions were carried out in accordance with the MAI by HELCOM and with scientifically validated proposals for the OSPAR Commission[36, 37].

For the North Sea, percentages for total nitrogen and total phosphorus are given for each coastal country and for the largest rivers in the North Sea region. These percentages refer to average inputs from 2009 to 2014 and represent the reduction targets (see Table A.7.1 in OSPAR, 2022[37]). Atmospheric deposition is not affected by the reduction.

For the Baltic Sea (including the Skagerrak), the MAIs include inputs from rivers and the atmosphere. In the reference run (1993-2018), which reflects reality as closely as possible, the MAIs for the entire Baltic Sea region were almost reached in 2018 (inputs still 9 % too high for nitrogen and 23 % too high for phosphorus). In order to reach the MAIs in the reduction run, riverine and atmospheric inputs in 2018 were reduced by these 9 % and 23 % for nitrogen and phosphorus, respectively. These reduced 2018 inputs were then repeatedly prescribed for each simulation year in the Baltic Sea area. Figure 2 illustrates the annual loads of dissolved inorganic nitrogen for the reference run and the nutrient reduction run.

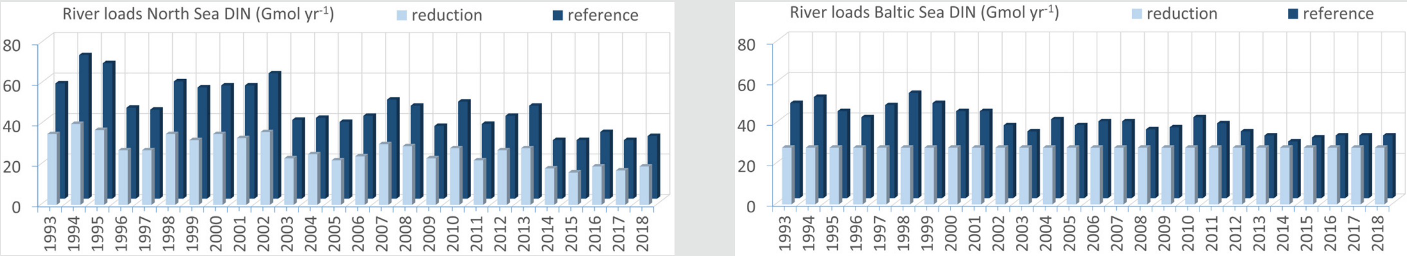

Figure 2: Dissolved inorganic nitrogen (DIN) loads for the reference run and the nutrient reduction run for the North Sea (left) and Baltic Sea (right). Figures based on unpublished model forcing data provided by Cahill.

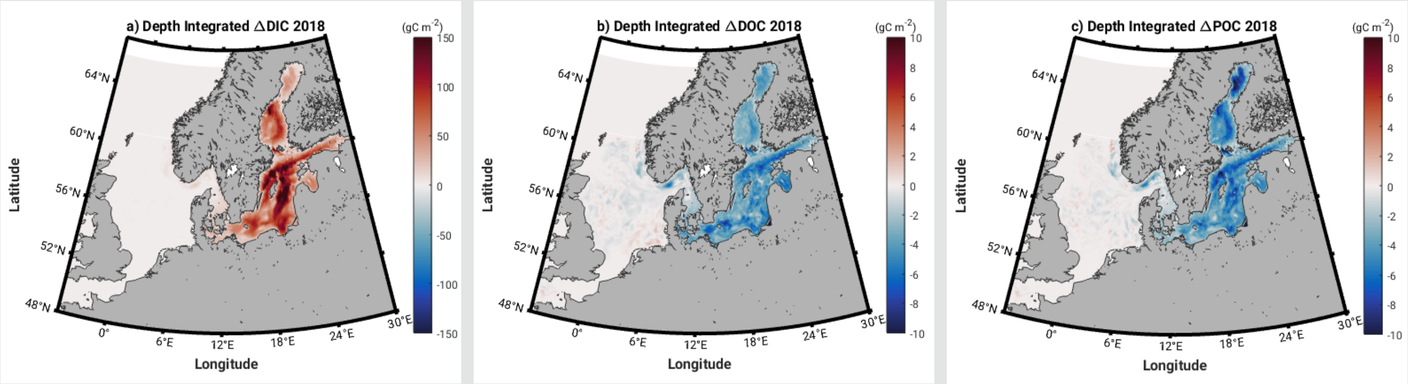

Figure 3: Horizontal distribution of ΔDIC (left), ΔDOC (middle), and ΔPOC (right), the differences between the reduction run and the reference run for the year 2018 (Cahill, unpublished data). The values represent the whole water column (depth-integrated). DIC: Dissolved inorganic carbon; DOC: dissolved organic carbon; POC: particulate organic carbon.

Figure 3 illustrates the differences between the “reduction run” and the “reference run”. The simulation indicates that the DIC content in the water column of the North Sea hardly reacted to the nutrient reductions, while the DIC content in the Baltic Sea increased, especially in the water column of the deep basins.

The results for the Baltic Sea demonstrate that the DIC pool is larger in the reduction run, where the inorganic fraction dominates (left figure). This is due to a reduction in primary production, which in turn leads to a reduction in DIC consumption. DIC enrichment in the Baltic Sea responded to this nutrient reduction already after the first simulated year. However, it continued to increase over the course of the simulation. The North Sea is flushed by Atlantic waters and therefore has limited capacity to accumulate organic material from its production. In contrast, the Baltic Sea has a greater capacity to accumulate material due to a lower exchange with the neighbouring sea. These hindcast results can also be used to predict the future development of carbon pools in the North and Baltic Seas under nutrient reduction: The North Sea will probably show no change in carbon pools despite nutrient reductions. The DIC pool in the Baltic Sea will increase if the MAIs are strictly adhered to, even though the uptake capacity of atmospheric CO_2 is reduced.

Bottom trawling

The impact of bottom trawling on biogeochemistry and carbon pools has already been investigated globally and for the North Sea region (see also *APOC* project results about the impacts of bottom trawling on POC cycling and accumulation in the North Sea). It has been found that over the last two decades, more than 0.34-0.37 Gt CO_2 per year have been released into the atmosphere globally from bottom trawling[38]. This is about 1 % of annual global CO_2 emissions. The North Sea study by De Borger et al. (2021)[39] found a significant reduction in benthic remineralisation even at shallow penetration depths due to the release of organic carbon and nitrate induced by bottom trawling. This remobilised organic carbon is remineralised in the water column, increases the proportion of inorganic carbon and leads to a reduction in the absorption capacity for atmospheric CO_2. A new study for the North Sea[40] revealed that bottom trawling leads to additional oxygen being supplied to agitated sediments, resulting in additional remineralisation under oxygen consumption, DIC release and a subsequent lowering of the uptake of CO_2 from the atmosphere. Porz et al. (2024)[41] confirm that this effect can be found particularly in the muddy areas of the North Sea. Consequently, with the continued practice of bottom trawling, the frequency of remineralisation in the absence of oxygen will diminish. However, this type of decomposition of organic material releases alkalinity. From a carbon budget perspective, this means that continued bottom trawling will result in a decreased absorption capacity of atmospheric CO_2. Legge et al. (2020)[3] also see an additional release of nutrients from the sediment into the water column in the Northwest European Shelf due to bottom trawling. This could promote primary production and enhance the uptake of CO_2 from the atmosphere.

Table 1 summarises the main environmental factors and anthropogenic pressures affecting the North Sea's capacity to absorb atmospheric CO_2.

Environmental and anthropogenic pressures	Derived environmental changes	Uptake capacity of atmospheric CO_2
Sea Surface Temperature increase	CO_2 solubility ↘	↘
	Stratification ↗	↘
	Net primary production ↘	↘
	Oxygen-deficient areas ↗	↘
	Plankton composition ?	?
	Wadden Sea turnover ↗	↗
	Marine heatwaves ↗	↘
Salinity decrease	Stratification ↗	↘
	Alkalinity ↘	↘
Sea level rise	Coastal erosion ↗	↘
	Area of coastal habitats ↘	↘
Changing wind patterns	Mean wind speed ↘	↗
	Winter storm activity ↗	↘
Increase in water turbidity	Phytoplankton production ↘	↘
Changing fresh water and nutrient inputs from rivers and the atmosphere	?	?
Bottom trawling	Alkalinity ↘	↘
	Nutrient release ↗	↗

Table 1: Potential uptake capacity of atmospheric CO_2 by the North Sea in response to changing environmental factors and anthropogenic pressures relevant to carbon storage. The symbol ↘ represents reduced CO_2 uptake capacity by the North Sea or increased outgassing and decreasing environmental factors in column 2, the symbol ↗ represents increased CO_2 uptake capacity by the North Sea or decreased outgassing and increasing environmental factors in column 2, while the symbol ? indicates that the CO_2 uptake capacity or the environmental change in column 2 is unclear.

The Baltic Sea

Similar environmental factors and anthropogenic pressures as in the North Sea will influence future carbon storage in the Baltic Sea. Rising sea surface temperature will have different consequences for marine carbon storage. The prediction of future changes in salinity and wind speed is subject to great uncertainty[5], making it difficult to identify clear impacts on future carbon storage. The Baltic Sea is also affected by sea level rise[5, 42], with varying effects on carbon storage. One likely consequence of rising sea levels is the increasing weathering of carbonate-containing rocks, which could support additional carbon storage[43]. A reduction in nutrient inputs could lead to increased DIC pools in the short term, as shown by model experiments. Finally, anthropogenic impacts such as bottom trawling disturb carbon storage in the sediments, thereby reducing the uptake capacity of atmospheric CO_2.

Sea surface temperature

Warming of the surface water is also expected for the Baltic Sea. Recent global model results from the latest IPCC report show a range between 0.2 and 2.5° C (mean: 1.4° C) for the low emission scenario SSP1-2.6, while the high emission scenario SSP5-8.5 covers the range 2.2-5.8° C (mean: 4° C) relative to a 1991–2020 average[10]. It is predicted that the northern regions of the Baltic Sea will warm twice as fast as the southern regions. The rise in water temperature will have several consequences for future carbon storage:

- → Transport of oxygen-rich surface water to deeper water masses will be reduced due to intensified stratification in the future. The strong rise in surface temperature inhibits redistribution between the surface and deeper water, leading to increased stratification. As a result, the already highly isolated deep layers will become even more isolated from the surface. The consequences are further oxygen deficiency and larger hypoxic areas. Combined with a high proportion of organic matter, this leads to acidification of the hypoxic areas[44] and a reduction in the CO_2 buffering capacity, which means a reduction in the ability to absorb CO_2 from the atmosphere.
- → The productive period is prolonged. This has already been observed with the occurrence of earlier spring and later autumn phytoplankton blooms[45]. This increases primary production, which in turn leads to an increase in the uptake of atmospheric CO_2. Dead, decomposing algae near the surface release CO_2, which together with algae growth creates a CO_2 zero-sum game for CO_2 absorption and release[1]. However, in deeper areas, decomposition leads to oxygen consumption[46] and acidification, which in turn reduces the ability to absorb CO_2 from the atmosphere. Only a small proportion of the additional organic material produced is buried in sediments[2].
- → Higher water temperatures facilitate the growth and earlier appearance of blue algae (cyanobacteria) in summer. The presence of dead organic matter from these algae in the water allows additional nitrogen from the atmosphere to enter the water, which can then lead to further algal growth. As discussed in the previous section, the net effect of increased algal growth on the CO_2 uptake capacity in the nutrient-rich environment of the Baltic Sea is negative.

- → Marine heatwaves (MHWs) have already increased in the Baltic Sea and will continue to increase until the end of the 21st century[5]. It is generally assumed that MHWs reduce the production of macroalgae and, in combination with acidification, increase the production of microalgae in the higher latitudes to which the Baltic Sea belongs[47]. Overall, this change means that less atmospheric CO_2 can be stored.
- → Less sea ice in the northern basins by the end of the 21st century will lead to an increase in the overall exchange of CO_2 between the atmosphere and the ocean[5]. In these areas, large quantities of organic carbon are carried in by rivers and are remineralised, resulting in an increasing concentration of dissolved inorganic carbon₂. If the two effects of increased exchange with the atmosphere and the accumulation of remineralised carbon occur simultaneously, a rise in CO_2 emissions can be assumed under these circumstances.

The temperature increase therefore has a predominantly negative impact on carbon uptake and storage. Although the extension of the phytoplankton growth phase initially indicates that more atmospheric CO_2 is being taken up, in the long term only the small proportion of POC that is buried in sediments counts. However, the larger proportion of organic carbon is decomposed with oxygen consumption, increasing the hypoxic areas, and thus reducing the buffering efficiency of the carbonate system, so that less atmospheric CO_2 can be absorbed.

Salinity

The salinity of the Baltic Sea covers a broad spectrum. It ranges from open ocean salinity at the interface with the North Sea to freshwater conditions in the northern Baltic Sea. The salt content of each basin is determined by different factors. Large rivers are a dominant feature of the north. The salinity of the south-west and much of the central Baltic Sea is determined by the varying inflow of saline North Sea water. The average salinity of the Baltic Sea therefore depends on many different factors, some of which are counteracting. Climate modelling scenarios based on the former greenhouse gas emission scenarios A1B and A2 (between RCP6.0 and RCP8.5) indicate only a small tendency towards lower salinity in the Baltic Sea in the future[48]. Newer ensemble averages of projections under high global emission scenarios (RCP4.5 and RCP8.5) demonstrate minimal overall change[5]. In general, desalinisation results in a reduction in alkalinity, which consequently leads to a decline in the capacity to absorb CO_2. However, the influence of the predicted average, slightly varying salinity of the Baltic Sea on carbon dynamics will be minimal. The construction of offshore wind farms and other infrastructure in large parts of the Western Baltic Sea could result in significant environmental impacts. For instance, the Arkona Sea and the Bornholm Channel could experience a decrease in bottom salinity due to a weakening of the sporadic inflow of salty and oxygen-rich water from the North Sea[49]. Such an increase in hypoxic areas would lead to a reduction in the absorption capacity of atmospheric CO_2.

Sea Level Rise

The land masses around the Baltic Sea have risen since the last ice age, so the sea level is rising more slowly than the land, or even falling, especially in the northern part of the Baltic Sea[50] (Figure 2). A new report based on the latest global model results from the last IPCC report[22] takes this into account and arrives at a range of SLR estimates between -20 cm in the north and 60 cm in the south for the high emission scenario SSP5-8.5.

The following effects of sea level rise on carbon storage have been identified:

- → The nearshore sediment transport is enhanced by SLR[51]. This means that the particulate organic carbon produced in these marine areas can be transported to deeper layers, where storage is supported. This implies a potential increase in the capacity to absorb atmospheric CO_2.
- → SLR has the potential to exacerbate coastal erosion[52]. This effect increases the amount of terrestrial carbon entering the sea, which in turn replenishes existing marine carbon pools and hinders the additional storage of atmospheric CO_2. In contrast to the marine material removed from the coastal zone by SLR, additional terrestrial material enters the water body through SLR and then partially contributes to additional remineralisation.
- → In contrast, stronger coastal erosion will also lead to increased input of alkalinity from carbonate-containing rocks. This effect will enhance the capacity of the Baltic Sea to absorb atmospheric CO_2[43]. This process has been ongoing for decades and is likely to continue. It may even intensify, as the climate-induced temperature increase and the rising CO_2 content in the air have the potential to accelerate the erosion of calcareous rocks. Such a source of alkalinity is scarce in the North Sea.
- → SLR harms seagrass meadows and macroalgae beds in the Baltic Sea, which have the potential to store carbon effectively. This is because the light available to these plants is reduced, as it has to penetrate through a larger water column[53]. Stevenson et al. (2023)[54] estimate that seagrass meadows in the German Baltic Sea area can offset 0.6 Mt C of future emissions. Although this figure only describes the German area, a comparison with the annual river input of 11 Mt C into the Baltic Sea shows that the carbon content of seagrass meadows is of minor importance for carbon storage here.

In summary, SLR will have different effects on carbon storage: In northern areas, SLR will be minimal or even negative due to land uplift. In other areas, accelerated erosion of marine and terrestrial material will have opposite effects on the carbon balance. Erosion of carbonate-containing rocks and the input of alkalinity could be the dominant factor here. The loss of seagrass meadows and macroalgae, which are limited in area, will not have a significant impact on the overall carbon budget of the Baltic Sea.

Wind speed

Possible future meteorological developments in the Baltic Sea region have been analysed in broad-based studies, mainly based on the greenhouse gas emission scenarios RCP4.5 and RCP8.5 (high emission scenarios)[55, 5]. There is a considerable spread between the different models, indicating a high degree of uncertainty in the prediction of wind speeds at a height of 10 m. A slight increase is expected only in winter. The reduction of sea ice is also expected to increase wind speeds. The probability of extreme wind speeds will also increase. Furthermore, such extreme weather conditions can lead to flooding and coastal erosion. The effects of coastal erosion

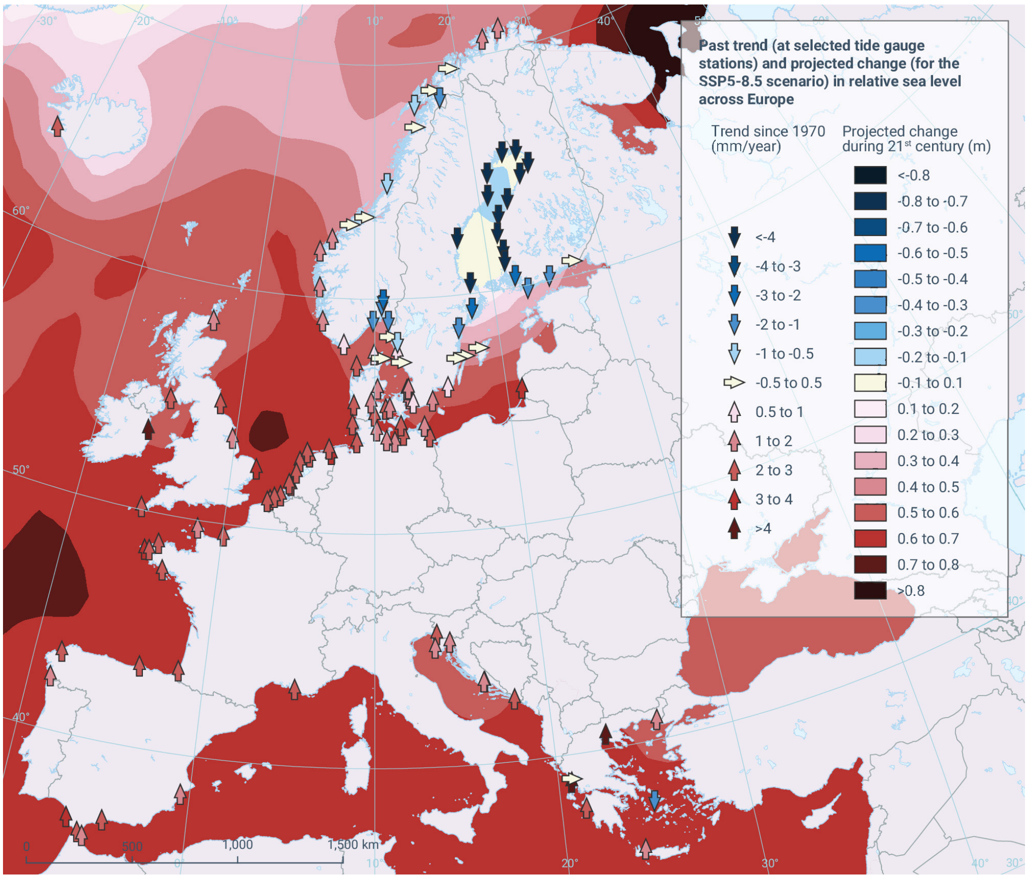

Figure 2: Past trend and projected change in relative sea level across Europe for the high emission scenario SSP5-8.5. Source: European Environment Agency, Global and European sea level rise, Figure 2[22], licensed under *CC 4Y 4.0 DEED* **.**

on carbon storage are described in the Sea Level Rise chapter. As these extreme wind speeds tend to be concentrated in winter, these wind changes are not expected to have an impact on biologically driven carbon dynamics.

Water Turbidity

Turbidity in the Baltic Sea increased even more than in the North Sea during the 20th century. The Baltic Sea with its brackish water has a high concentration of terrestrial organic matter[56]. Increasing turbidity reduces the light-flooded area in which photosynthesis can take place. This implies a decrease in the capacity to absorb atmospheric CO_2.

Fresh water and nutrient inputs from rivers and the atmosphere

The annual freshwater input from rivers has been more or less constant for centuries[57]. However, with rising surface air temperatures, an overall increase is expected. The increase will be stronger in the north than in the south of the Baltic Sea due to different precipitation and evaporation patterns[58]. In a natural manner, this also alters the riverine nutrient loads. However, socio-economic effects, such as fertiliser use in agriculture, also play a significant role. The implementation of the Baltic Sea Action Plan by the Baltic Sea states has reduced the riverine nutrient loads, which were at their maximum in the 1980s[59]. Nitrogen deposition from the atmosphere has also been reduced[60]. However, ammonium deposition as part of these loads, mainly from agricultural activities, will increase with rising temperatures[61]. For phosphorus deposition, no trend has been observed in recent years[62].

In contrast to the North Sea, reductions in nutrient loads in the Baltic Sea have a very slow effect on nutrient concentrations in the sea. Phosphorus accumulates in sediments and is released back into the water column due to hypoxic conditions, and primary production remains at high levels because cyanobacteria extract molecular nitrogen from the air[59]. Furthermore, the production of cyanobacteria is expected to increase in the future due to rising temperatures[63].

Future changes in freshwater input and nutrient supply may have the following effects on carbon storage:

- → An increase in freshwater supply from typically low alkalinity rivers in the north will reduce salinity and alkalinity in these northernmost areas. This leads to a reduction in the absorption capacity of atmospheric CO_2[64].
- → In the northern parts of the Baltic Sea, the increasing future river loads of dissolved organic material (DOM) from terrestrial sources will also play an important role, as they stimulate bacterial remineralisation, which in turn produces inorganic carbon that can outgas into the atmosphere[65].

→ When additional ammonium from increased atmospheric deposition is taken up by phytoplankton, alkalinity and CO_2 uptake capacity are reduced[66].

→ For the Baltic Sea, model results from the CARBOSTORE project[33] show that substantial reductions in nutrient inputs lead to a decrease in organic matter production and an increase in DIC, which is consumed in primary production. This effect persists over the years, unlike in the North Sea (Box 1). These findings are supported by the results of model calculations by Gustafsson & Gustafsson (2020)[64], which also found elevated DIC concentrations in nutrient reduction scenarios. These elevated DIC levels are associated with increased partial pressure in the water. This indicates a reduced capacity to absorb atmospheric CO_2 under river nutrient reductions.

In summary, it can be seen that natural processes such as increased freshwater supply due to climate change will reduce the ability to absorb atmospheric CO_2. In contrast, significant reductions in nutrient inputs are likely to improve carbon storage in the long term by reducing hypoxic areas. In the short term, however, these nutrient reductions lead to lower primary production and higher DIC levels in the Baltic Sea, which counteract the effective uptake of atmospheric CO_2. It is expected that natural processes over which humans have no direct control will dominate.

Bottom trawling

The impact of bottom trawling on biogeochemistry and carbon turnover has been widely studied. A recent study[67] has revealed that bottom trawling can increase the horizontal transport of sediments by up to 30 % in two so-called depo centers in the southwestern Baltic Sea. This means that the carbon-enriched sediments are removed from the depo centers and remineralised, mainly in the water column. Therefore, continued bottom trawling would lead to a decrease in carbon storage in Baltic Sea sediments, resulting in higher DIC concentrations in the water column and ultimately a decrease in the capacity to absorb atmospheric CO_2. Furthermore, unlike in the North Sea, the stirring up of nutrients probably does not have a significant impact on primary production, as there is less nutrient limitation here. A new modelling study by Rooze et al. (2024)[68] found less mechanical disturbance of benthic habitats by bottom trawling in a sandy silt region of the southern Baltic Sea, with little effect on atmospheric CO_2 uptake capacity, than other studies show[67]. This study covers only a small area of the Baltic Sea. Therefore, their results should not be extrapolated to the whole Baltic Sea.

Environmental and anthropogenic pressures	**Derived environmental changes**	**Uptake capacity of atmospheric CO_2**
Sea Surface Temperature increase	Stratification ↗	↘
	Cyanobacteria ↗	↘
	Production period ↗	↘
	Marine heatwaves ↗	↘
	Sea ice reduction ↗	↘
Salinity changes	no change	no change
Massive expansion of offshore wind farms	Salinity ↘	↘
Sea Level Rise	Marine particle export ↗	↗
	Terrestrial carbon input ↗	↘
	Erosion of carbonate-containing rocks ↗	↗
	Seagrass areas ↘	↘
Changing wind speed	?	?
	Winter storms/coastal erosion ↗	?
Increase in water turbidity	Phytoplankton production ↘	↘
Changing freshwater and nutrient inputs	Northern salinity ↘	↘
	Northern DOM ↗	↘
	Ammonium deposition ↗	↘
	Riverine nutrient loads ↘	↗ (long-term)
Bottom trawling	Remineralisation of resuspended matter ↗	↘

Table 2: Potential uptake capacity of atmospheric CO_2 in the Baltic Sea in response to changing environmental factors and anthropogenic pressures relevant to carbon storage. The symbol ↘ represents reduced CO_2 uptake capacity by the Baltic Sea or increased outgassing and decreasing environmental factors in column 2, the symbol ↗ represents increased CO_2 uptake capacity by the Baltic Sea or decreased outgassing and increasing environmental factors in column 2, while the symbol ? indicates that the CO_2 uptake capacity or the environmental change in column 2 is unclear.

Summary and conclusion

Sea surface temperatures are projected to increase between 0.6° C and 2.9° C for the North Sea and 1.4° C and 4° C for the Baltic Sea[10] compared to the 1991-2020 average, depending on whether a low or high emissions scenario is used. The longer exchange time of Baltic Sea water masses compared to the North Sea explains this difference.

The effects on the ability to store atmospheric CO_2 are similar for both seas, but there are some special features to consider:

The most crucial aspect of CO_2 storage in the North Sea appears to be the reduction in CO_2 solubility due to rising water temperatures. While reduced solubility also applies to the Baltic Sea, other temperature-related mechanisms, such as changes in vertical stratification, appear to be more important there. Additionally, there exist large hypoxic areas in the Baltic Sea, the extent of which is largely dependent on the strength of vertical stratification. Expanding these hypoxic areas increases acidification, thereby reducing the capacity to absorb atmospheric CO_2. The progressive melting of sea ice is a process that only occurs in the Baltic Sea. This process also reduces the absorption capacity of atmospheric CO_2.

It is unlikely that the salinity of the entire Baltic Sea will undergo a significant change. However, individual basins may exhibit a wide range of responses[5]. This does not apply to the North Sea, where many studies indicate that the (surface) salinity will decrease[11, 13, 69]. This will result in a reduction in the absorption capacity of atmospheric CO_2 due to increasing stratification and decreasing alkalinity[3].

It is predicted that sea level rise in the Baltic Sea will be negative or zero in the north and up to 60 cm in the south. In the North Sea, it is estimated to be 60-70 cm[22] by the end of the 21st century. The ocean currents of the Baltic Sea are weaker than those of the North Sea due to very low tides, which results in SLR being more noticeable in a coastal increase in currents and coastal erosion in the Baltic Sea area. SLR increases the transport of both, marine and terrestrial material, partly into the deeper parts of the Baltic Sea, with opposite effects on atmospheric carbon storage. However, if the increased erosion also washes massive amounts of calcareous rock into the Baltic Sea, an overall increase in the storage capacity of atmospheric CO_2 can be expected.

Wind speed drives gas exchange between the ocean and the atmosphere[70] and it is therefore important to consider the seasons with respect to changing wind speeds. A decrease in wind speed during the phytoplankton growth phase increases the uptake of atmospheric CO_2 in the North Sea. In the Baltic Sea, future changes in wind speed are very uncertain. However, increased storm activity is expected in both seas in winter. During this time, the water and the atmosphere are in equilibrium concerning CO_2 exchange. Therefore, the absorption capacity of atmospheric CO_2 will not change. The heightened risk of storms is likely to result in damage to coastal vegetation, thereby releasing sequestered carbon.

Turbidity has increased in both seas in recent decades, but the Baltic Sea is more affected than the North Sea. Turbidity is caused by suspended matter. There are several components that account for the increased concentration of suspended matter, including an increase in coastal erosion due to increased (winter) storms and a decrease in sedimentation in south-eastern UK estuaries. In the case of the Baltic Sea, with its typical brackish water zones, terrestrial organic matter also plays a role. The effect of increased turbidity is an increasing light limitation for phytoplankton growth and thus a reduction in the absorption capacity of atmospheric CO_2.

Predicting freshwater and nutrient inputs from rivers is difficult in the case of the North Sea. However, modelling has shown that strong nutrient reductions have almost no effect on carbon pools. In the case of the Baltic Sea, an increase in freshwater input from northern rivers is expected. Model calculations for the Baltic Sea show that a further reduction of nutrients from rivers and the atmosphere has two different effects: On the one hand, it increases the DIC content and thus reduces the absorption capacity of atmospheric CO_2. On the other hand, hypoxic areas are reduced in the long term, which increases the absorption capacity of atmospheric CO_2.

Bottom trawling generally destroys bottom habitats and stirs up sediments. As a result, organic matter is released and partially remineralised. This increases the concentration of DIC and reduces the absorption capacity of atmospheric CO_2. In the case of the North Sea, it can also lead to input of nutrients into the water column with increased primary production. This increases the absorption capacity of atmospheric CO_2.

It has been shown that future uptake of atmospheric CO_2 and marine carbon storage will be determined by many environmental changes. Human activities that affect the ocean's ability to store carbon, and which are discussed in the text, are:

→ Rise of CO_2 in the atmosphere, followed by increased CO_2 uptake by the marine system and acidification
→ Riverine and atmospheric nutrient inputs, e.g. from agricultural sources, including ammonium input
→ Bottom trawling
→ Massive expansion of wind farms in the western Baltic Sea

All these activities are expected to reduce the carbon storage capacity. This also applies to anthropogenic nutrient inputs in the short term in the Baltic Sea, which are decreasing but are still too high. It is expected that natural processes over which humans have no direct control will dominate. Nevertheless, anthropogenic pressures must be minimised in order to stabilise the carbon storage capacity of the North and Baltic Seas.

In summary, the North Sea is currently a sink for atmospheric CO_2. However, increasing CO_2 emissions and rising water temperatures will make the North Sea a less efficient sink or even a source of atmospheric CO_2. The Baltic Sea currently has a near-zero net exchange of CO_2 with the atmosphere. At present, it is not possible to identify a general trend in the future development of the Baltic Sea as a net sink or source of atmospheric carbon, as uncertainties are still high and there are large regional differences.

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