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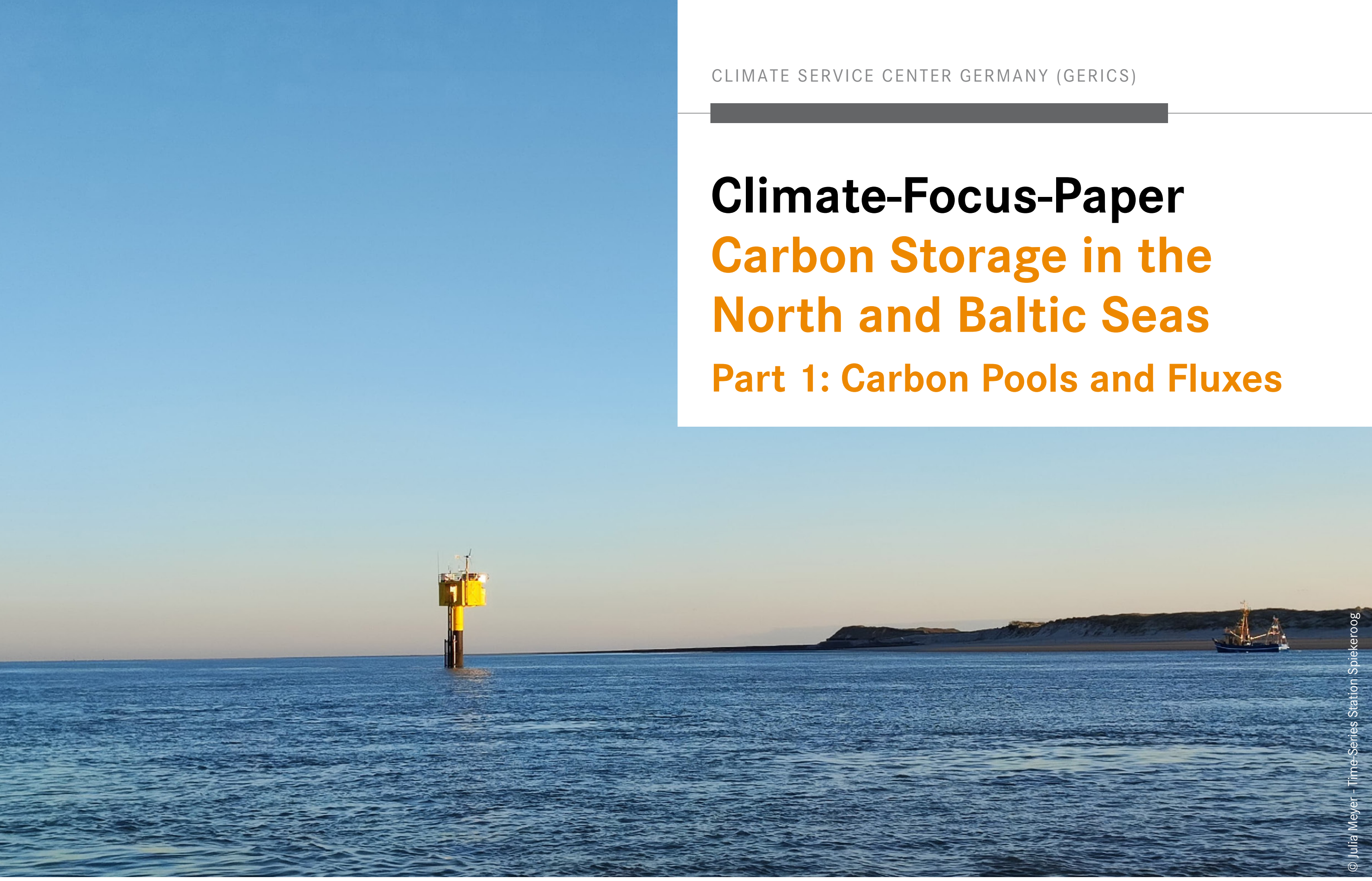
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Climate-Focus-Paper
Carbon Storage in the North and Baltic Seas
Part 1: Carbon Pools and Fluxes

Speed read

- → Over the past two decades, the oceans have absorbed between 20 and 30% of total anthropogenic CO_2 emissions.
- → The largest pool of carbon is dissolved inorganic carbon in the water column of the North Sea and the Baltic Sea.
- → Currently, the North Sea is a sink of 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.
- → As long as the local absorption of atmospheric CO_2 still functions, the circulation of the North Sea effectively transports the absorbed carbon out of the North Sea. It is transported to deeper layers in the North Atlantic and is stored there for centuries.
- → Large deposition centers of organic carbon can be found in the Skagerrak and the Norwegian Trench. The carbon there has been transported from large parts of the North and Baltic Seas.
- → Carbon burial in sediments is negligible in the Wadden Sea, here defined as the area below the high tide line.
- → The Baltic Sea has a close to net-zero uptake of atmospheric CO_2.
- → The inflow of carbon from the rivers plays a major role in the carbon budget of the Baltic Sea. Around a quarter of this is stored sustainably in the sediments, and the rest is exported to the North Sea.
- → It is not possible to demonstrate 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 will be large regional differences.

Introduction

The oceans play an essential role in regulating and stabilising the Earth‘s climate system. Indeed, they are an extremely important carbon sink. Rising levels of the greenhouse gas carbon dioxide (CO_2) in the atmosphere are leading to increasing amounts of carbon derived from atmospheric CO_2 in the oceans. In the last two decades, the oceans have absorbed 20-30% of total anthropogenic CO_2 emissions[1].

To provide background information and the latest findings on carbon storage in the North Sea and Baltic Sea based on the CARBOSTORE project (Carbon Storage in German Coastal Seas, see: *http://www.carbostore.de*), this Climate Focus Paper gives an overview of the main carbon pools and fluxes in these two marine areas. It concentrates on carbon storage in the water column and in the marine sediments. A second Climate Focus Paper will examine in

CARBO STORE Carbon Storage in German Coastal Seas
GERICS Climate Service Center Germany
Bundesministerium für Bildung und Forschung

greater depth the environmental parameters, anthropogenic pressures such as nutrient loads by rivers, and the impacts of climate change on future carbon storage in the North Sea and Baltic Sea.

Carbon dioxide is a highly significant greenhouse gas, but there exist other relevant greenhouse gases such as methane. For example, regarding methane, the ocean is always a source for the atmosphere. As CARBOSTORE concentrates its research and modelling on carbon storage processes, it only includes CO_2, the carbonate system, and organic carbon compounds in its investigations. A comprehensive overview of methane storage in the ocean's shelves can be found in Rosentreter et al. (2023)[2].

Background

With the onset of industrialisation, societies have used fossil fuels on a massive scale, releasing carbon dioxide into the atmosphere. As a result, the CO_2 content of the atmosphere has increased by almost 50% over the last 150 years. CO_2 (and other greenhouse gases with a less strong increase) absorbs some of the long-wave radiation from the atmosphere back into space. This causes the atmosphere to warm, leading to global climate change. However, during this increase in atmospheric CO_2, the ocean and the terrestrial biosphere have buffered the amount of CO_2 that has entered the atmosphere by absorbing equal parts, which amount to about 60% of the total CO_2 emitted[3]. Without this buffering effect, the CO_2 content of the atmosphere would be much higher today and climate change would have accelerated more rapidly. The ocean and terrestrial biosphere are only effective as carbon reservoirs if they store carbon removed from the atmosphere over a long period. In the case of the ocean, the carbon dissolves in the water where it is effectively bound as inorganic carbon compounds by a chemical buffer. The carbon is transported to deeper ocean layers and sometimes even into the sediment in particulate form. In this way, carbon is stored for centuries. The ocean therefore plays a very important role in slowing down global warming and mitigating climate change.

The acid-binding capacity of water (also known as alkalinity) influences the extent to which seawater acidifies by absorbing atmospheric CO_2. If alkalinity is increased (e.g. by rock weathering), more CO_2 can be absorbed by the seawater without negative effects such as increasing acidification. However, CO_2 uptake, acidification, and concurrent warming of the ocean are already having effects that can be observed today, such as coral bleaching and species shifts. Finally, because of increasing acidification, the chemical buffer that effectively binds carbon is gradually losing its effectiveness.

The North Sea and the Baltic Sea store large amounts of carbon in the water, the so-called pelagic zone, and in their sediments, the benthic zone. The carbon content of the pelagic zone of the North Sea is equivalent to about one-tenth of current annual global emissions (Box 1). Carbon from the surface pelagic zone is directly exchanged with atmospheric carbon, while carbon stored in the sediments is exchanged with the bottom pelagic zone. Biological processes within the pelagic zone are responsible for the accumulation of carbon pools in the sediment. These sedimentary carbon pools are largely returned to the water column by biological degradation processes. This reservoir is therefore in indirect contact with the atmosphere.

What are marine carbon pools and fluxes?

Carbon is almost always present in the ocean in molecular compounds. These can be divided into different classes: There are organic and inorganic compounds, dissolved and particulate compounds (e.g. plankton, detritus or dissolved CO_2). Further classifications are made where necessary. In addition, these compounds are found in the open water and the seafloor. Reasonable spatial subdivisions (e.g. North Sea, Wadden Sea, German Bight) are also often used.

A carbon pool is defined here as a class of carbon compounds (e.g. dissolved inorganic carbon - DIC, particulate organic carbon - POC) in the pelagic or benthic zone within a defined area (e.g. North Sea, Wadden Sea, German Bight). Such a pool is measured by indicating the mass of carbon atoms in the given pool. It can be expressed, for example, in terms of mol/m^2 or a specific mass (kg, t, Gt) of carbon (see Box 1) in a defined area. The carbon storage capacity is then the largest possible amount of carbon atoms in the corresponding pool.

Carbon fluxes change the amount of carbon atoms in a carbon pool in a given time. A typical unit of a carbon flux is $g\ C/m^2/s$ (or $g\ C\ m^{-2}\ s^{-1}$), which corresponds to carbon turnover (e.g. primary production) in a water column with a 1 m^2 area in one second. This unit can also refer to the horizontal transport of carbon atoms through an imaginary vertical wall of 1 m^2 area in one second.

There are different ways of determining the mass of carbon dioxide. Today‘s global emissions are sometimes put at around 9.5 Gt per year and sometimes at around 35 Gt per year. The difference is that the former uses only the mass of carbon, while the latter uses the mass of all carbon dioxide, including the mass of the oxygen atoms. In this Climate Focus Paper, only the mass of the carbon atoms is used.

Box 1: CO_2 emissions, carbon pools and fluxes - some examples in figures:

9.5 Gt C yr^{-1}	mass of carbon in global CO_2 emissions in 2011 - 2020, equivalent to approx. 35 Gt CO_2 yr^{-1}
176.5 Mt C yr^{-1}	mass of carbon in total German CO_2 emissions (GE) in 2020[4], equivalent to approx. 0.6 Gt CO_2 yr^{-1}
~1000 Mt C	mass of carbon (as DIC) in the entire North Sea in 2014 (equivalent to ~9.7% of global CO_2 emissions in 2014)[5]
~500.0 Mt C	mass of carbon (as DIC) in the entire Baltic Sea in 2014 (equivalent to ~4.9% of global CO_2 emissions in 2014)[5]
32.8 Mt C yr^{-1}	net carbon transport from the North Sea to the North Atlantic[6]
9.5 Mt C yr^{-1}	North Sea carbon uptake from the atmosphere for the years 2001 - 2002 (equivalent to 5.4% of GE)[6]
0.5 Mt C yr^{-1}	Baltic Sea carbon loss to the atmosphere for the years 2000 - 2009 (equivalent to 0.3% of GE)[7]
0.9 Mt C yr^{-1}	long term carbon burial in North Sea sediments (equivalent to 0.6% of GE)[8]
2.7 Mt C yr^{-1}	long term carbon burial in Baltic Sea sediments (equivalent to 1.5% of GE)[7]

Box 1 lists some examples related to CO_2 emissions, carbon pools and fluxes. Please note that these are only estimates. The values labelled ~ are estimates from new, yet unpublished model calculations from the CARBOSTORE project[5].

Paths of carbon into the ocean and different carbon compounds

How does carbon enter the ocean? The direct pathway is for atmospheric CO_2 to enter the ocean via the ocean surface (Figure 1). Like many physical and chemical processes, this is an equilibrium reaction. If the partial pressure of atmospheric CO_2 (pCO_2) is greater than that which would create an equilibrium with the ocean, the ocean will take up CO_2 molecules. At present, as atmospheric pCO_2 continues to rise, there is no equilibrium between the ocean and the atmosphere, and the ocean is absorbing more CO_2 than it is emitting. In the ocean, CO_2 is dissolved and reacts to form other components of the inorganic carbonate system. These dissolved carbon components enter the biological food web, in part through photosynthesis by phytoplankton.

Other sources of marine carbon are rivers, water discharges from marsh areas, and groundwater. Here, carbon also enters the marine environment in organic form. Its decomposition releases CO_2 into the atmosphere, especially in estuaries.

The burning of fossil fuels has produced large amounts of atmospheric CO_2, which has contributed to the large pool of dissolved inorganic carbon (DIC) in the ocean, formed mainly by rock weathering over long periods of time. Phytoplankton take up inorganic carbon and convert it into organic components: particulate organic carbon (POC) and dissolved organic carbon (DOC). Particulate inorganic carbon (PIC) is formed by shell-forming organisms. When, where and how these carbon compounds decompose plays an important role in the long-term fate of carbon in the North and Baltic Seas.

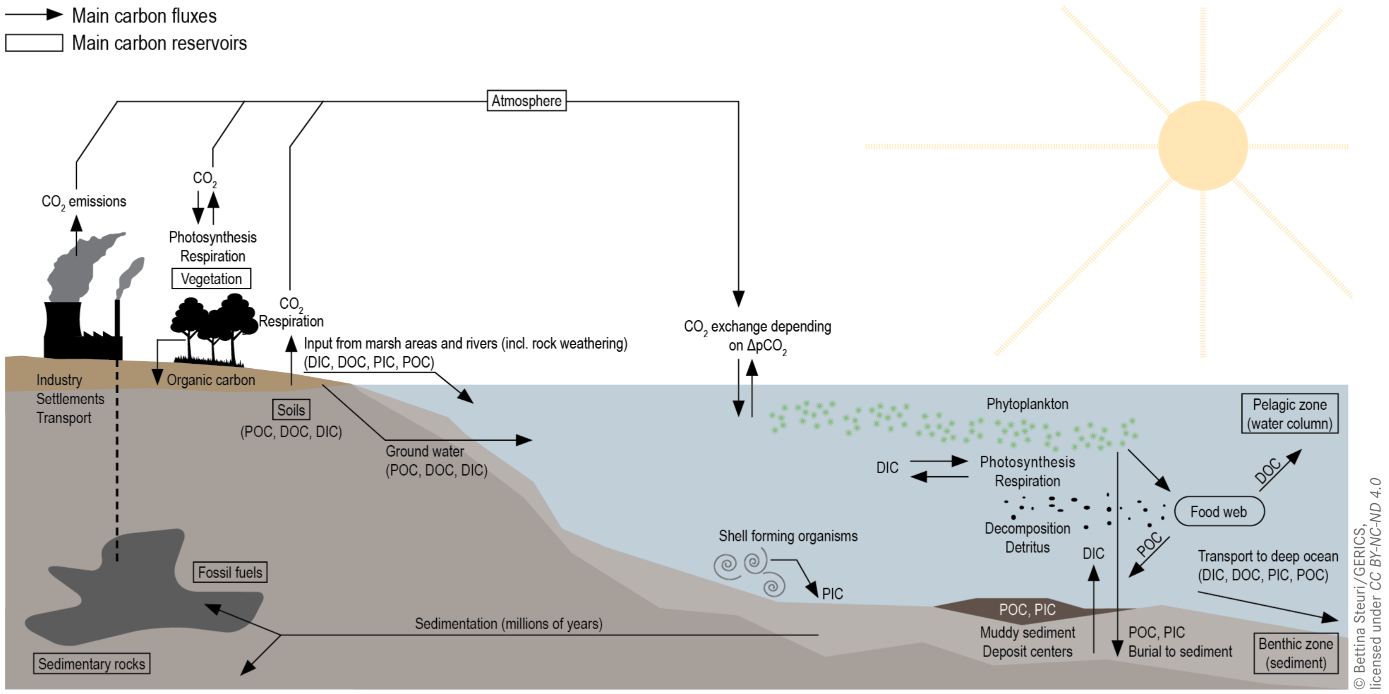

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Figure 1: Simplified representation of the global carbon cycle. The focus here is on marine carbon pools and fluxes. DIC: dissolved inorganic carbon, formed by remineralisation of rocks during weathering, and by the absorption of atmospheric CO_2; DOC: dissolved organic carbon, formed by decomposition of organic material and during primary production; POC: particulate organic carbon, e.g., plankton, other living organisms and detritus; PIC: particulate inorganic carbon, mostly calcite, found in the shells of plankton, mussels and snails; pCO_2: partial pressure of CO_2, proportional to the CO_2 concentration.

Characteristics of the North Sea and Baltic Sea hydrography and exchange with adjacent seas

The exchange between the very different basins of the North Sea and the Baltic Sea is controlled by the hydrography and bed characteristics of the basins.

In addition to the English Channel, which forms a small opening to the Celtic Sea, the North Sea has a long open boundary with the North Atlantic. This results in an almost complete exchange of North Sea water about once a year[9]. The tides and prevailing westerly winds give rise to the typical cyclonic current pattern, which is particularly pronounced off the continental coast and drives the water along the coasts towards Norway, effectively transporting substances away from the land. This results in relatively high salinity and a general absence of oxygen deficiency.

The Baltic Sea is only connected to the open ocean via the Skagerrak and the narrow Belts. Consequently, the Baltic Sea water is less well-ventilated and less effectively exchanged than the North Sea water. Freshwater input from the rivers significantly reduces the salinity of the Baltic Sea. There is also an accumulation of anthropogenic substances from the surrounding land, which in part is densely populated. For example, fertilisers containing nitrogen and phosphorus enter the Baltic Sea and lead to increased biological uptake of carbon. The decomposition of the increased amount of organic matter leads to very low oxygen concentrations in the Baltic Sea, especially in deeper areas. In these toxic areas, biogeochemical transformations can only take place in the absence of oxygen. Therefore, the decomposition of organic carbon is very limited. Only a small fraction of the biologically fixed carbon enters the North Sea via the Skagerrak, where it is effectively transported northwards along the Norwegian coast.

The North Sea

Carbon in marine sediments

The circulation pattern of the North Sea determines the path of the absorbed carbon. This carbon is effectively transported out of the North Sea, with 20% reaching the deep northern North Atlantic[10]. The North Sea floor is mostly sandy, where most of the carbon from subsided organic particles is returned to the water column. There are only a few areas of muddy surface sediments where carbon is sequestered more effectively (also known as deposit centers, Figure 2). One small area is located to the southeast of Helgoland (also known as the "Helgoländer Schlickgebiet"). This area has been intensively studied[11,12,13]. Another smaller area is the Oyster Ground[14]. The largest area of muddy sediments is found in the Skagerrak and the Norwegian Trench. As the water depth here is very large (up to 700 m), a considerable amount of carbon has been accumulated in the sediments, transported from large parts of the North Sea and Baltic Sea[8,15]. Another large muddy area (the "Fladen Ground") is located near Scotland in the north-west of the North Sea (Figure 2). In these deposit centers, human activity can be traced back up to 1000 years[12]. Until the beginning of industrialization, the North Sea ecosystem was an undisturbed body that inhaled CO_2 in spring and exhaled it at other times of the year. The exchange with the atmosphere was almost balanced over the year, with the sea tending to be a net sink. Decadal climate variations, with cooler and warmer years, caused perturbations of the ecosystem, which were then reflected in the carbon balance of the North Sea. However, the muddy sea floor has formed a small sink for organic carbon that has accumulated over centuries.

As mentioned above, the deposit centers have been very effective in accumulating carbon from the North and Baltic Seas in deep sediments for centuries: each year, they store an amount of carbon equivalent to about 10% of the annual atmospheric carbon uptake by the North Sea[17]. In the area of the Norwegian Channel and Skagerrak, 1 Gt of carbon has been buried in deep sediments over the last 1000 years[8]. This means that these deposit centers have stored an amount equivalent to about 10% of recent annual global CO_2 emissions.

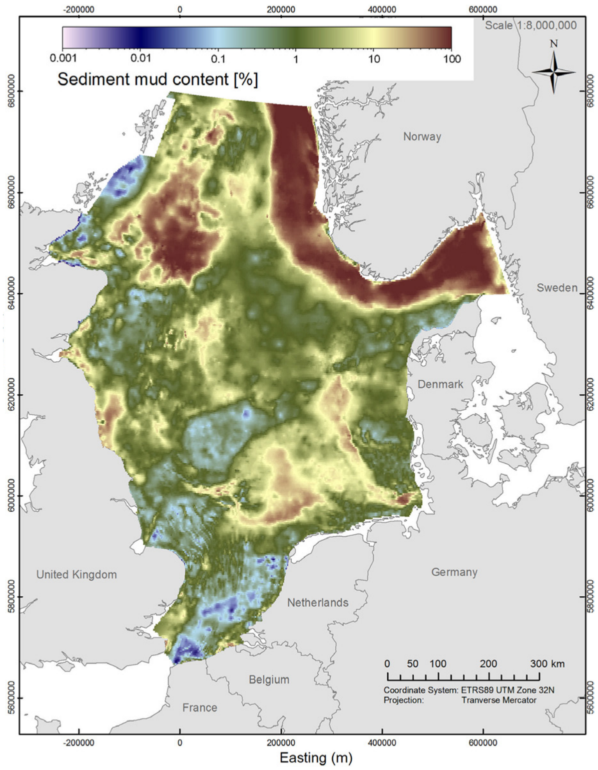

Figure 2. Mud content in surface sediments of the North Sea from Bockelmann et al. (2018)[16] *

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At the same time, the Skagerrak and Norwegian Trench are areas of very high pressure from bottom trawling. Bottom trawls repeatedly plough up the upper layers of the sediment, stirring up particulate sedimentary carbon and potentially transferring it into the dissolved inorganic phase in the water column. However, this pressure is limited to depths of 200 meters. The depth range of the sediment affected by bottom trawling depends on sedimentation rates and trawling history. The Skagerrak has high sedimentation rates of up to 1 cm/year[8] and a trawling history of no more than 100 years. Consequently, no evidence of trawling activity is expected below the 1 m horizon of the sediment. Most of the sedimented material, some of which is very old, is buried at depths of more than 1 m. Therefore, this deep material would not be expected to be remobilised by storms or bottom trawling. However, the accumulation of additional layers of carbonaceous sediment is hindered by trawling activity.

Carbon in the water column

The much larger pool, however, is dissolved inorganic carbon (DIC) in the water column. Figure 3 shows its relatively homogeneous distribution caused by strong winds and tidal mixing[5]. North Sea water with its dissolved inorganic carbon is replaced by North Atlantic water almost every year. The DIC concentration in the water column has increased by about 50 mmol C m^{-3} [18] over the past 15 years, representing a rise of approximately 2.5%. This increase is largely due to the absorption of atmospheric CO_2, which has led to acidification and thus to a reduction in the North Sea water's ability to absorb CO_2. This indicates that the uptake of atmospheric CO_2, as illustrated in Figure 5 for the years 2001/02 with 9.5 Mt C yr^{-1}, has already diminished in subsequent years[19]. Figure 4 depicts a clear decline in CO_2 uptake by the North Sea water from the mid-1990s onwards. This decline was caused by rising water temperatures and decreasing pH values. A similarly strong downward trend cannot be shown by model calculations for the Baltic Sea[22].

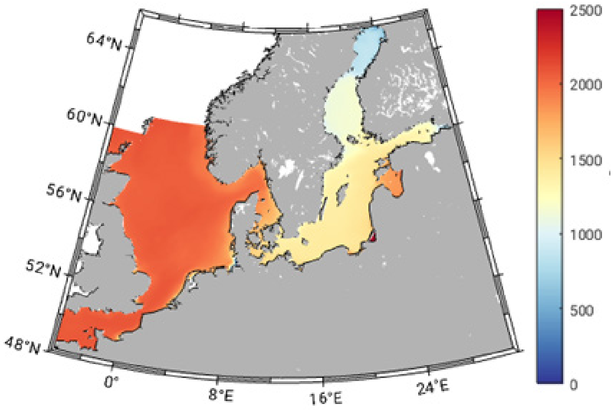


Figure 3. Simulated mean surface dissolved inorganic carbon (DIC) concentrations for 2001 (mmol C m^{-3}). The mean DIC concentration in the North Sea amounts to 2000 mmol C m^{-3} or 24 g C m^{-3}, whereas its concentration in the Baltic Sea is much lower and shows a strong decrease towards the northern basins (Cahill, unpublished data). This year was selected for comparison with the data presented in Figure 5.

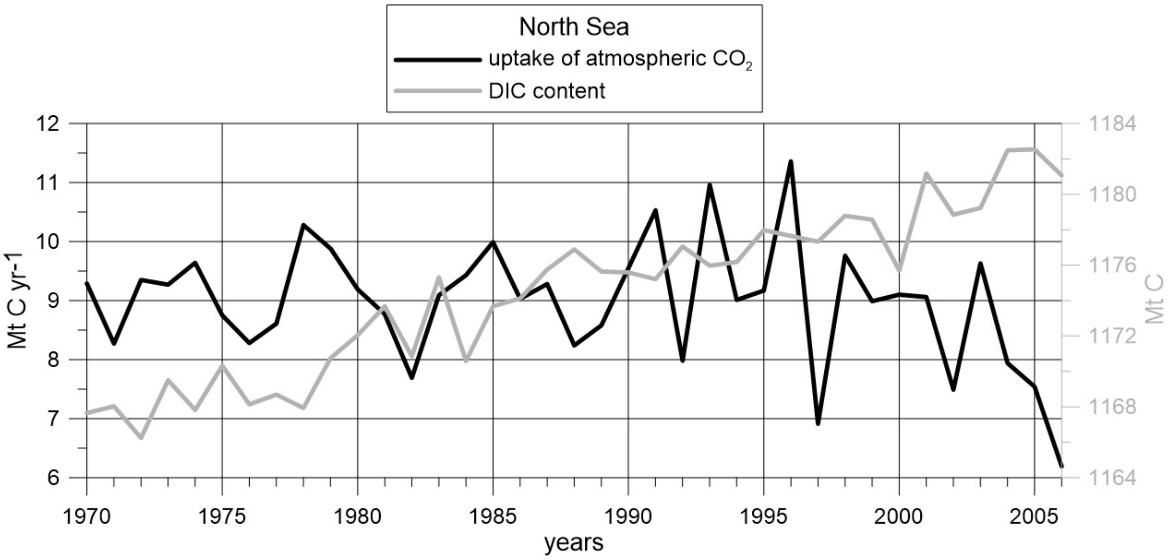


Figure 4. Simulated uptake of atmospheric CO_2 for the North Sea region (derived from Figure 5a in Lorkowski et al., 2012[20]) and increasing dissolved inorganic carbon (DIC) content in the water column (derived from the simulation used in Lorkowski et al., 2012[20]). Measurements show that the trend of declining CO_2 uptake from 1996 to 2006 continued similarly in the southern and central North Sea region in the years 2014 - 2019[21].

Overview of the main carbon fluxes in the North Sea and Baltic Sea

The amount of dissolved and particulate organic carbon in the water column is subject to seasonal variations, which are largely caused by varying primary production and remineralisation rates. While the temperature-related CO_2 exchange dominates the uptake in the first three to four months of the year, the net uptake of CO_2 in May, June, and July is determined by biological processes[23].

When the two processes of consumption and remineralisation occur in the same water body, there is near-zero uptake or outgassing of CO_2 over the year. However, in deeper areas with temperature-dependent stratification of the water column during the summer months, such as the central and northern parts of the North Sea, these two processes occur in different water bodies: Biological uptake occurs in the light-flooded, usually warmer upper part of the water column, while decomposition of sinking organic products is mostly accomplished in the deeper, usually colder areas or in the sediment. Dissolved inorganic carbon decreases in the upper zone during the growth phase, and the ocean then absorbs atmospheric CO_2. The decomposition products or the particles that are still preserved are transported to the "outflow" of the North Sea, namely the Norwegian Coastal Current, and eventually to the North Atlantic. Additionally, parts of the particles reach the northern deposit centers in the Skagerrak and the Norwegian Trench along this path.

Given that the water is exchanged approximately once a year, it can be said that the entire water body essentially drains through this outflow, along with the dissolved carbon. Concurrently with the outflow, North Atlantic water (with dissolved carbon) also enters the North Sea. Consequently, the difference in the carbon contents of the outflow (1497.0 Mt C yr^{-1}) and the inflow (1464.2 Mt C yr^{-1}) accounts for the net export of carbon of 32.8 Mt C yr^{-1} (Figure 5). This corresponds to about 3.5 times the net uptake of CO_2 from the atmosphere of the total North Sea region. Due to the nature of the sporadic measurements available, this net export, which is also attributable to the river input and the inflow from the Baltic Sea, has to be considered with an uncertainty of ±1 Mt C yr^{-1}. The same applies to the exchange between the North Sea and the Baltic Sea: Here, the authors calculated figures which differ by 5.4 Mt C yr^{-1}, depending on the sea area balanced (Figure 5).

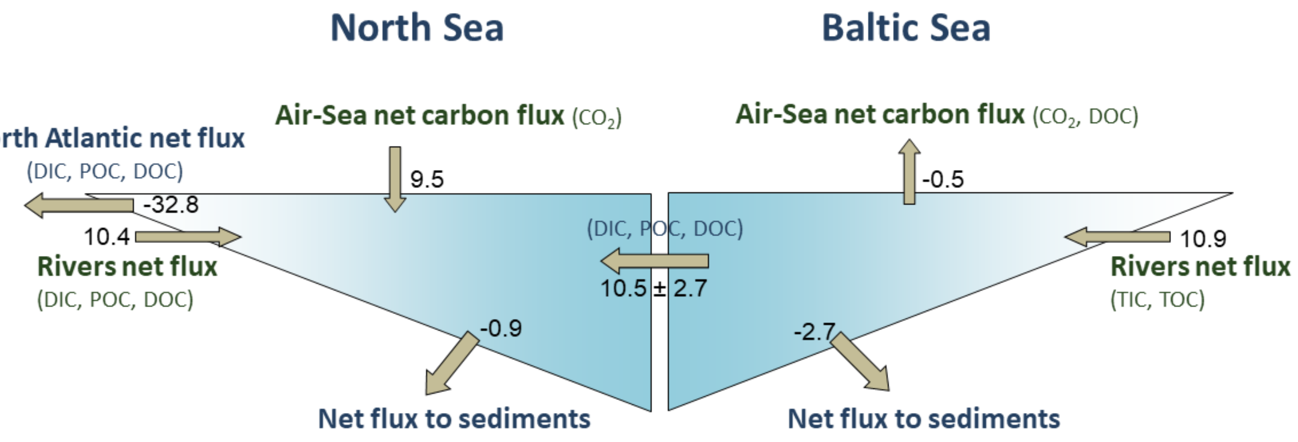


Figure 5. On the left side: The North Sea carbon budget after Thomas et al. (2005)[6] (data from 2001/2002). On the right side: The Baltic Sea carbon budget after Schneider et al. (2017)[7] (data from 2000-2009). Units are Mt C yr^{-1}. Note that there are different estimates for the exchange between the two basins. This carbon budget does not include vegetation-rich coastal ecosystems such as seagrass meadows and salt marshes, which also represent carbon pools. The following abbreviations are used: DIC: dissolved inorganic carbon; DOC: dissolved organic carbon; PIC: particulate inorganic carbon; POC: particulate organic carbon; TIC: total inorganic carbon (DIC+PIC); TOC: total organic carbon (DOC+POC). (Figure adapted from Cahill et al., in prep[5], used under *CC BY 4.0*).

Wadden Sea

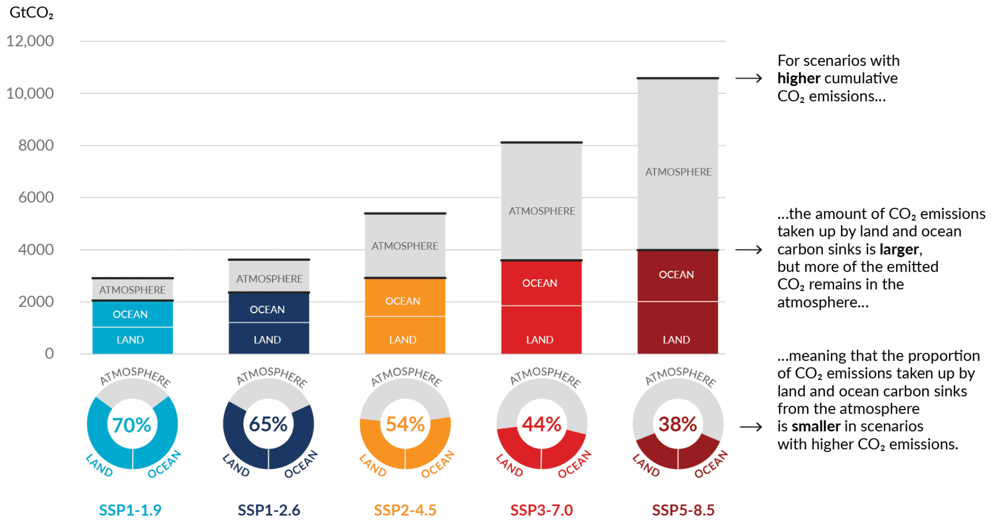
The Wadden Sea, situated at the south-eastern boundary of the North Sea, is a unique coastal area. In this paper, the Wadden Sea is defined as the area between the islands and the mainland that is covered by water at high tide. This excludes salt marshes, which also bind carbon, from consideration. Some of the features of the Wadden Sea are not visible to the naked eye: Due to the shallow and intermittently dry nature of the Wadden Sea, its sandy soils are particularly important for carbon remineralisation: The tidal channels between the islands facilitate the exchange of water between the Wadden Sea and the North Sea. This exchange imports organic carbon into the Wadden Sea, where it is effectively remineralised mainly in anoxic soils and returned to the North Sea in inorganic form. This so-called anoxic decomposition partly releases substances (summarised as alkalinity with the ability to absorb CO_2) that counteract acidification and thus favour the uptake of atmospheric CO_2 in the southern North Sea[24]. In the Wadden Sea, carbon storage through burial in the sediment is negligible, as most of the organic carbon becomes remineralised and either exported to the southern North Sea or released into the atmosphere as carbon dioxide[25].

A short outlook: future pools and fluxes

The future development of carbon pools and fluxes in the North Sea will be crucially dependent on the ability to halt or at least slow down global warming. Figure 6 shows five significant SSP scenarios (Shared Socioeconomic Pathway) about the development of global CO_2 emissions. The impact of a strong increase or a significant reduction in CO_2 emissions on marine carbon storage will be discussed in more detail below: Could, on the one hand, a strong reduction in CO_2 emissions (IPCC scenario SSP1-1.9) restore pre-industrial conditions? On the other hand, what are the potential consequences of a significant or even unabated increase in emissions on carbon storage, as exemplified by the SSP2-4.5 scenario (the 2.7-degree pathway currently being pursued by the world) and scenarios with even higher CO_2 emissions (SSP3-7.0, SSP5-8.5)?

The proportion of CO_2 emissions taken up by land and ocean carbon sinks is smaller in scenarios with higher cumulative CO_2 emissions

Total cumulative CO_2 emissions **taken up by land and ocean** (colours) and remaining in the atmosphere (grey) under the five illustrative scenarios from 1850 to 2100



For scenarios with **higher** cumulative CO_2 emissions…

…the amount of CO_2 emissions taken up by land and ocean carbon sinks is **larger**, but more of the emitted CO_2 remains in the atmosphere…

…meaning that the proportion of CO_2 emissions taken up by land and ocean carbon sinks from the atmosphere is **smaller** in scenarios with higher CO_2 emissions.

Figure 6. Cumulative anthropogenic CO_2 emissions taken up by land and ocean sinks by 2100 under the five illustrative scenarios. The cumulative anthropogenic (human-caused) carbon dioxide (CO_2) emissions taken up by the land and ocean sinks under the five illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) are simulated from 1850 to 2100 by Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models in the concentration-driven simulations. Land and ocean carbon sinks respond to past, current and future emissions; therefore, cumulative sinks from 1850 to 2100 are presented here. During the historical period (1850–2019) the observed land and ocean sink took up 1430 $GtCO_2$ (59% of the emissions).

The **bar chart** illustrates the projected amount of cumulative anthropogenic CO_2 emissions ($GtCO_2$) between 1850 and 2100 remaining in the atmosphere (grey part) and taken up by the land and ocean (coloured part) in the year 2100. The **doughnut chart** illustrates the proportion of the cumulative anthropogenic CO_2 emissions taken up by the land and ocean sinks and remaining in the atmosphere in the year 2100. Values in % indicate the proportion of the cumulative anthropogenic CO_2 emissions taken up by the combined land and ocean sinks in the year 2100. The overall anthropogenic carbon emissions are calculated by adding the net global land-use emissions from the CMIP6 scenario database to the other sectoral emissions calculated from climate model runs with prescribed CO_2 concentrations. Land and ocean CO_2 uptake since 1850 is calculated from the net biome productivity on land, corrected for CO_2 losses due to land-use change by adding the land-use change emissions, and net ocean CO_2 flux. *Source*: Figure SPM.7 in IPCC, 2021a.[3]

It should be noted that, in contrast to the rest of the text, the mass of carbon dioxide (CO_2) and not the mass of carbon (C) is considered in this figure.

Assuming increasing emissions: Will the carbon pools become saturated?

Should emissions continue to increase at a significant or unabated rate (as illustrated in the scenarios SSP2-4.5, SSP3-7.0, SSP5-8.5 in Figure 6), the following general environmental changes can be expected:

→ Increase in global temperature by more than 2 degrees,

→ Increased heating of ocean surfaces and thus increased stratification of the water body,

→ Uncertain future development of freshwater inflows from rivers (increase or reduction, depending on region and projection) with sporadic heavy water discharges.

Gases such as CO_2 dissolve less effectively in warmer water. This means that the North Sea has become less effective at absorbing

CO_2 and may even become a source of CO_2 for the atmosphere. The increase in sea surface temperature by about 1.5° C between 1970 and 2006 has already reduced the CO_2 absorption in the North Sea by about 50%[20]. According to Belkin et al. (2009)[26], the North Sea, along with the Baltic Sea, is one of the marine ecosystems most strongly affected by warming. The UN Climate Agency[27] has indicated that global warming is currently on a 2.7-degree path (corresponding to SSP2-4.5), which would result in an average surface air temperature increase of 2.7 degrees by the end of the 21st century compared to pre-industrial times. This would further reduce the North Sea's capacity to absorb CO_2.

The biogeochemistry and biology of coastal areas are significantly influenced by the nutrient loads of rivers[28]. However, the nutrient loads of the North Atlantic water have a profound biogeochemical impact on the northern and central North Sea[29]. Stronger stratification of the adjacent North Atlantic reduces the concentration of nutrients in the upper layers, which limits the import of nutrients into the North Sea and reduces primary production there[30]. Consequently, less atmospheric CO_2 is taken up in the northern and central North Sea area.

The reduction of freshwater inflow, as has already been observed for the Elbe River[31], also reduces the nutrient loads and thus primary production in the North Sea[32], which leads to a reduction in CO_2 uptake from the atmosphere. On the other hand, winter high runoff events during heavy precipitation are likely to increase[33]. The most recent IPCC report[34] predicts a decrease in runoff for the SSP5-8.5 scenario for rivers originating from the continent, particularly during the summer months (see Figure 8.18 in IPCC, 2021b[34]). However, deriving this information from global models, as employed in the IPCC report, with considerable variations between the models used, and applying it to regional seas such as the North and Baltic Seas, is risky. It is therefore challenging to provide definitive conclusions regarding future freshwater inputs by rivers.

Projections of nutrient loads are even more uncertain than projections of river discharge due to the unknown future land use and socioeconomic scenarios[35]. Sporadic heavy water discharges due to extreme precipitation events transport more nutrients into the North Sea, but these cannot be taken up by phytoplankton in quantity, especially in fall and winter, and remain largely unconsumed in the water and sediment. The occurrence of sporadic, very high nitrate concentrations with very low oxygen concentrations in deep layers (or at the bottom) induces degradation processes, which temporarily reduce acidification and increase the tendency to absorb CO_2 in the short term[36]. However, it is difficult to predict how primary production and the resulting absorption of atmospheric CO_2 in the North Sea will develop in the future, given the significant uncertainties involved[37].

In summary, the North Sea has become less efficient at absorbing CO_2 due to rising emissions and increasing acidification. This is likely to result in the North Sea becoming even a source of atmospheric CO_2 in the future. As Figure 6 shows, the relative share of CO_2 absorbed by the ocean (and land areas) decreases strongly in the scenarios SSP2-4.5, SSP3-7.0, and SSP5-8.5, leading to an even higher CO_2 concentration in the atmosphere.

Assuming strong emission reductions: will the pools be recreated?

The "greenest" scenario described in the 6th IPCC Report is SSP1-1.9 (Figure 6), in which emissions will fall below zero from 2055, when CO_2 concentrations reach their peak. This scenario envisions the active CO_2 removal from the atmosphere. Nevertheless, even in this scenario, the atmospheric partial pressure of CO_2 will not fall below today's level until 2100. This means that pre-industrial conditions will not be reached again in the foreseeable future[35] (see Figure TS.4 in IPCC, 2021b[34]).

In a global model (using the SSP1-4.5 scenario, which considers a warming of 2° C), a reduction in nutrients from rivers is assumed through a sustained reduction in fertilisation[38]. However, the primary production remains at a constant level due to clearer water and a greater availability of underwater light[32], which in turn supports carbon uptake. This demonstrates that a reduction in nutrients from rivers does not necessarily result in a reduction in primary production, and consequently a reduction in CO_2 uptake from the atmosphere into the ocean.

Given that the global temperature rise is likely to remain below or equal to 2 degrees in these scenarios, the stratification in the North Atlantic would not drastically intensify. Consequently, the supply of nutrients from the North Atlantic to the North Sea is expected to remain at the current level. This implies that the central and northern North Sea will continue to absorb atmospheric CO_2. The southern North Sea, which already has a balanced CO_2 exchange, could show a tendency of a net CO_2 release to the atmosphere, depending on suspended matter distribution[32]. However, Thewes et al. (2021)[32] showed that there is no clear correlation between nutrient concentration and phytoplankton growth, and thus also no clear link between nutrient supply and atmospheric CO_2 absorption. Overall, under these assumptions, the carbon storage and fluxes of the North Sea would remain at today's levels.

Table 1 summarises the potential environmental influences with respect to the scenarios depicted in Figure 6 and their impact on the capacity of the North Sea to absorb atmospheric CO_2. It reveals that almost all environmental changes within scenarios with a strong temperature increase (SSP2-4.5, SSP3-7.0, SSP5-8.5) result in a reduction in the North Sea's CO_2 uptake capacity or an increase in the tendency to outgas CO_2. Occasional, very high-volume discharges from rivers can temporarily enhance the North Sea's CO_2 uptake capacity, but this may also exacerbate oxygen deficiency. For scenarios that aim for a more ambitious reduction in greenhouse gas emissions (SSP1-1.9, SSP1-2.6), the impact on the primary production in the North Sea is less clear. However, these scenarios generally result in more favourable CO_2 uptake capacity trends.

Projected environmental change	Uptake capacity of atmospheric CO_2
Sea surface temperature increase	↘
Stratification increase in the North Atlantic	↘
Sporadic heavy water discharges	↗
Decrease in primary production	↘
Increasing DIC content	↘
Freshwater input by rivers	?
Nutrient input by rivers	?

Table 1: Potential future development of the uptake capacity of atmospheric CO_2 in the North Sea in response to changing environmental parameters. The symbol ↘ represents less uptake by the North Sea or increased outgassing, the symbol ↗ represents more uptake by the North Sea or decreased outgassing, while the symbol ? indicates that the reaction is unclear.

The Baltic Sea

The environmental conditions that control the accumulation and degradation of organic compounds in the Baltic Sea are more heterogeneous than in the North Sea. Consequently, the exchange of CO_2 between the Baltic Sea water and the atmosphere is almost continuous throughout the year. In spring, primary production, which is fed mainly by nitrate, removes CO_2 from the surface water. In summer, a second algae bloom, controlled by blue-green algae, which removes nitrogen from the atmosphere, induces a second CO_2 decrease. Later in the year, the degradation of organic compounds releases CO_2 again. Furthermore, a significant proportion of labile organic material in the sea originates from river inflow[39].

Carbon pools and fluxes within the different Baltic Sea basins

In contrast to the North Sea, the Baltic Sea shows a strong lateral gradient of dissolved inorganic carbon concentration (Figure 3): In the Skagerrak region, conditions are very similar to those observed in the North Sea. As salinity declines, dissolved inorganic carbon concentrations also decline. On the one hand, this is due to the strong dilution of the Baltic Sea by freshwater from rivers. On the other hand, the low horizontal mixing maintains the gradients of salinity and DIC in a relatively stable state.

Figure 5 illustrates the different components of the carbon budget of the Baltic Sea. The inflow of total organic and inorganic carbon from the rivers represents the largest component. It is almost balanced by the sum of sustained storage as burial in the sediment and lateral export to the North Sea. In comparison to the North Sea, the exchange with the atmosphere appears to be very small. However, the proportion of sustainably buried carbon is quite high. This is because tidal movement is almost absent, and the depth is characterised by much less turbulence than in the North Sea. Additionally, large areas of the sediments are anoxic. The decomposition processes of organic particles that have sunk are slower there than in sandy aerobic areas of the North Sea.

The western and eastern basins of the Baltic Sea show significant hydrological and biogeochemical differences: The Skagerrak and Kattegat are still strongly influenced by the salt- and oxygen-saturated North Sea. This results in the presence of calcareous shell-forming plankton groups, which exert a profound influence on the carbonate system.

Salinity levels decrease from the Skagerrak/Kattegat to the deep Gotland Basin, which is situated in the Baltic Proper. Here, long periods of stagnation in the water body prevail, during which lateral exchange of water is minimal. At about 60 m depth, one finds the halocline (which means a stratification due to a vertical salinity gradient). Below this depth, the oxygen content decreases sharply, and dissolved inorganic carbon from anoxic remineralisation processes accumulates. Irregular decadal Major Baltic Inflow events (MBIs) are of great importance for the supply of oxygen and salt-rich water in the Baltic Sea. The oxygen supply also promotes the release of nitrogen from the sediments but has a relatively low impact on DIC-release[40].

The Bothnian Bay, situated to the north, is characterised by very low salinity due to a substantial inflow of fresh water from rivers. This is accompanied by deep mixing, resulting in an increased oxygen content. The rivers, in turn, transport organic carbon compounds into the Bothnian Bay, where they undergo remineralisation and release inorganic carbon. This process leads to the outgassing of CO_2 into the atmosphere[7].

The Baltic Sea reached its peak level of eutrophication in the early 1980s[7], similar to the North Sea. Nutrient inputs subsequently decreased, yet the consequences of eutrophication persisted. In areas with anoxic remineralisation, substances (summarised as alkalinity) are released that counteract acidification caused by atmospheric CO_2 intrusion, preventing these areas from becoming an effective source of CO_2.

Is the Baltic Sea a carbon sink or a carbon source?

The scientific debate, on whether the Baltic Sea as a whole is a net sink or source of carbon to the atmosphere is still ongoing. For several years, scientists considered the Baltic Sea in its entirety as a minor source of carbon for the atmosphere. Kulinski et al. (2011)[41] and Schneider et al. (2017)[7] estimated a net release of 0.5 Mt C yr^{-1}. This understanding is based on a balance calculation of all carbon fluxes over the boundaries of the Baltic Sea, as shown in Figure 5. However, new estimates with reworked riverine inputs show a low net uptake of 2.0 Mt C yr^{-1} [42,43]. This small total uptake corresponds to 1.1% of the German CO_2 emissions in 2020.

Two factors ensure that the CO_2 exchange with the atmosphere is almost balanced over the year, which means that the Baltic Sea has a net uptake of atmospheric CO_2 close to zero:

1. The proportion of carbon buried in the sediments over the long term (2.7 Mt C yr^{-1}, Figure 5) is very high compared to primary production and differs considerably from year to year[7]. A rough estimate of Baltic Sea-wide primary production yields 150 g C m^{-2} yr^{-1} [44]. With an area of 412.500 km^2, the percentage share of permanent storage by burial in the sediment is 4.4% of primary production. In the North Sea, the percentage share is only 1.3%[8] with a long-term burial of 0.9 Mt C yr^{-1} [6], although uncertainties regarding the determination of carbon storage in the North Sea sediments are still high[18]. This shows that organic material is removed from the pelagic carbon cycle in the Baltic Sea more effectively than in the North Sea. The sources of this buried material remain unclear. Figure 5 suggests that large parts of organic carbon are transported directly from rivers into sediments. However, this is a contribution to the carbon balance of the Baltic Sea.
2. The erosion of carbonate-containing rocks at the coast and at the bottom or in deeper layers of the Baltic Sea releases alkalinity, thereby increasing the ability of the Baltic Sea to take up atmospheric CO_2[45]. This process has been ongoing for decades and is likely to continue. An intensification is even possible, as the climate-induced rise in temperature and the increase in CO_2 levels in the air may accelerate the erosion of calcareous rocks.

Without these two factors, the Baltic Sea would be a significant source of atmospheric CO_2, driven by the large input of riverine carbon.

A short outlook: future pools and fluxes

Climate change projections indicate that the Baltic Sea region will experience a greater increase in air temperatures than the global average[26]. This increase is more pronounced in the northern part of the Baltic Sea due to the melting of snow and ice[46]. The sea surface temperatures follow the atmospheric temperatures, and together with the increased freshwater input from the rivers[47], the upper water column stratification will be enhanced[48]. These changes have strong implications for biogeochemical dynamics, such as increased oxygen-depleted areas, reduced nutrient supply from lower water layers, and a subsequent decline in primary production.

These projected environmental influences, in conjunction with the possible increase in alkalinity due to erosion, have diverse implications for carbon uptake and storage in the Baltic Sea region. Table 2 provides an overview of these mechanisms and their potential impact on carbon uptake. For a more detailed summary of the possible future development of physical and biogeochemical parameters in the Baltic Sea area, please refer to Ahola et al. (2021)[49]. Most of the underlying projections are based on the global emission scenario A1B, which represents an older classification and stands between SSP2-4.5 and SSP5-8.5.

Table 2 shows that most indicators point to a decrease in CO_2 uptake in the water column and an increase in CO_2 release. However, the potential for a strong positive feedback loop between climate change and the erosion of calcareous rocks, and the large uncertainties in the future uptake of CO_2 in the different Baltic Sea basins, do not allow the indication of a general trend in atmospheric CO_2 storage.

Projected environmental change	**Uptake capacity of atmospheric CO_2**
Sea surface temperature increase	↘
Snow and ice melting	↘
Stratification increase	↘
Decrease in primary production	↘
Supply of alkalinity by erosion	↗
Higher supply of organic matter by rivers	↘

Table 2: Potential future development of the uptake capacity of atmospheric CO_2 in the Baltic Sea in response to changing environmental parameters[49]. The symbol ↘ represents less uptake by the Baltic Sea or increased outgassing, the symbol ↗ represents more uptake by the Baltic Sea or decreased outgassing. These projected environmental changes are based on global scenarios corresponding to a global temperature change of 2 - 5 degrees.

Summary and conclusion

The far largest pool of carbon in the North Sea and the Baltic Sea is the fraction of dissolved inorganic carbon (DIC) in the water column (approximately 1 Gt C and 0.5 Gt C, respectively)[5]. This pool is modified by a variety of factors, including biological activities such as primary production, exchange with the atmosphere, remineralisation in sediments, as well as lateral and vertical transport.

Direct anthropogenic actions, such as nutrient input via rivers, can have two distinct effects: An increase in load can enhance the CO_2 uptake from the atmosphere but it can also cause severe hypoxia with damage to the entire ecosystem. Conversely, a reduction in nutrient loads can reduce primary production and thus reduce the uptake of atmospheric CO_2.

Reducing the increase of greenhouse gases in the atmosphere would have a positive impact on the ecosystem and would lead to a reduction of dissolved inorganic carbon in the two regional seas. Mitigated greenhouse gases in the atmosphere would reduce the pressure on the carbonate system and limit acidification, resulting in a better buffering effect, which would allow continued absorption of CO_2.

The significant increase in DIC content over the past 15 years, as presented by Legge et al. (2020)[18], is largely attributed to the rise in atmospheric CO_2 levels and the resulting increase in the partial pressure of CO_2 in the atmosphere. If the partial pressure continues to rise similarly over the next 15 years, the North Sea will inevitably be unable to absorb as much CO_2 as it does today.

Thomas et al. (2005)[6] characterised the North Sea carbon system as a "bypass-pump". As the North Atlantic water flows through the North Sea, it is enriched and takes large portions of carbon from rivers and the atmosphere back into the North Atlantic. In comparison, the Baltic Sea system could be characterised as an "injection pump": Carbon taken up in this area is held in the pelagic or benthic zone for extended periods. Some of the carbon leaves the Baltic Sea for the North Sea via the narrow link through the Belts and Skagerrak. If bottom-trawl fishing were to cease in the large deposit centers of the Norwegian Trench and Skagerrak, which are also fed by these pumps, carbon could be effectively stored in these areas, including in the upper sediment layers, in the future.

The North Sea appears to be more resilient to anthropogenic disturbances. It can effectively absorb carbon from the atmosphere due to its strong connection to the North Atlantic. However, numerical projections show that increasing warming and acidification will diminish this effectiveness[20]. In the case of the North Sea, it is unclear whether a reduction in nutrient loads, which would initially have a positive effect on the entire ecosystem, would reduce primary production.

The Baltic Sea appears to be less resilient to anthropogenic disturbances due to a weak water exchange. Some processes, such as the effective carbon flow through the food web and aerobic remineralisation, are severely limited below 60 m depth. To prevent the risk of oxygen deficiency, further substantial reductions in nutrient inputs are required[50]. Model calculations show no changes in the CO_2 exchange with the atmosphere for the last 30 years[22].

As observed, the North Sea is still an effective sink for atmospheric CO_2. However, the role of the Baltic Sea in this process remains unclear, with the possibility that it acts as either a small sink or a small source of atmospheric CO_2. In the case of the North Sea, carbon uptake and storage will likely decrease in the near future. In the case of the Baltic Sea, the accelerating erosion of carbonate-bearing rocks could lead to an increase in the storage capacity of CO_2. Given the high level of uncertainty and the large regional differences, it is not possible to predict the future development of carbon storage in the Baltic Sea region. The potential impact of active human interventions, such as the additional supply of alkaline material or the expansion of seagrass meadows, has not been considered in this context.

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