Photo: Sandy mudflat. CWSS/ Bostelmann.

Wadden Sea Quality Status Report

Climate change

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1. Introduction

In **2017**, the Quality Status Report (QSR) chapters on ‘Climate Change’, described a further increase in temperature and precipitation (Oost et al., 2017). More species had shifted their geographical distribution and/or changed their timing of migration and reproduction. In addition, new long-distance impacts were found such as the reduced survival of juvenile migratory birds (red knot). This is due to changing food availability at their Arctic breeding grounds (see references in Philippart et al., 2017). For the period 2071-2100, it was then expected that air temperature would continue to increase with 0.9-4.8 °C, and that warm extremes would become more frequent. Furthermore, that precipitation and storm surges would increase, and that the sea-level would rise by 10-90 cm. All these developments would further be impacting habitats and species (Oost et al., 2017; Philippart et al., 2017).

In **2020**, an expert workshop identified three key climate stressors impacting the Outstanding Universal Value (OUV) of the Wadden Sea World Heritage, being temperature trend (air and/or water), extreme temperature events and sea level rise (Heron et al., 2020). The vulnerability of the OUV to impacts from sea level rise was considered low in 2050 and high in 2100, whilst that of the two temperature-related climate stressors was assessed as high in both timeframes.

In **2021**, the Intergovernmental Panel on Climate Change (IPCC) stated that human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years (IPCC, 2021a). For Northern Europe (which includes the trilateral Wadden Sea), there was an observed increase in pluvial flooding attributed to human influence. This was projected to further increase at global warming of 1.5 °C (medium confidence) and 2 °C and above (high confidence). Also, a projected decrease in river discharges at global warming of 2 °C and above (medium confidence) was expected, as was a projected increase in severe windstorms at global warming of 2 °C and above (medium confidence) (IPCC, 2021b).

In **2022**, Europe’s essential waterways have become under-replenished and, increasingly, heated driven by an unusually dry winter and spring followed by record-breaking summer temperatures and repeated heatwaves (Toreti et al., 2022). So far, there were no other events in the past 500 years like the drought of 2018, and the year 2023 had the highest seawater temperatures in June in more than 160 years (Figure 1). In the summer of 2018, the Wadden Sea was confronted with a mass mortality of cockles (Troost & van Asch, 2018). The impacts of the (early) heatwave in 2023 are so far unknown.

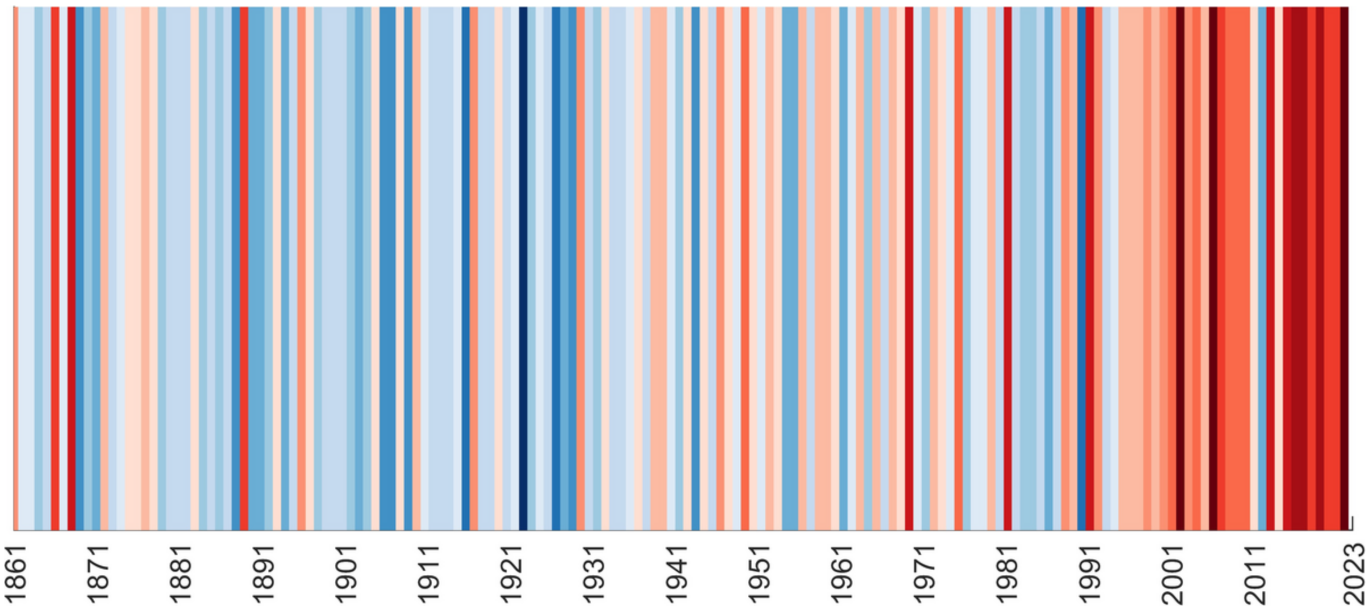

Figure 1. Warming of the Wadden Sea waters in the Marsdiep tidal inlet. The warming stripes of the western Wadden Sea, based on the average water temperature of each June from 1861 until 2023 (SST 15.3 °C). NIOZ has been measuring the temperature of seawater in the Marsdiep tidal inlet since 1861. As of 2001, this has even been done every ten minutes, allowing a very reliable daily average to be determined, regardless of high or low tide. After the relatively warm winter of 2022/2023 followed by an initially chilly spring, temperatures suddenly rose in mid-June. June turned out to be the warmest seawater (18.5 °C) month in the Wadden Sea in 160 years (Figure made by Sonja van Leeuwen, NIOZ).

Human responses to the impacts of climate change include increased fishing on warmwater species (e.g., shellfish and fish) and increased storage of freshwater inland (resulting in a reduction of freshwater discharges to the sea). In addition to ongoing and new human activities, climate-driven actions might reduce or enhance the impacts of climate change on habitats, species and ecosystem functioning of the Wadden Sea. Such **cumulative impacts**, from one or more sources, may accumulate over time and impact on ecosystem functioning and ecosystem services.

In this thematic report, we will first give a condensed update on the status and trends in climatic factors, ecological effects, ecosystem impacts and ecosystem services. These findings will be subsequently used to evaluate the present and future consequences for targets that are set for the Wadden Sea. This assessment will form the base of the recommendations for monitoring, scientific research, and management of human behaviour. As this chapter is connected to many other chapters of the QSR, we will refer to those when relevant.

2. Status and trends

2.1 Greenhouse gases

Human-induced global warming is mainly caused by changes in the global atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several industrial gases (Tans et al., 2023).

The first three are natural greenhouse gases that have been in the atmosphere for at least hundreds of millions of years but have very sharply increased recently. The other greenhouse gases are, or have been, made by the chemical industry, and were not present in the atmosphere before the mid-20th century. All these greenhouse gases trap solar heat reflected from the Earth's surface in the atmosphere.

The contribution of each gas to global warming depends on the concentration and its capacity to trap heat. In 2021, 64 % of the annual average radiative forcing was brought about by CO_2, 19 % by methane (CH_4), 6 % by N_2O, and 11 % by industrial gases (Tans et al., 2023).

Carbon dioxide (CO_2)

Carbon dioxide concentration in the atmosphere is regulated by photosynthesis and respiration as primary processes. Carbon dioxide enters the atmosphere through burning fossil fuels (coal, natural gas, and oil), solid waste, trees, peats, and other biological materials, and because of certain chemical reactions (e.g., manufacture of cement). In 2019, global emissions of fossil CO_2 reached a new record value of 36.7 gigatonnes, which implies that the emissions were 62 % higher than 30 years before (World Meteorological Organization, 2020).

In 2020, global emissions were reduced by 5 % due to widespread lockdowns and subsequent decline in economic activity associated with the COVID-19 pandemic. In 2021, however, the CO_2 emissions returned to pre-pandemic levels with a preliminary estimate of 39.3 Gt CO_2 per year (Stuart et al, 2022). Between 2002 and 2018, CO_2 concentrations in the Wadden Sea (at Lutjewad) showed a mean long-term increase of 2.31 ± 0.07 ppm per year (Nguyen et al., 2022).

Higher CO_2 concentrations in the air generally results in more acidic conditions (lower pH) in the water. A decline in pH of 0.23 units was observed in the seawater of the adjacent German Bight between 1984 (the start of continuous measurements) and 2019 (Rick et al., 2023). Recently, it was concluded that this is not caused by increased atmospheric CO_2 concentrations but resulting from nutrient fluxes from the Wadden Sea (Yakubov & Protensko, 2021). This finding is in line with a previous conclusion that the pH in Dutch coastal waters is, at least so far, governed by changes in nutrient availability, and thus biogeochemical processes (Provoost et al., 2010).

Although Wadden Sea species and habitats, such as bivalves beds/reefs and saltmarshes, store carbon, their exact role in net C-sequestration is not yet fully clear. Whilst saltmarshes are generally considered as net carbon sinks, the role of bivalves as net sinks or sources of carbon is still being discussed (BOX 1; Figure 2).

BOX 1. The role of Wadden Sea biota in carbon sequestration

The estimated total carbon stock in the Dutch Wadden Sea by bivalve tissue and shell material is 50,000 tonnes C in the intertidal areas and 42,000 tonnes C in the subtidal areas (of which 7,000 is cultured stock). The net contribution of bivalves to carbon sequestration is, however, debated in literature (Jansen & van den Bogaart, 2020).

Bivalves in the Wadden Sea might even contribute to an increased CO_2 concentration in the atmosphere. In the process of biogenic calcification, one mole of CO_2 is released for each mole of generated $CaCO_3$ (the so-called carbonate counter pump) (Munari et al., 2013). The release of CO_2 during calcification induces a shift in the seawater carbonate system; when $CaCO_3$ is removed from seawater, its pH shifts toward the acidic, and the CO_2 concentration and pCO_2 of the water increase, leading to increased concentrations of CO_2 in the atmosphere (Zeebe & Wolf-Gladrow, 2001). Then there is also CO_2 release through respiration, and largely unknown fluxes related to biodeposition and remineralization (Figure 2, redrawn from Jansen & van den Bogaart, 2020).

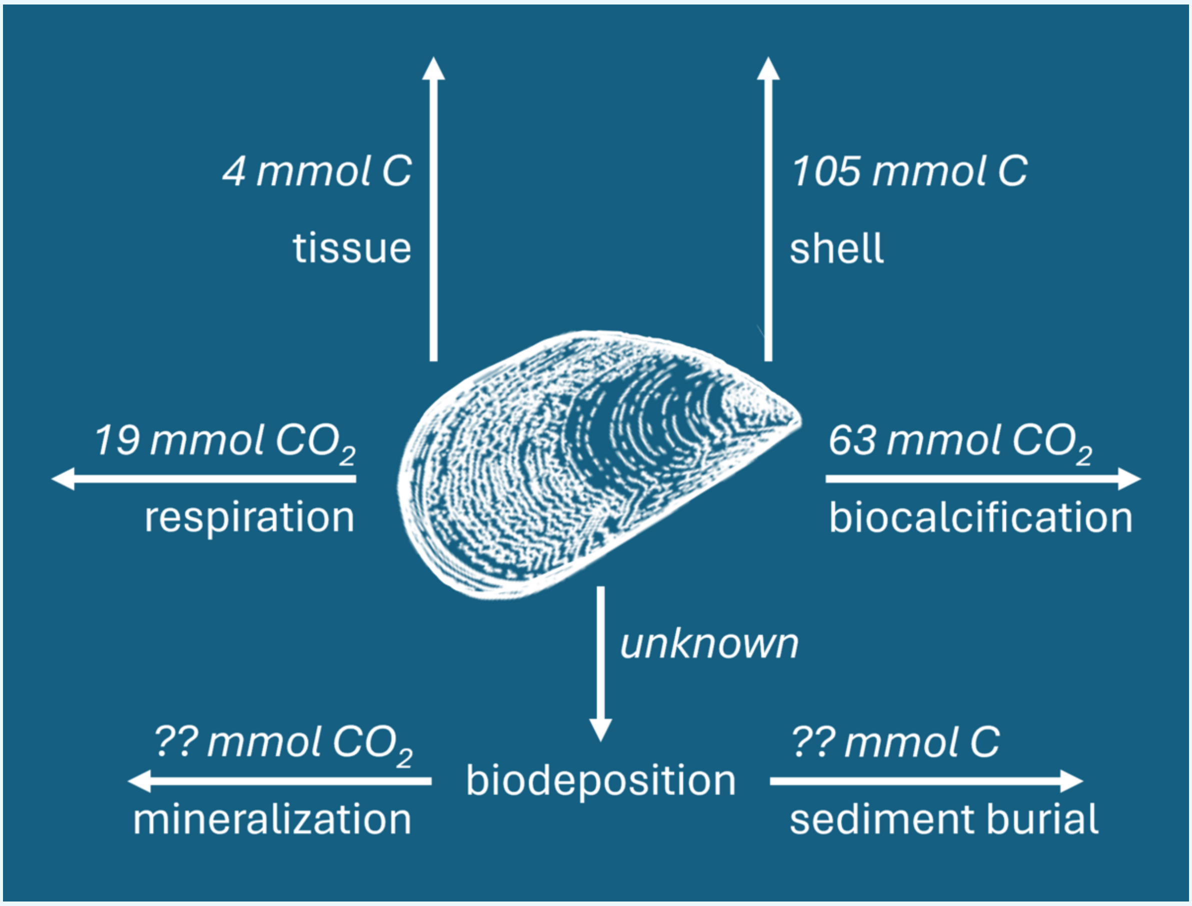

Figure 2. Schematic overview of carbon fluxes in bivalves. Carbon fluxes (in mmol C) for an individual mussel during one (commercial) production cycle of, on average, two years (figure redrawn from Jansen & van den Bogaart, 2020).

The question is not, whether bivalves store or release carbon (they do both, because they accumulate tissue and shell material, but also respire), the question is whether the net effect of for example mussel beds on CO_2 concentrations of the atmosphere is net positive or negative. This balance also needs to include habitat induced effects like increased sedimentation in bivalve beds. Overall, a greater understanding is required before shellfish can be included in the quantification of carbon sequestration (Filgueira et al., 2015).

Salt marshes are considered to be carbon sinks (Mueller et al, 2019). Measurements in the Netherlands and Germany provide estimates between 0.99 to 13.5 tonnes CO_2-eq per hectare per year (van de Broek et al., 2018; Teunis & Didderen, 2018; Elschot et al., 2015). There are large spatial, temporal, and vertical variations in organic carbon stocks in salt marsh sediments. Sequestration rates in salt marshes very, depending on plant production, oxygen availability, salinity, decomposition, clay thickness, age, and management (grazing). Some 50 % to 80 % of carbon is allochthonous (Mueller et al., 2017), i.e. not produced by the salt marsh vegetation and this is relevant for C-crediting approaches. Future research is necessary to refine estimates of C sequestration provided by Wadden Sea marshes.

Methane (CH_4)

Methane is a strong greenhouse gas which decays into CO_2 and H_2O over time. Methane is emitted from various natural and anthropogenic sources at the Earth's surface. They are usually grouped in three categories, being biogenic sources (e.g., agriculture and farming, waste, biogas production, wetlands, and inland water systems), thermogenic sources (fossil fuel extraction, combustion and consumption, geological sources), and pyrogenic sources (biomass and biofuel burning) (Menoud et al., 2020).

Measurements of methane at 60 m height at the 'Lutjewad' atmospheric station (from November 2016 to March 2017) showed that dominant CH_4 sources at this location were microbial (e.g., resulting from cattle farming and waste management), and that fossil fuel related sources of CH_4 appear to be mainly located east from the sampling location (pointing towards facilities to extract natural gas in the Groningen production field or the German Ruhr area) (Menoud et al., 2020; Yacovitch et al., 2008).

In the German Bight, the dilution of methane-rich riverine water (e.g., 40 to 50 nmol CH_4 l^{-1} in the Elbe and Weser) with methane-poor seawater (5 nmol CH_4 l^{-1}) of the North Sea determines the coastal distribution of methane concentrations in the water (Bussman et al., 2021). The calculated methane flux from the water into the atmosphere revealed local values of approximately 128 µmol CH_4 m^{-2} d^{-1}, which is 3.5 times higher than background values (median of 36 µmol CH_4 m^{-2} d^{-1}). The high methane flux value was presumably due to high wind speeds and high methane concentrations at those times and locations.

Nitrous oxide (N_2O)

Nitrous oxide is emitted during agricultural land use, and industrial activities, combustion of fossil fuels and solid waste as well as during treatment of wastewater. Estuaries are also potential sources of nitrous oxide and, together with coastal wetlands, contribute approximately 0.17 to 0.95 × 10^{12} g N_2O-N per year to the global nitrous oxide budget of 16.9 × 10^{12} g N_2O-N per year (Schulz et al., 2022).

Based on nitrous oxide concentrations in the water, the emission of the Ems estuary in 2020 was estimated to be 0.57 × 10^8 g N2O yr^{-1} (Schulz et al., 2022). This relatively high emission rate for such a small estuary was presumably caused by enhanced suspended particulate matter concentrations and the linked oxygen deficits, being the result of the ongoing deepening and dredging of this estuary (Schulz et al., 2022).

At the end of 2021, the global average N2O concentration at the Earth's surface was more than 335 ppb, which is 24 % higher than the pre-industrial level of about 270 ppb around 1850. Whilst the increase was +0.85 ppb per year over the last 25 years, it rose to +1.20 ppb per year during last two years. This implies that the emissions of N_2O in the atmosphere appears to be accelerating (KNMI, 2022).

2.2 Weather & climate

Temperature

Within the Netherlands, the annual average air temperature has increased by 1.1 °C between 1961-1990 (average yearly temperature 9.4 °C) and 1991-2020 (average yearly temperature 10.5 °C), which is twice as fast as the global increase in temperature (KNMI, 2021). The increase in spring and summer temperatures are partly due to the strengthening in solar radiation (KNMI, 2021). Along the German North Sea coast, temperature increased by 0.9 °C among 1961 and 2015 (Das Helmholtz-Zentrum Hereon, 2023).

From the start of air temperature measurements in 1901, heatwaves in the Netherlands have become more frequent, from seven times in six years between 1901 and 1950, to 14 times in 11 years from 2000 to 2022 (KNMI, 2023a). The frequency of severe winters has declined during this time, from 16 times in 12 years between 1901 and 1950 to one time between 2000 to 2022 (KNMI, 2023b).

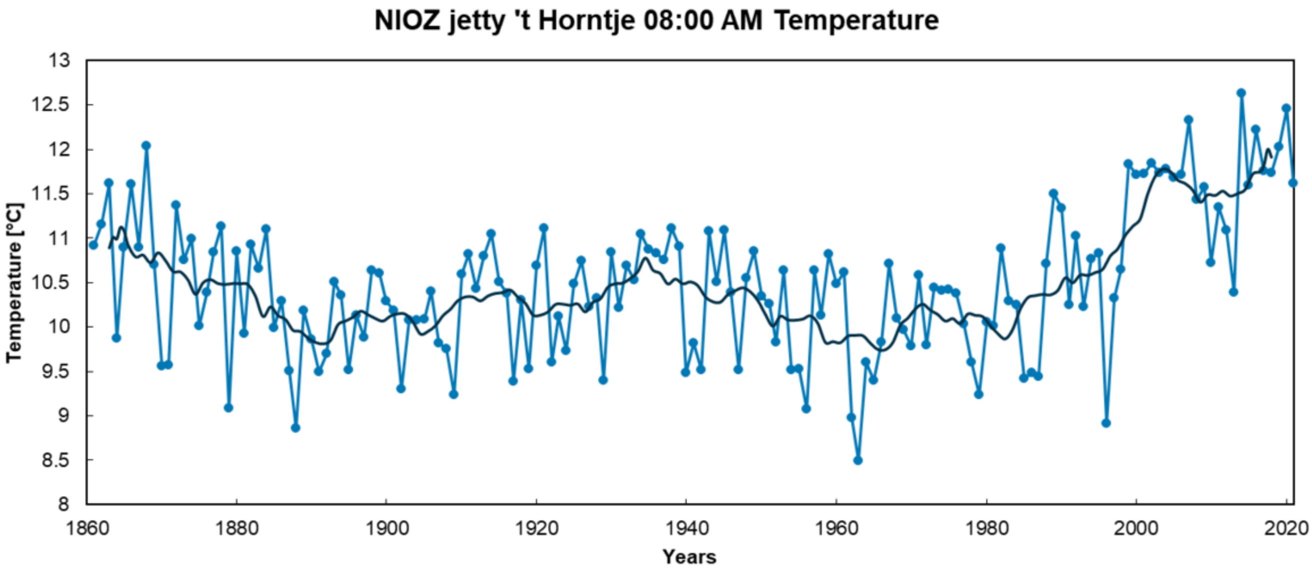

Figure 3. Trends in water temperature in the Marsdiep tidal inlet. Annual means (blue dots and line) and running average (black line) of long-term observations in annually averaged water temperatures at 8:00 AM in the Marsdiep tidal inlet between 1860 and 2021 (Data supplied and figure made by Sonja van Leeuwen, NIOZ).

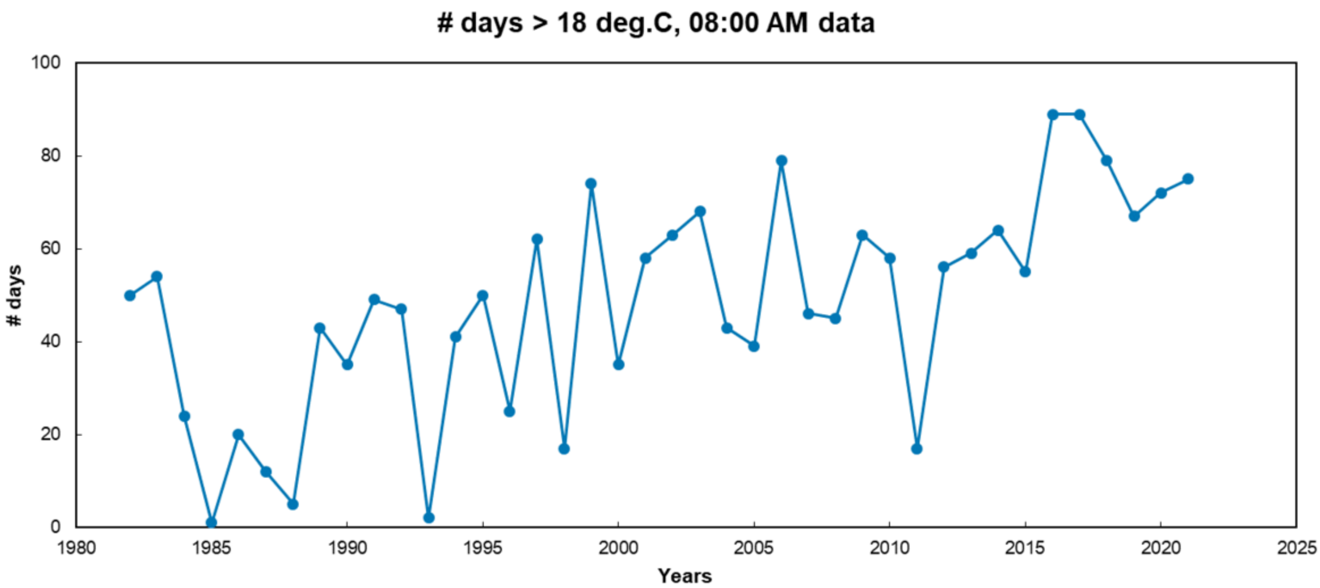

Figure 4. Trends in high (≥ 18 °C) water temperatures in the Marsdiep tidal inlet. The number of days each year that a temperature of ≥ 18 oC at 08:00 AM was recorded at the NIOZ jetty in the Marsdiep inlet (data supplied and figure made by Sonja van Leeuwen, NIOZ).

Between 1860 and 2021, the average annual seawater temperatures of the western Wadden Sea (measured in the Marsdiep tidal inlet) reached unprecedented high values in 2007, 2014 and 2020 (Figure 3). Both 2018 and 2021 had strong heatwaves but also very cold snaps, pushing the annual mean temperature towards lower values. From 1982 to 2021, the number of days annually with temperatures higher than 18 °C generally increased, with highest values (89 days with water temperatures above 18 °C within a year) occurring in 2016 and 2017 (Figure 4). Although the absolute temperatures remained cooler than in the Southern Wadden Sea, a similar warming trend of 1.8 °C surface water temperature increase over the last 60 years has been observed in the Northern Wadden sea in Germany, indicating that surface water temperatures increase faster than air temperature (Amorim et al., 2023).

There are no data available to determine long-term temperature trends in the sediments of the Wadden Sea, but local measurements at tidal flats showed that bottom temperatures followed those in the air and could rise to over 30 °C during heatwaves at 3 cm depth (BOX 2; Figure 5).

BOX 2. Bottom temperatures on tidal flats during heat waves

In the western Wadden Sea, maximum temperatures measured in the sediment of Mok Bay (Texel) were 29 °C at 3 cm depth and 25 °C at 15 cm depth around noon on 7 August 2018 during the heatwave in 2018. The top layer of the sediment (-3 cm) cooled down during the night, temperatures deeper in the sediment (-15 cm) showed much less variation and stayed between 20 °C and 25 °C for two weeks (Figure 5, based upon unpublished data by Philippart & Dethmers, NIOZ).

In the Eastern Scheldt, measurements taken during four months in the summer of 2020 showed that the temperature in the sediment of tidal flats is related to depth below surface, emersion time, tidal synchronisation (low tide in the afternoon), water temperature and sediment characteristics. There, temperatures over 30 °C at 3 cm depth occurred for more than 6 hours per day in four consecutive days on a high tidal flat with 80 % emersion time during a heatwave in August 2020. A measured maximum temperature of 35 °C at 3 cm depth prolonged for 135 minutes (Suykerbuyk et al., 2021).

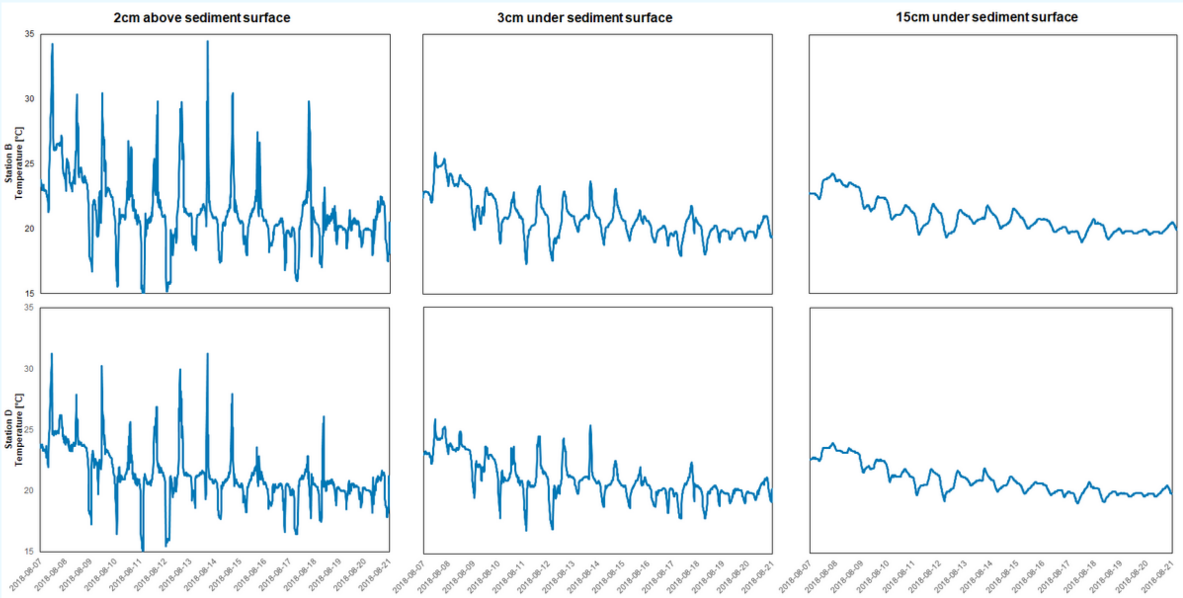

Figure 5. Bottom temperatures in the western Wadden Sea during a heat wave. Temperatures as measured on two depths (2 cm above, and 3 and 15 cm under the sediment surface) at two stations at the tidal flats of the Mok, an embedded bay in the westernmost part of the Wadden Sea, during a heatwave from 7 August (00:00 UTC) to 20 August, 2018 (23:45 UTC) (Philippart & Dethmers, unpublished data).

Wind

Since the 1990s, the annual average wind speed over land in the Netherlands has decreased by an average of 2 % every 10 years (KNMI, 2021). The highest hourly average wind speed per year has also decreased. This decrease is probably partly related to more building development and therefore a greater ‘roughness’ of the land surface that inhibits the wind. For the North Sea there is no significant trend in power or direction of the wind speed.

Along the German North Sea coast, the annual average wind speed increased non-linearly by about 2 % among 1961 and 2015. From 1961 until the early 1990s, average wind speed (as well as storm intensity) increased; since then there has been a slight calming down (Das Helmholtz-Zentrum Hereon, 2023).

Decadal changes in large-scale atmospheric pressure systems led to a recent increase in south-westerly and southerly wind events. Wind events from these directions are also predicted to increase with ongoing climate change and will disproportionately affect sea level rise in the Northern Wadden Sea, while smaller effects can be expected in the southern parts (Rubinetti et al., 2023).

Amongst others, wind plays a major role in (i) actual sea levels, generating wind-driven currents and waves in coastal waters, (ii) the increase in concentrations of suspended particulate matter in (and, subsequently, the turbidity of) seawater during storms in the Wadden Sea (Hache et al., 2019) and (iii) the exchange of water, sediment, and nutrients between tidal basins of the Wadden Sea (Sassi et al., 2015) as well as between the North Sea and the Wadden Sea (Van Weerdenburg et al., 2021).

Sea level

The average global sea level rise between 1901 and 2018 was about 20 cm (KNMI, 2021). Recently, there has been an acceleration in global average sea level rise to 3.7 mm per year over the period 2006 to 2018. Increase in sea-level have been measured during 1850-2011 in the Danish, Dutch and German Wadden Sea (Wang et al., 2013).

Recent studies show, however, that sea levels in the North Sea are subject to a multidecadal mode of variability in the wind forcing leading to considerably higher values of up to 6.6 mm per year in recent years in the northern German Wadden Sea (Keijzer, 2022; Steffelbauer et al, 2022; Das Helmholtz-Zentrum Hereon, 2023; Wahl et al., 2013).

A re-analysis of data, including corrections for this variability in wind conditions but also tidal effects results in a present sea level rise over the period 1993-2020 of about 3 mm per year, and more in line with the global trend (Stolte et al., 2023).

Precipitation

In the Netherlands, the annual precipitation increased since 1910, but this net trend has ceased since 2000 which might, however, be a temporal fluctuation (KNMI, 2021). There is a strong seasonal effect: precipitation has increased in summer and winter, but this effect is largely compensated by a decrease in spring and autumn. The maximum precipitation deficit, or drought during the growing season, increased by 8 % every 10 years in the period 1991-2020. Along the German North Sea coast, no significant changes in average annual and seasonal precipitation occurred among 1961 and 2015 (Das Helmholtz-Zentrum Hereon, 2023).

Over the last 30 years, heavy rainfall events in the Netherlands have become even more extreme (KNMI, 2021). The most extreme rainfall events, which occur at most once every 10 years, are now characterized by 10 to 15 % more precipitation. Since 2000, rainfall events with more than 40-50 mm per hour have also become more frequent.

Along the German North Sea coast, no significant changes occurred in the number of days with heavy rainfall, i.e. number of days when the fallen precipitation (snow + rainwater) is at least 20 mm (Das Helmholtz-Zentrum Hereon, 2023).

In 2018, 2019, 2020 and 2022, north-western Europe was faced with extreme droughts (European Drought

Observatory, 2021). Amongst others, these droughts resulted in a reduction in the outflow of the main rivers to the Wadden Sea particularly in spring (Figure 6).

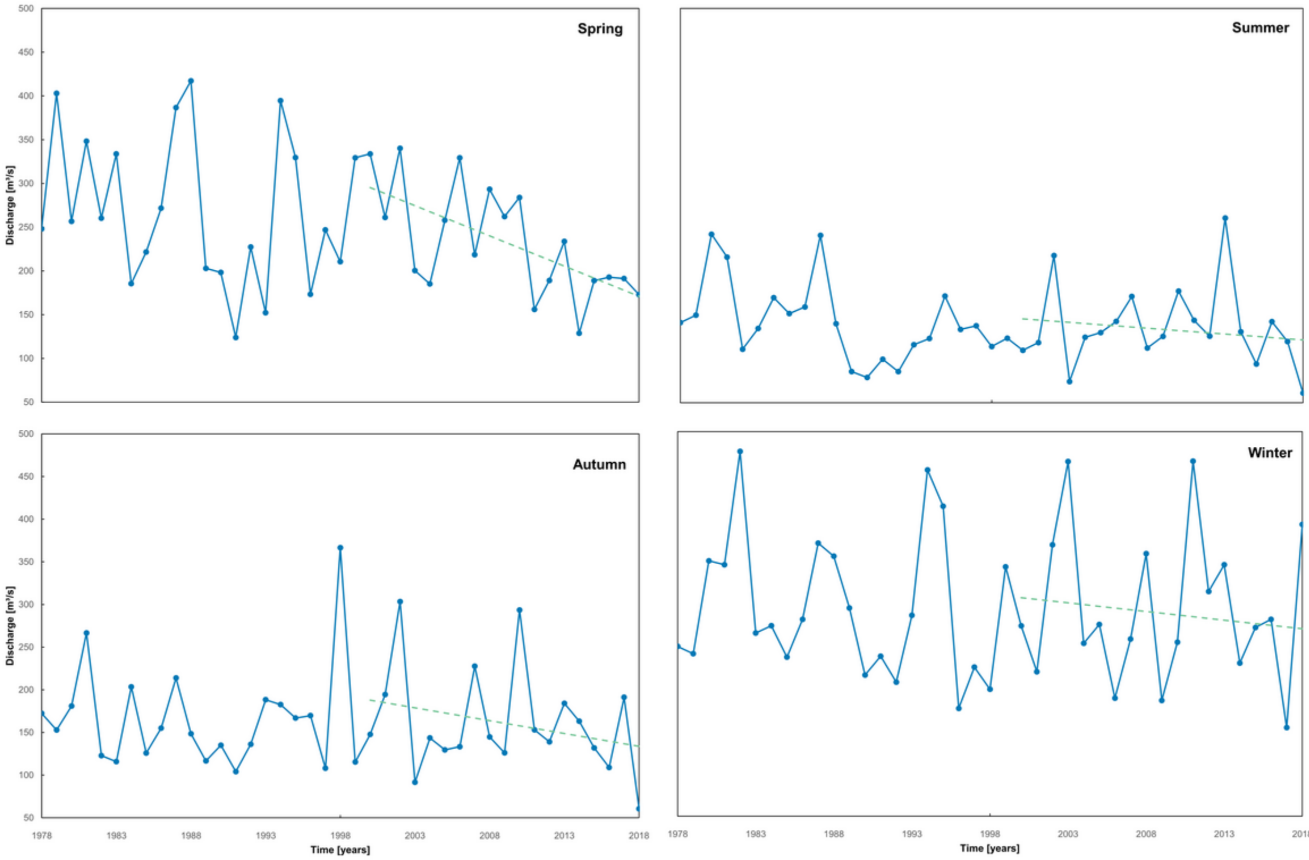

Figure 6. Trends in freshwater discharges in the trilateral Wadden Sea. Mean seasonal signals of the combined discharge of the larger entrance points of freshwater into the trilateral Wadden Sea (Arlau, Bongsieler Kanal, Eider, Elbe, Ems, Lake Ijssel West, Lake Ijssel East, Miele, Weser). Here, spring is defined as March-April-May, summer is defined as June-July-August, autumn as September-October-November and winter as subsequent December-January-February. Data up to and including 2019 were used, due to the definition of winter discharge only results up to 2018 are shown. The linear trends for 2000-2019 have been included as dashed lines. Data from the OSPAR Intersessional Correspondence Group on Eutrophication Modelling (ICG-EM) riverine database (hosted by Sonja van Leeuwen, NIOZ). Dutch data from Rijkswaterstaat, German data from the Lower Saxon State Department for Waterway, Coastal and Nature Conservation (Niedersächsische Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz, 22 December 2023) and the Elbe portal (Flussgebietsgemeinschaft Elbe, 2023).

Salinity

Between 1860 and 2021, the salinity in the western Wadden Sea generally declined (Figure 7). The long-term trend is mainly due to engineering works in the rivers Rhine and IJssel, whilst variations in salinities around the trend were due to variations in precipitation and freshwater management (van Aken, 2008). The recent increase in salinity is likely due to the combined impact of increased periods of drought (leading to more fresh water retention for agriculture and drinking water), increased air temperatures (leading to more evaporation), and the reversal of the Marsdiep net outflow to net inflow of North Sea waters as induced by global warming (van der Molen et al., 2022).

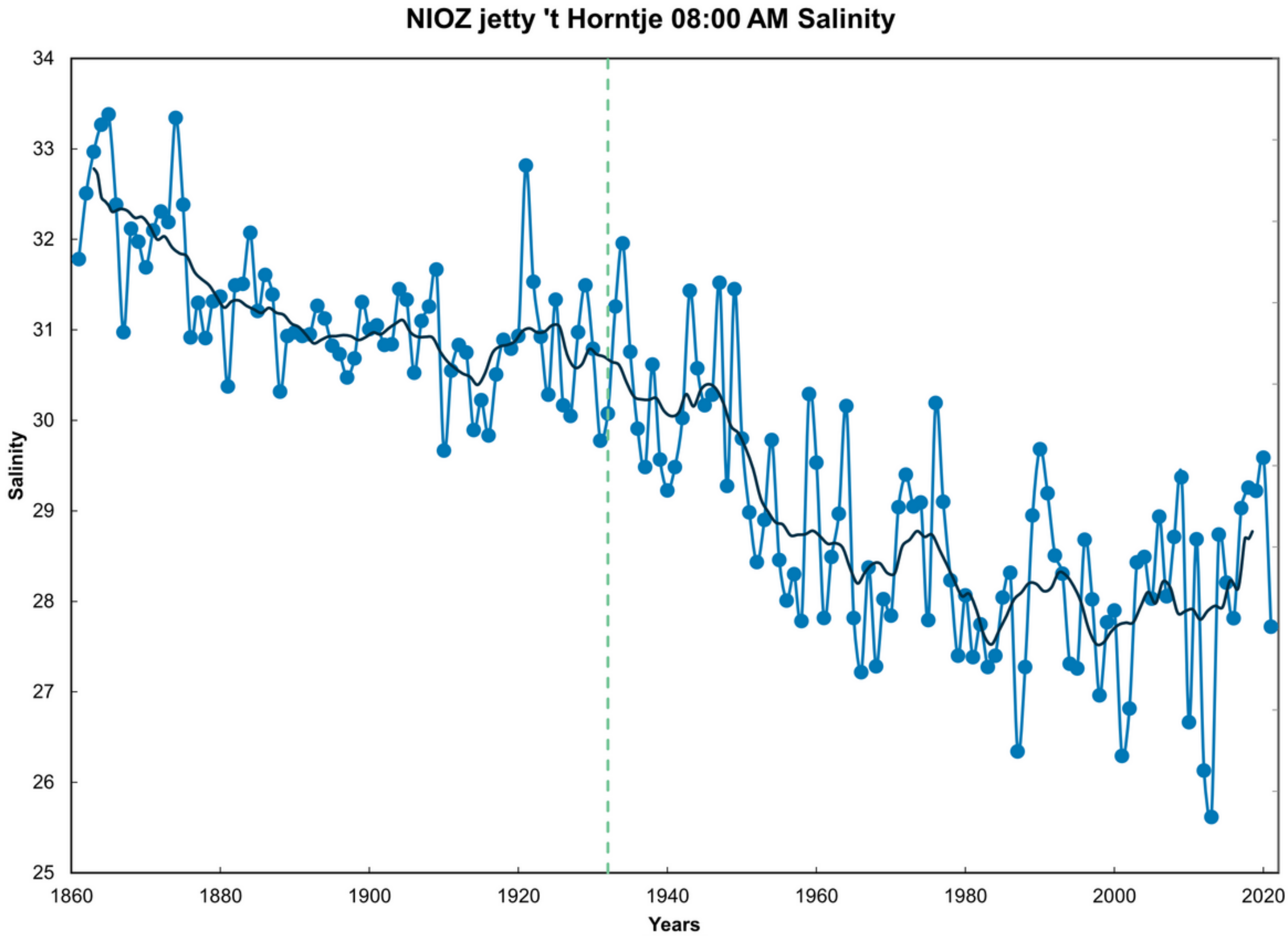

Figure 7. Trends in salinity in the Marsdiep tidal inlet. Long-term trend in annually averaged salinity at 8:00 AM in the Marsdiep tidal inlet between 1860 and 2021 (Royal Netherlands Institute for Sea Research Texel (NIOZ TX)). The green dashed line indicates the year (1932) when the Afsluitdijk was completed (Data supplied and figure made by Sonja van Leeuwen, NIOZ).

Salinity-temperature relationships

Although water temperatures (sea surface temperature, SST) generally increased whilst salinity generally decreased, plotting both trends against each other suggests that the western part of the Dutch Wadden Sea has experienced three clusters of salinity-temperature conditions over the recorded period: the 1860s-1930s (low SST, high salinity), the 1940s-1980s (low SST, low salinity), and the 1990s-2020s (high SST, low salinity) (Figure 8). Note that changes are happening increasingly rapidly, with most years of the 161-year time span clustered in the top part representing the first cluster.

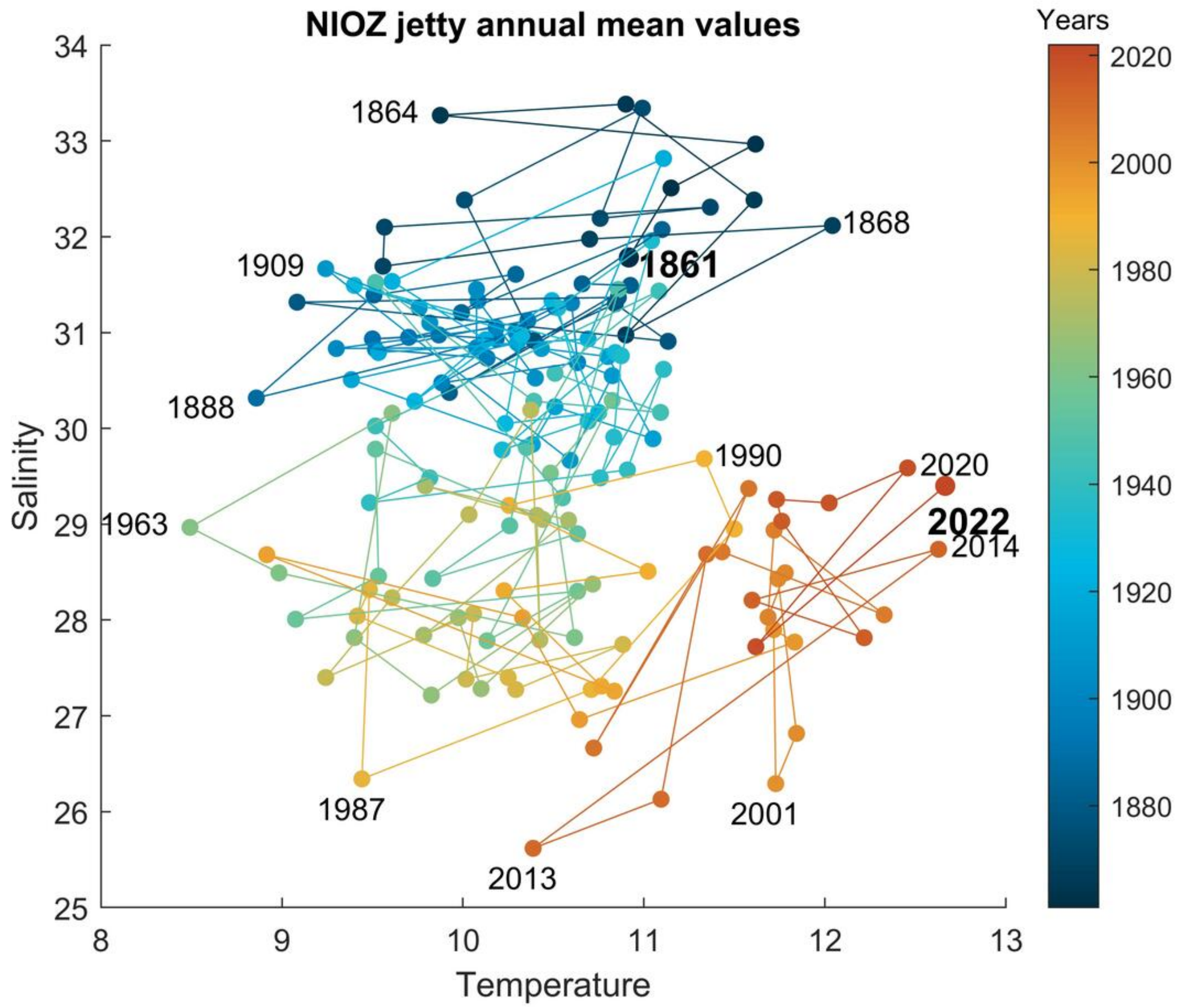

Figure 8. Trends in temperature versus salinity in the Marsdiep tidal inlet. Long-term relationship between trend in annually averaged water temperatures and salinity at 8:00 AM in the Marsdiep tidal inlet between 1860 and 2021 (Data & figure: Sonja van Leeuwen, NIOZ).

2.3 Hydrodynamics

Circulation patterns, currents & tides

Tides, wind-driven currents, and estuarine circulation patterns are generally responsible for generating flows between the North Sea and Wadden Sea, and between adjacent tidal basins (Duran-Matute et al., 2016).

In the westernmost tidal inlet of the Dutch Wadden Sea, wind-driven inflow by dominantly SW winds generally opposes tidally driven residual outflow to the North Sea. Variations in wind create, therefore, a large variability in the residual export of water masses. In recent years, however, the tide-driven residual outflow has decreased, resulting in occasional net import of seawater (van der Molen et al., 2022). This change is presumably due to large-scale tidal changes in the Atlantic Ocean, and by an increased strength and duration of stratification in the southern North Sea resulting from global warming (van der Molen et al., 2022; Jänicke et al., 2021).

In the German Wadden Sea, along-channel estuarine circulation is generally characterised by a net inflow of seawater near the bottom and a net outflow of more riverine water near the water surface (Becherer et al., 2016). Increased westerly winds, however, can weaken or even reverse this estuarine circulation. Furthermore, the flood duration and flood currents in the period from 1996 to 2016 decreased within most tidal basins of the German Wadden Sea, most probably due to a change in geomorphology (more tidal flats, smaller channels) in these areas (Hagen et al., 2022).

Water quality

The water quality in the tidal basins of the Wadden Sea is affected by a range of factors, where local concentrations of nutrients, sediment and pollutants are determined by:

1. direct riverine influxes, such as those from the Ijssel, Ems, Weser and Elbe,
2. indirect riverine influxes, such as those present in the adjacent coastal waters of the North Sea (with a residual current from east to north), which originate from the rivers Scheldt, Meuse and Rhine,
3. the dynamics in circulation patterns, currents and tides between the North Sea and the Wadden Sea (see previous paragraph),
4. local processes (e.g., resuspension of sediments, local losses of pollutants, benthic mineralisation),
5. atmospheric conditions (precipitation, aerial deposition and release).

Globally pollution by plastics, for example, is a result of the garbage produced by the local population within an area of 50 km from the coast (60 %), input by rivers (12 %), and products of fishing activities (nets, ropes, etc.; 18 %) (van Duinen et al. 2022). For the Dutch Wadden Sea, mass concentration of polystyrene nanoplastics was 4.2 µg l^{-1} on average, indicating a substantial contribution of such nanoplastics to the total plastic budget of this area (Materić et al., 2022). Occasional loss of cargo by container vessels, such as that by the MSC Zoe (1 January 2019, loss of 342 containers) (Onderzoeksraad voor de Veiligheid, 2020) adds to the supply and dispersion of plastics and the pollution of Wadden Sea ecosystems.

The mixing of water masses and flushing times affect the overall water quality in the Wadden Sea. Both waves and currents determine the transparency of the water column and resuspension of suspended particulate matter (SPM) may create high turbidity levels. A change in the direction and/or strength of residual inflows due to climate change may have far-reaching consequences for temperature, salinity, and the SPM concentrations in the adjacent tidal basin (van der Molen et al., 2022).

2.4 Morphodynamics

The Wadden Sea is part of a larger strongly connected system, where mud and sand are exchanged with the North Sea coasts of the barrier islands, the ebb deltas in front of the tidal inlets and between the tidal basins of the Wadden Sea itself. This strong connectivity implies that any climate-driven change in any part of this system will impact on other parts, e.g., moving sediments from erosion sites towards deposition sites (Schra et al., 2022).

In 2021, a trilateral scientific community provided the first mud balance for the trilateral Wadden Sea. The mud balance includes detailed information about the supply of mud from the main sources in the Southern Bight of the North Sea, the transport pathways and the sinks due deposition or artificial extraction of these fine sediments (Oost et al., 2021).

Tidal flats and backbarrier basins

Accelerated sea level rise without any geomorphological response would result in deeper coastal waters, shorter emersion times of tidal flats and enhanced flooding of salt marshes. These impacts could, however, be compensated by an increase in the natural deposition of sediment, depending on the size and shape of these areas, the hydrodynamic conditions such as tidal amplitudes, and the sediment supply from rivers and the sea (Leuven et al., 2019).

For the Dutch Wadden Sea, almost all tidal basins (except for the Eijerlandse Gat) accumulated sediment with sedimentation rates (2.5 to 6.7 mm per year) nearly equal to or larger than the current rate of sea level rise, and with largest volumes of sediment imported into the western basins (still reflecting the ongoing morphological adaptation after the closure of the Afsluitdijk) between 1935 and 2000 (Wang et al., 2018).

Accumulation of sediments on intertidal flats has also taken place in the German sector, where intertidal flats in almost all tidal basins (except in two tidal basins) has increased in average by 7.9 mm per year (Benninghoff & Winter, 2019).

Analyses based on models and measurements on tidal amplitude along the entire Wadden Sea coast show that tidal flats will follow sea level rise especially in sectors with surplus of sediment such as off the coast of Schleswig-Holstein and Denmark (Jordan et al., 2021; Madsen et al., 2010). During the most recent years, however, the import of sediment decreased in almost all basins (Elias & Wang, 2020).

For the Vlie tidal basin, according to the “Representative Concentration Pathways 2.6” scenario which describes the development of greenhouse gases corresponding with a very ambitious climate policy and based on conceptual morphological modelling sea level rise may exceed the local critical rate for drowning of tidal flats (6.3 mm per year) by 2030. In general, doubling the rate of sea level rise would nearly double the loss in intertidal flats of the Dutch Wadden Sea (Huismans et al., 2022).

For the German Wadden Sea, further sea level rise causes an increase in tidal current velocities in tidal inlets and channels of the Wadden Sea (Wachler et al., 2020). A sediment budget analysis for the period 1998–2016 revealed that the German Wadden Sea is accumulating sediment. Changes in the ratio of intertidal to subtidal surface area indicate an extension of the intertidal zone. Most of the intertidal flats accumulate sediments with rates higher than the observed mean sea level rise in the German Bight, while simultaneously the subtidal mean depth increases.

Average yearly accumulation on the tidal flats amounted to 7.9 mm per year, average deepening of the tidal channels to 20 mm per year. Tidal channels and the outer coast act as sediment sources for tidal flats. (Hofstede et al., 2018). Due to the strong accumulation and the larger tidal range, intertidal sediment volume increased by about 20 % from 1998 to 2016 (Benninghoff & Winter, 2019).

For the Danish Wadden Sea, the import of fine-grained sediment in three tidal basins showed an accretion of tidal flats of about 3.5 mm per year, which was estimated to be sufficient to compensate for current levels of sea level rise (Pedersen & Bartholdy, 2006). The future sea level rise is expected to transform the tidal-flat-dominated system of the present Sylt-Rømø Bight into a lagoon-like system (Becherer et al., 2018).

Changes in accretion of tidal flats have consequences for waders. Wader species are connected to certain sediment types, and when sediment change, the abundance of waders change too. The changes of geomorphology in the German sector of the Wadden Sea described above have affected large changes in number of waders. These changes were also influenced by sea level rise (Laursen et al., 2023).

Sediment composition

Sediment in the trilateral Wadden Sea is composed of sand, mud (particles smaller than 63 µm) and biogenic particles (e.g., shell fragments). The supply, deposition and distribution of sand and mud is an important parameter for the morphological development and ecological functioning of the Wadden Sea. A recent study describes the major sources, sediment pathways and sinks of mud in the Trilateral Wadden Sea and includes the first mud balance for the entire system (BOX 3).

Remarkably, the total infilling of part of the Dutch tidal basins over the last century was caused by at least a high percentage of mud (Oost, et al, 2021). Almost 32 % of the deposited volume is mud, a value that is much higher than the average mud content of the bed. Meanwhile, in the last two decades the net import of sand decreased significantly over time and has been fluctuating around zero. This may be an issue of major concern given the current and projected future acceleration in sea-level rise.

BOX 3. Major sources, sediment pathways and sinks of mud

Until recently, much research effort was concentrated on the role of coarse-grained sediment although muddy sediments also are a vital element of the Wadden Sea (Oost et al., 2021). Mud accumulation contributes to the growth of tidal flats and saltmarshes and the evolution of major estuaries in the region. Mud also plays a role in the food web of the Wadden Sea. High concentrations of fine-grained suspended particulate matter in the water column are commonly responsible for limiting primary production of phytoplankton (pelagic microalgae) by increasing turbidity levels and reducing the penetration of light. High densities of microphytobenthos are often found on the muddier parts of tidal flats, amongst others in response to higher concentrations of nutrients in the pore waters of finer sediments.

A recent study (Oost et al., 2021) describes the major sources, sediment pathways and sinks of mud in the Trilateral Wadden Sea and includes the first mud balance for the entire system. Major observations based on this study are given here.

- The North Sea Continental Flow (NSCF) is the residual flow from the Dover Strait, which follows the Belgian and Dutch coast and reaches Marsdiep Inlet and subsequently moves along the Wadden Sea coast. It represents the major source of mud. Estimated transport rates of mud along the Dutch coast are about 10 to 14.4 × 106 tonnes per year but are extremely variable due to meteorological and oceanographic forcing. The NSCF in itself is already variable, being a product of tide-driven currents, the impact of density-driven circulations due to Rhine outflow and wind forcing, making the flow and the supply of mud very sensitive for effects of climate change. It is clear though that the NSCF is not able to supply unlimited resources of mud since the supply of mud primarily depends on the erosion rates of the East coast of the UK and the seabed in the Strait of Dover.
- Average net annual sediment rates in the Trilateral Wadden Sea are large in comparison to the annual supply of mud.
- Although annual variation in sedimentation and erosion may occur in the NSCF coastal zone and the more energetic parts of the Wadden Sea, it is not yet possible to quantify these processes.
- Mud sedimentation is large in the estuaries and represents (in terms of volume) several tens of percentage points of the total net deposition. Marine input of Suspended Particulate Matter (SPM) is largest in the Ems estuary. Possible explanations for this are the low river discharge, a higher mud supply (in comparison to e.g., Weser and Elbe) and the sediment trapping efficiency of the estuary.

- Mud extraction is common practice in several regions and is of the order of 2 × 106 tonnes per year in all estuaries combined. Relatively high extraction rates are observed in the Ems and Elbe estuaries. In the Elbe this also includes strongly contaminated mud of fluvial origin.
- Sand and mud transport and deposition on the scale of one or two tidal basins and in response to engineering works (Colina Alonso et al., 2021) demonstrate that these types of interventions result in redistribution of sand and mud sedimentation. Soon after the construction of the Afsluitdijk, the abandoned tidal channels were filled with large volumes of mud. Currently, most mud deposition is observed along the tidal flats and salt marshes along the mainland coast.

Salt marshes

Salt marshes are responsible for significant reduction of wave energy and, in combination with engineered structures, provide coastal safety by limiting dike breaching and impacts of flooding (Vuik et al., 2016; Zhu, et al., 2020; Esselink et al., 2017). In a model study, it could be demonstrated that the volumes of water that flow through a dike breach are significantly reduced, if a salt marsh is present in front of the dike. This results in lower water depths in the flooded polder and thus reduced damages (Thorenz et al., 2017).

In case of (accelerated) sea-level rise, the degree of wave attenuation of marshes strongly depends on the deposition of sediment (Möller, et al., 2014). Average sediment deposition in the back-barrier saltmarshes of barrier islands during the last decades was about 4.4 mm per year, so larger than the current rate of sea-level rise.

The nature management measure of allowing livestock to stimulate a diverse vegetation composition can hamper the ability to grow along with sea level rise, especially when the sediment load in the water column is reduced (Elschot et al., 2023).

As a result of deep subsidence (7.0 mm per year) from natural gas extraction, the saltmarshes near Ameland showed increases in flooding frequency, duration, and depth (van Dobben et al., 2022). Such developments may be a proxy for a response to enhanced sea-level rise.

In the Schleswig-Holstein sector of the Wadden Sea, the average yearly accumulation rate on the salt marshes for the period 1996 to 2018 amounted to 0.90 ± 0.55 mm per year, which clearly exceeds local mean sea level rise of about 0.28 mm per year. In general, average accumulation rates along the mainland coast (1.00 ± 0.55 mm per year) were significantly higher than along the more exposed islands and Halligen (0.53 ± 0.46 mm per year) (Hofstede, 2022).

In the Danish Wadden Sea submerge situations of saltmarshes apparently due to wind-driven high water level events which increased after 1980 (Kim et al., 2013). The role of atmospheric oscillations (e.g., North Atlantic Oscillation) as drivers of wind generated water level stimulate surface accretion of the saltmarshes of Skallingen, as supposed effect of climate change. Such changes in climate conditions can enhance the plant communities on salt marshes with higher possibilities of abrupt and complex system reorganizations (Kim & Phillips, 2013).

Sediment deposition declines from the marsh edges and the creeks to the inner parts of the salt marshes. Model results suggest that marsh deposition, at least for the marsh edge and along the creeks, should be able to keep pace with a constant sea-level rise of 4.0 to 8.0 mm per year over the next century (van Dobben et al., 2022). However, in the meantime the inner marsh characterized by less deposition may drown.

Based on experiments in the German Wadden Sea (Koop-Jakobsen & Dolch, 2023), the salt marsh pioneer zone (dominated by *Spartina anglica*) is expected to profit from increased CO_2 concentrations (800 ppm) and temperatures (+3 °C) which will enhance the resilience of this zone towards sea level rise and harsher weather patterns. The low marsh zone (dominated by Elymus athericus) may not be directly affected by increase in CO_2 and temperature, but indirectly from a more robust pioneer zone.

2.5 Biodiversity

Geographical distribution

With global warming, species generally (but not always) shift towards the poles, so that in any location in the northern hemisphere between the equator and the Arctic one might expect to see more and more species entering from the south and other species departing toward the north (Chust et al., 2023; Rutterford et al., 2023).

In the Wadden Sea, for example, the bivalve *Abra tenuis* has been expanding to the northeast, whereas that of *Macoma balthica* has been shrinking at the southern edge of its range, apparently due to climate warming (Dekker & Beukema, 2021). It is expected that *A. tenuis* will ultimately become more numerous than *M. balthica* in the Wadden Sea (Dekker & Beukema, 2021). Also, the lugworm (*Arenicola marina*), an important ecosystem engineering species for (vertical) mixing and moving of sediment, is expected to move northwards due to global warming (Wethey & Woodin, 2022) and may therefore become reduced in the Wadden Sea.

Migratory waterbirds formerly staged during winter in the south-western parts of Europe have increased in numbers in the Wadden Sea, whereas those that formerly staged mainly in the north-eastern parts have decreased in numbers as their wintering grounds have shifted towards the northeast (Hornman et al., 2022).

Temperatures currently increase especially fast in the Arctic. Migratory birds breeding in the Arctic are affected by this. For example, the bar-tailed godwits need to shorten their stay in the Wadden Sea to catch up with the earlier hatching of mosquitoes in Siberia. Because of a shorter refuelling time, an increasing proportion of individuals do not obtain optimal body condition before departing for the breeding areas, and this has fitness consequences (Rakhimberdiev et al., 2018).

Mortality

During cold spells and heatwaves, the temperatures of the water and the sediment may reach lethal values for organisms (in particular of those species that do not have the capability to move to less threatening environments) (Suykerbuyk et al., 2021). For instance, a sediment temperature of 35°C for more than six hours consecutively leads to 100 % mortality of cockles (*Cerastoderma edule*) in laboratory experiments (Verdelhos et al., 2015).

In the Dutch Wadden Sea, the mortality of two-year-old cockles reached 60 %, and the mortality of older cockles reached 66 % during the heatwave of 2018, while mortality rate for cockles in years without heatwaves can be as low as 28 %. The relative low mortality of 1-year-old cockles (20 %) was likely due to life history traits: juveniles do not spawn in their first summer, conserving energy for survival (as growing requires less energy than spawning) (Troost & Van Asch, 2018).

In addition, heatwaves are often characterised by eastern winds (resulting in longer emersion times of the tidal flats) and reduced freshwater discharges (resulting in reduced riverine food supply to the Wadden Sea), which may indirectly lead to starvation because benthic animals have less access to their food. If temperature-induced mortality and starvation of benthic animals reduces the food availability for waders, then lower numbers of birds can be maintained in the various tidal basins.

Increased temperature in the upper mud layer favours the microphallid trematode and affects the tube-building amphipod *Corophium volutater* on the mudflats in the Danish sector with severe effect on the *Corophium*-populations. Since this amphipod is an important food source for a number of migratory wader species, this may have effects on several wader populations (Poulin & Mouritzen, 2006).

Salt marsh plants also suffer from increased mortality due to climate change. Prolonged periods of drought negatively affect the germination success and promote mortality of glasswort seedlings (*Salicornia procumbens*), and this may affect the overall salt marsh stability (van Regteren et al., 2020).

Recruitment

Recruitment success of cold-blooded organisms (including jellyfish, bivalves, and fish) is often related to ambient temperatures during their early life stages (including that of the reproductive phase of the parents). High water temperatures may, therefore, favour the recruitment success of one species (e.g., the invasive jellyfish *Mnemiopsis leidyi*; Figure 9) whilst reducing that of another. After mild winters, predation pressure of shrimps on bivalve spat is higher than after cold winters, resulting in lower recruitment success (Philippart et al., 2003).

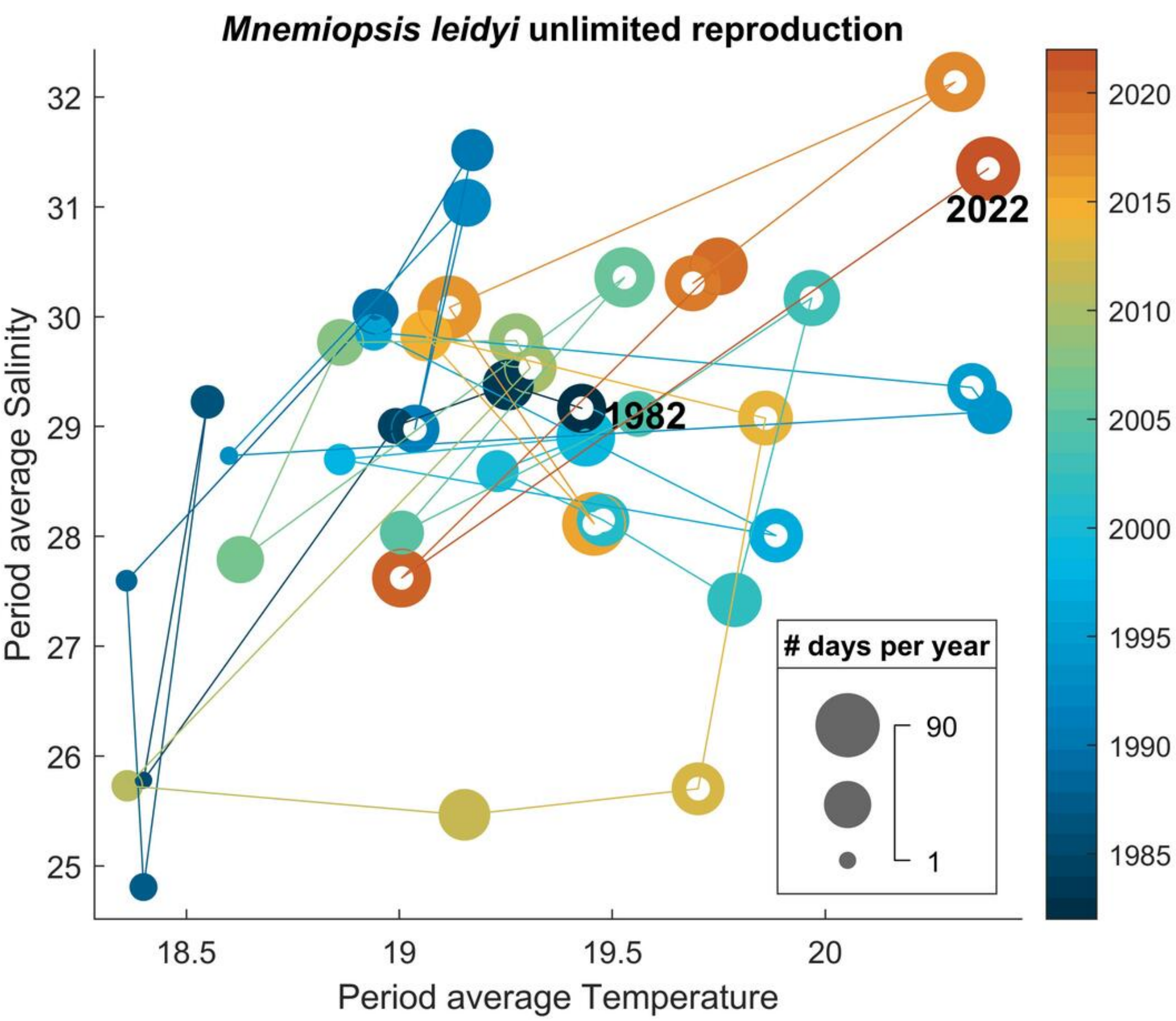

Figure 9. Projected reproduction Mnemiopsis if driven by temperature and salinity. Potential for unlimited reproduction by the jellyfish Mmemiopsis leidyi, based upon threshold values in temperature (T) and salinity (S), between 1982 and 2022 in the Marsdiep tidal inlet. The years are indicated by colour, the size of the bubbles indicates the number of days

in total that fulfil the requirements for unlimited reproduction (T >= 18.0 °C, S >=10.0) (Collingridge et al., 2014). Dots with a white centre indicate years in which the days fulfilling the T, S requirements outlined above are met for at least 40 consecutive days (life span of Mnemiopsis at 15 °C), allowing for multigeneration blooms. On average, the reproductive periods are getting warmer, meaning a shorter life cycle span for the species (~ 40 days at 15 °C, ~16 days at 30 °C) (Figure: Sonja van Leeuwen, NIOZ).

Within the Wadden Sea, 55 % of the breeding bird populations have experienced significant declines over the last years (Koffijberg et al., 2022). For this decline, summer flooding has been mentioned as one of the most important causes for clutches not hatching successfully or chicks not surviving the chick-rearing period. This flooding risk occurs both along the mainland coast and on islands and has increased in time through a combination of sea-level rise and an increased occurrence of storms during the breeding season (van de Pol et al., 2010).

Phenology

Phenology is the timing of annually recurring events in the life of plants and animals (Chen et al., 2011), such as the time at which young flatfish return to the North Sea (Tulp et al., 2017) and the time at which migratory birds visit the Wadden Sea to fatten up during their migration (Rakhimberdiev et al., 2018). Climate warming driven changes in phenology can cause uncoupling of links in the food web, such as those between prey and predators (Saborowski & Hünerlage, 2022).

Adaptation

Climate change can change selection pressures on species in a range of ways, e.g., species can adapt to shifts in geographical distribution, phenological changes and new local conditions (Lurgi et al., 2012; Cheung et al., 2013). In the case of fish, for example, warming seems to lead to smaller individuals (Cominassi et al., 2020; Pörtner & Peck, 2010). Non-genetic transgenerational plasticity, however, has the potential to buffer these negative effects as has been observed for three-spined sticklebacks in the Wadden Sea (Shama et al., 2014). In the case of breeding birds, oystercatchers seek higher ground to reduce the risk of their nests being inundated during a summer storm whereas other species of breeding birds have shown no sign of adaptation in their choice of nesting site (van de Pol et al., 2010; Bailey et al., 2017).

Teleconnection

Local effects of climate change can have a knock-on effect on a much larger spatial scale. It has been observed in the case of migratory birds, for example, that limited growth of chicks due to lack of food in the Arctic is ultimately followed by higher mortality in their overwintering grounds in the tropics (van Gils et al., 2016). The possibility cannot be ruled out that such long-range effects also exist with regard to other species that have a large distribution range during their lifetime, such as eels.

Invasive species

Like other coastal ecosystems, the Wadden Sea is experiencing an exponential increase in the introduction of non-indigenous species and more than 100 benthic and planktonic species have already established (Büttger et al., 2022; Schourup-Kristensen et al., 2023; Stæhr, et al., 2023). Since many of these species come from warmer areas, increasing temperatures will shift their favoured climatic niche into the Wadden Sea area and can contribute to their establishment success (Thomas et al., 2016; Lackschewitz et al., 2022; Reise & Lackschewitz, 2023).

With current projections of intensifying global trade, the accelerating trend of species introduction is likely to continue. Given that environmental resistance to invasion in the species poor Wadden Sea is comparatively small, the relative contribution of optimized climatic niche matching to the actual rate of introduction (Lovell et al., 2021) as well as the consequences for the Wadden Sea ecosystem seem to be rather minor (Reise et al., 2023).

Parasites and diseases

Climate change can drive host-pathogen interactions and infectious disease outbreaks in marine systems (Burge et al., 2014). Compared to vertebrates (e.g., distemper virus in seals, H5N1 flu in migrating birds), disease outbreaks are only poorly monitored in invertebrates of the Wadden Sea, although mass mortality events are regularly reported, but only rarely connected to parasite or pathogen infections (Jensen & Mouritsen, 1992).

The effect of different climate change phenomena on parasite infection rates are also not uniform for different groups of parasites and pathogens. Transmission of trematode parasites is likely to be decreased with rising temperatures (Diaz-Morales et al., 2022), while bacterial pathogens become more frequent (Wendling et al., 2014).

Sea level rise, on the other hand, can increase transmission of parasites due to short emergence times of their hosts in a more lagoon-like system (Weniger et al., 2022). Furthermore, the combined effects of climate change and parasite burden do not have to be additive, and high trematode infection loads may even have a protective effect against heat stress in blue mussel hosts (Selbach et al., 2020).

The poor documentation of disease outbreaks and the opposing signs of combined effects complicate the determination of net effects of climate change on parasitism and disease outbreaks in the Wadden Sea. The more general relationship between temperature and parasite metabolism and increasing heat stress of the host suggest, however, that parasitism and disease might also intensify in the Wadden Sea with unpredictable secondary effect on benthic and pelagic communities (Byers, 2021).

2.6 Ecosystems

Cumulative impacts

In the Wadden Sea, climate change has already altered the abundance, distribution, physiology and phenology of plants and animals (see 'Biodiversity'). These changes have not and will not be restricted to one trophic level or one local region but affect the entire Wadden Sea ecosystem and beyond (see 'Teleconnection'). In combination with other human activities (e.g., fishing, habitat destruction, pollution), climate change impacts intensify pressures on the system, complicating status assessment and sustainable usage (Horn et al., 2021).

An ecosystem modelling study in the Sylt-Rømø Bight concluded that the ecosystem would become less organized, more dissipative and shift towards detritus-based food webs at higher water temperatures (Baird et al., 2007).

Food webs

The introduction of predatory species originating from warmer coasts, which have been able to establish in the Wadden Sea due to higher temperatures, have caused changes in predator-prey interactions.

Pacific shore crabs (*Hemigrapsus sanguines* and *H. takanoi*), for example, achieved densities of several hundred individuals per square meter in epibenthic mixed reefs of native *Mytilus edulis* and introduced Pacific oysters *Magallana gigas*. They compete with native shore crabs *Carcinus maenas* for prey organisms and increase overall predation pressure in this habitat (Cornelius et al., 2021).

Many introduced species are filter feeders, such as non-native bivalves and various tunicate species. Therefore, it can be assumed that the overall filter activity has increased. Effects on benthopelagic processes and trophic interactions are so far largely unknown.

Functionality

Climate-driven changes in environmental conditions and lower trophic levels of the food web may affect the functions of the Wadden Sea. Overall, the nursery function of the Wadden Sea for juvenile fish appears to have declined since the 1980s and has stabilised in the last decade, potentially resulting from warming and climate-driven mismatches (Tulp et al., 2022).

The role of the Wadden Sea as a crucial fuelling station for migratory waterbirds may be affected because birds to a large extent adjust their distribution (and numbers) to changes in the amount and availability of the various species of benthos such as shellfish and worms (Kleefstra et al., 2021, 2022).

2.7 Human activities

Landscape and culture

As for the rest of Europe, the coasts of the Wadden Sea are drastically being changed to adapt to enhanced sea level rise, with consequences for coastal landscapes and heritage (Egberts & Riesto, 2021). Whereas the reinforcement of dikes barely meets resistance of the local human populations, dynamic coastal management (e.g., wash-overs in dunes, dike relocation and opening of summer polders in low-lying marshes and adjacent fenlands) is less accepted, so past experiences may be helpful in the adoption of these measures (Schroor et al., 2017).

Coastal risk management

Beyond a critical rate of sea-level rise in combination with potential impacts of bottom subsidence (de la Barra et al., 2023), parts of the Wadden Sea are projected to drown due to insufficient sediment supply, which will have major consequences for the distribution of different ecotopes. Ecotopes are the smallest ecologically distinct features in a landscape or ecosystem mapping and classification system (Becherer et al., 2018; Huismans et al., 2022).

One nature based strategy that is discussed with regards to functionality and feasibility is the concept of dike relocation. This measure results in an extension of natural tidal environments but may imply extra efforts to protect the behind lying populated lowlands (Timmerman et al., 2021; Hofstede, 2019).

One of the ideas for how to tackle sea-level rise, enhance coastal flood defence and create additional nature (or develop aquaculture), is the conceptual idea of transition of polders (Zhu et al., 2020). In Schleswig-Holstein, transitional polders with inlets for tidal water were implemented in the last century in Beltringharder Koog, and Kronenloch at the mainland coast and at on the isle of Sylt (Hofstede, 2019). In these former polders, a semi-natural tidal environment developed and sustained. An enhanced functionality for coastal flood defence by means of significant accumulation in the polder was not observed.

Along the Dutch Wadden coast, pilot experiments are implemented to develop nature-based flood protection measures that include promoting salt marsh growth with dredged sediment disposal (Baptist et al., 2019), transition polders with multiple functions between double dikes (Marijnissen et al., 2021), the development of salt marshes in front of dikes (Baptist et al., 2021), the application of broader instead of higher dikes (broad green dike) (van Loon-Steensma & Vellinga, 2019), the concept of "living" dikes with more vegetation (NWO, 2023) and the stepwise heightening of dikes (grow-along-dikes) (Forzoni et al., 2021).

Harbours and shipping

Hamburg, Bremen (Bremerhaven) and Wilhelmshaven (including the new deep-water Jade-Weser-Port) in Germany are the major ports in the Wadden Sea region (Bahlke, 2017). Smaller, more specialized ports include Delfzijl, Den Helder, Eemshaven and Harlingen in the Netherlands, Brunsbüttel and Emden in Germany, and Esbjerg in Denmark.

Most, if not all, of these ports are located at open coasts and/or in low-lying estuaries and deltas, which makes them susceptible to impacts of climatic change such as rising sea levels, storm surges, high waves and strong winds, and riverine and pluvial floods (Asariotis, 2021; Schultze & Nehls, 2017).

To limit these risks, harbours are exploring climate adaptation strategies such as a construction of a tidal polder in the Drepte lowlands in the Lower Weser area (Wadden Seaports, 2018).

Fisheries and marine aquaculture

The economically most important fishing activities in the Wadden Sea are harvesting of wild stocks (shrimps, mussels, and cockles) and aquaculture of mussels (Baer et al., 2017). Yields of fishing (e.g., for shrimps) and aquaculture (e.g., seed mussel collectors) may change due to the impacts of warming (Baer et al., 2017).

For shrimps, for example, a higher frequency of warm winters is expected to lead to a more frequent mismatch between larval appearance with spring food sources and, thus, higher mortality due to malnutrition (Saborowski & Hünerlage, 2022).

The overall decline of mussels in coastal waters has contributed to excessive exploitation of mussel banks combined with effects of climate change (e.g., increased sea surface temperature, precipitation, and extreme weather events) (Baden et al., 2021). High mortalities of (mainly adult) cockles during heat waves may result in a reduction of stocks (see 'Mortality').

Tourism

Climate change is not yet considered to be a key force that drives changes in tourism in the Wadden Sea region (Hartman et al., 2022). Climate-induced loss of comfort due to thermal stress and heat waves at main summer destinations in southern Europe (Arabadzhyan et al., 2021), however, may possibly result in a further increase of visitors to the Wadden Sea.

Military activities

Military activities in the Wadden Sea area are performed on land (e.g., shooting ranges for ground forces and aircrafts), in the air (e.g., low altitude flights by military aircrafts), and in the water (e.g., routes for submarines), with the western part of the Dutch Wadden Sea being the main centre of these activities (Brenner et al., 2017).

Although there may be no direct impacts of climate change on these activities, the toxicity of the previously dumped and presently deteriorating munitions and warfare agents poses an indirect risk, in particular when windfarms (and/or pipelines and cables for energy transport) are constructed within the contaminated areas (Brenner et al., 2017).

Energy

Climate change is one of the major drivers for the transition from fossil fuels towards renewable energies, particularly resulting in an expansion of wind turbines surrounding the Wadden Sea (Christoph et al., 2022). Climate-induced changes in wind characteristics (e.g., wind speed) may cause a risk for our reliance on this renewable energy source (Solaun & Cerdá, 2020).

Extraction and dredging

Dredging activities and extraction of sediments (Schultze & Nehls, 2017) is concentrated in major estuaries (such as those of the Ems, Weser and Elbe) and navigation channels (e.g., the ferry connection between Ameland and the mainland coast) (BOX 4). So far, there are no model results for future trends in sediment budgets at different climate scenarios for the estuaries of the Wadden Sea.

Projected increases in average depth due to increasing tidal currents and erosion (Becherer et al., 2018) may lead to a reduction in the need for dredging navigation channels with rising sea levels. In the Schleswig-Holstein sector of the Wadden Sea, the extraction of sediments is prohibited, as this would further increase the expected sediment deficits due to stronger sea level rise (Hofstede & Stock, 2018).

BOX 4. Major dredging & dumping efforts in the Wadden Sea

In the Netherlands, a major dredging effort occurs in the channel between the island of Ameland and the mainland coast. Annual dredging volumes are about 2.0×10^6 m^3 per year, equivalent to almost 3 m^3 for each passenger taking a ferry trip. The annual dredging volumes for the Ems (including Eemshaven) are about $6.7\text{-}7.2 \times 10^6$ m^3 per year. Large dredging volumes are extracted from the port of Den Helder (1.5×10^6 m^3 per year), the port of Harlingen (1.4×10^6 m^3 per year) and various navigation channels adding up to 2.0×10^6 m^3 per year (Arcadis, 2011).

In Germany, total dredging in the Weser estuary (Lange et al., 2008), including harbours, amounts to about 10×10^6 m^3 per year (period 2014-2018). In the Port of Hamburg (located in the Elbe estuary), annual maintenance dredging is about $3\text{-}4 \times 10^6$ m^3 per year each year. Since part of this sediment is polluted, it is treated in the so-called METHA plant (Mechanical Treatment and dewatering of Harbour sediments) before it is used on land for other purposes (Berger et al., 2019). In 2019, dredging efforts increased to deepen the fairway to facilitate mega container vessels to enter the port of Hamburg.

3. Assessment

Since 1982, the Wadden Sea Board (WSB) organises every four years a Trilateral Governmental Conference at which a joint Ministerial Declaration is signed. From the Stade Declaration of 1982 (TWSC, 1982) to the Stade Declaration of 1997 (TWSC, 1997) these declarations addressed many threats to the natural values of the Wadden Sea but did not yet acknowledge the potential impacts of climate change.

In 1998, the WSB established a trilateral **Working Group Coastal Protection and Sea Level Rise** (CPSL), in which experts on coastal and nature protection and spatial planning delivered expert input to the Trilateral Governmental Conferences. In 2010, the need to strengthen natural processes of the Wadden Sea to cope with climate change was recognised.

3.1 Wadden Sea Plan (Sylt 2010)

In 2010, the trilateral Wadden Sea Plan (WSP) (Common Wadden Sea Secretariat, 2010a) was adopted at the 11th Trilateral Governmental Conference on the Protection of the Wadden Sea at Sylt (Germany). This plan has, as cross cutting issue for integrated ecosystem management, one focus on enhancing the resilience of the Wadden Sea ecosystem to the impacts of climate change. Besides adaptation, this plan also aims for mitigation, e.g., by “developing the Wadden Sea Region into a CO_2-neutral area by 2030 or before”. As common policy and management plan for the protection and sustainable management of the Wadden Sea Area, the plan contains targets for Wadden Sea species and habitats.

The Sylt Declaration (Common Wadden Sea Secretariat, 2010b) expresses concern with climate change and its consequences and acknowledges the urgent need to strengthen natural processes to mitigate the impacts of climate change. This declaration instructs the WSB to initiate a study on sustainable solutions to balance expected sediment deficits, to develop a spatial planning methodology to meet the challenges of climate change, and to establish a 'climate change' working group. Furthermore, the declaration calls upon all stakeholder to jointly develop the Wadden Sea region into a CO_2-neutral area by 2030.

3.2 Wadden Sea Climate Change Adaptation Strategy (Tønder 2014)

In 2011, the trilateral Task Group Climate (TG-C) took over the work of the CPSL (see 3., second paragraph). The TG-C developed a trilateral Climate Change Adaptation Strategy (CCAS) with seven strategic objectives and guiding principles, which was adopted at the 12th Wadden Sea Conference 2014 in Tønder, Denmark (CWSS, 2014).

It considers sea level rise, storm surges, precipitation patterns and (mean annual) temperatures as the most important aspects of climate change in the Wadden Sea region. The strategy aims to enhance the resilience of the Wadden Sea ecosystem to the impacts of climate change by allowing and restoring natural dynamics. Securing and enhancing connectivity of habitats should, for example, prevent species extinction and secure adaptation of characteristic biodiversity far beyond its former distribution limits.

The CCAS was evaluated as input for the 13th Wadden Sea Conference 2018 in Leeuwarden, the Netherlands (see 3.3).

3.3 Trilateral Research Agenda (Leeuwarden 2018)

At the 13th Wadden Sea Conference 2018 in Leeuwarden (The Netherlands), the evaluation of the CCAS by the TG-C was discussed and the Trilateral Research Agenda was adopted. The Task Group Climate (TG-C) was assigned to monitor the implementation of the Climate Change Adaptation Strategy (CCAS) that was adopted in 2014 (Wadden Sea Board - Task Group Climate, 2017).

The TG-C concluded that the strategic objectives and principles of CCAS are being applied in a wide range of strategic scientific projects and national policies. Not all these activities are linked, however, with CCAS and the aims of the Trilateral Wadden Sea Cooperation. This led to a general recommendation to strengthen the communication on the need for climate change adaptation in the Wadden Sea area and the objectives and principles in the CCAS. The TG-C also recommended that the Trilateral Wadden Sea Cooperation should strive to further improve knowledge on the Wadden Sea Ecosystem and its response to climate change, and to support trilateral cooperation and joint efforts and research projects.

In 2018, the trilateral scientific community published a Trilateral Research Agenda that was developed on the invitation of the Trilateral Wadden Sea Cooperation (Trilateral scientific community, 2018). Climate change was considered as one of the main challenges for this area, in particular the impacts of warming and sea level rise. It was advised to urgently improve our understanding of the coastal sediment and freshwater balance for the entire Wadden Sea Region under elevated temperatures, higher relative sea levels, more extreme storm surge levels, higher tidal ranges, and stronger wave action. This is considered essential for developing successful climate adaptation strategies, for purposes of nature conservation and coastal defence, and for interrelated economic sectors such as agriculture, fisheries, tourism, shipping and harbour activities.

3.4 Climate Vulnerability Index (2020)

In 2020, the vulnerability of the Outstanding Universal Value (OUV) of the Wadden Sea World Heritage was assessed by means of the Climate Vulnerability Index (CVI). The CVI is a methodology to rapidly assess vulnerability through expert appraisal of the best-available climate science, applicable to all types of World Heritage properties (natural, cultural, or mixed) (Day et al., 2020). In two timeframes (2050 and 2100) with a 'business-as-usual' climate scenario (RCP 8.5), main stressors identified for the Wadden Sea World Heritage were sea temperature rise, extreme heat events and sea level rise.

For the Wadden Sea, the OUV vulnerability was assessed as high (the highest category) for both timeframes (Heron et al., 2020). Whilst the vulnerability associated with the two temperature-related climate stressors was assessed as high in both timeframes, the vulnerability to impacts from sea level rise escalated from 'low' in ca. 2050 to 'high' in ca. 2100. Collectively and for both timeframes, there is potential for substantial alteration or major loss of the majority of the attributes that convey the OUV.

3.5 International & EU legislation for nature conservation

Climate change, in particular warming, is already impacting the Wadden Sea ecosystem and, even if CO_2 emissions would be strongly reduced at short notice, these impacts are not expected to slow down during the next decades. These developments challenge nature conservation as laid down in legal regimes (international and EU legislation) which vary in their objectives and requirements for restoration measures (Bastmeijer et al., 2023).

Comparison of the criteria for the OUV of the Wadden Sea as a World Heritage and the Guiding Principle of the Trilateral Wadden Sea Cooperation ("to achieve, as far as possible, a natural and sustainable ecosystem in which natural processes proceed in an undisturbed way") revealed, for example, that some legal regimes (e.g., two criteria of the OUV and the Guiding Principle) allow for adaptation to climate change, including shifts in habitats and species that will result from ongoing geomorphological, ecological and biological processes. Other regimes (e.g., criteria x of the OUV and N2000), however, may not allow for releasing strict protocols on fixed values for species and habitats and, therefore, do not provide opportunities for human activities that (further) enhance the impacts of climate change (Bastmeijer et al., 2023).

4. Recommendations

Valuable recommendations for monitoring, research, and management of the Wadden Sea area have been given in earlier and other Quality Status Reports (e.g., Klöpper et al., 2017, 2022) (such as those in 2017 on ‘Geomorphology and Climate’, ‘Climate Change’ and ‘Climate Ecosystems’), at dedicated workshops (e.g., on the CVI), during previous ministerial conferences since 2010 (see ‘Assessment’ of this QSR report), and by the Task Group Climate Change (Zijlstra, 2021).

Based on the recent status and trends in weather, climate, habitats and species as described in this edition of the QSR Climate Change report, most of the former advice is still more than timely and relevant. We, therefore, combine these previous recommendations with additional insights that have arose since then.

4.1 Recommendations for monitoring

Trilateral Monitoring and Assessment Programme

Monitoring needs are likely to increase in the future because of more and broader reporting obligations (e.g., towards the EU) and because of scientific interests and societal needs for a better understanding of the response of the Wadden Sea ecosystem to climate change and the interactions with socio-economic and demographic trends. The expected growth in the number of variables to be monitored, the increasing demand for higher monitoring frequencies and a better geographical data resolution will put pressure on the current monitoring capacities.

These urgent needs should be addressed by safeguarding and strengthening the Trilateral Monitoring and Assessment Programme (TMAP) framework, establishing an easy and open access to the data for involvement of the wider scientific community, comparing trends and developments between regions, and evaluating the findings at high frequency (e.g., annual) to enable rapid responses.

New technologies

Efficient monitoring should embrace new and developing technologies that significantly enhance current monitoring capacities in various fields, and technological advance. Techniques for future mapping and monitoring include satellite imaging, remote sampling by drones, big-data applications (such as machine learning), (environmental) DNA-techniques and others. While enhancing data quality and usability, such novel approaches have also the potential to reduce the annual costs of monitoring.

Citizen science

Enhancing the incorporation of citizen science (participation of non-scientists in the process of gathering data according to scientific protocols and in the process of using and interpreting that data) may be developed into a strong pillar for monitoring in the Wadden Sea Region. Involving citizens can strongly improve the efficiency and breadth of monitoring activities owing to the “many hands” or “many eyes” that can be used in such approaches.

Equally important, citizen science can significantly foster public support and engagement, thereby helping to build social capital fostering a robust link between science and society.

Another crucial aspect of citizen science is that these programs, if well developed, can have large geographic coverage, ideally covering the entire trilateral Wadden Sea and beyond, while at the same time, these programs can be highly cost efficient.

4.2 Recommendations for research

Impacts of climate change

Amongst others based upon the Trilateral Research Agenda (Trilateral scientific community, 2018) as developed in 2018 by the scientific community from Denmark, Germany and the Netherlands in a joint effort for identifying common future challenges and for developing and implementing comprehensive approaches to trilateral research, it is recommended to improve our understanding on:

1. The coastal sediment and freshwater balance for the entire Wadden Sea Region under elevated temperatures, higher relative sea levels, more extreme storm surge levels, higher tidal ranges and stronger wave action.
2. The consequences of changes in means and extremes in sea level rise, warming and precipitation patterns on food-chains, predator-prey and parasite-host interactions, ecosystem resilience and potential species loss.
3. Connectivity for water (e.g., import, export, retention times), sediment (e.g., sand and mud), plants (e.g., phytoplankton and saltmarsh seedlings) and animals (e.g., bivalve larvae, shrimps, fish and birds) between the Wadden Sea and the North Sea, between the Wadden Sea and the mainland, and between the Wadden Sea and other areas worldwide, which are needed for several fish and bird species to complete their life cycle (e.g., Banc d' Arguin for waders, Sargasso Sea for eel) under various climatic conditions.

Synergistic effects

In addition to climate change (e.g., warming, sea level rise), other human activities put a pressure on abiotic and biotic values of the Wadden Sea. If such multiple stressors result in cumulative impacts, then reducing the impacts of these human activities may allow more time for the ecosystem to adapt to the impact of climate change (Halpern et al., 2012; Hodgson et al., 2019).

If such cumulative impacts are studied following a Driver-Pressure-State-Impact-Response (DPSIR) approach, then more data and insights are required on drivers (e.g., fisheries, agriculture, dredging), pressures (e.g., habitat destruction, noise, pollution), state (e.g., concentrations of pollutants, distribution of birds on mudflats), impacts (e.g., population size of birds, nursery function for juvenile flatfish), and responses (e.g., wastewater treatment, reduction of dredging activities) (Bastmeijer et al., 2021).

Such information could be gathered by means of comparative analyses of data and insights (e.g., dose-effect relationships) from subareas (e.g., tidal basins) in time and space.

4.3 Recommendations for management

Trilateral climate change adaptation strategy

As stated in the trilateral CCAS, the overall aim of climate change adaptation in the Wadden Sea region is to safeguard and promote the qualities and the integrity of the area as a natural and sustainable ecosystem whilst ensuring the safety of the inhabitants and visitors, as well as the cultural heritage and landscape assets and sustainable human use.

The aim of the CCAS is enhance and promote policies and measures necessary for increasing the resilience of the Wadden Sea to impacts of climate change. The strategy defines seven strategic objectives and guiding principles for adaptation: natural dynamics, interconnectivity, integration, flexibility, long-term approach, site-specific approach and participation. For these elements, management priorities are listed.

The aim of trilateral cooperation in implementing the strategy is to achieve optimal benefit by focusing on activities with the highest trilateral relevance, in particular the exchange of knowledge and best practice, the exchange of experts, as well as performing trilaterally coordinated studies and pilot projects covering sites over the whole Wadden Sea.

Trilateral Research Agenda

In 2018, the scientific community from the Netherlands, Germany and Denmark developed a Trilateral Research Agenda in a joint effort for identifying common future challenges and for developing and implementing comprehensive approaches to trilateral research (Trilateral Scientific Community, May 2018).

In 2020, the Trilateral Programming Committee Wadden Sea Research (TPC-WSR) was installed and commissioned to develop a "Joint Trilateral Research Programme" to bring the Trilateral Research Agenda to life (Trilateral Programming Committee Wadden Sea Research, 2021).

A joint research call was opened in early 2023, new projects are expected to start in 2024. It is recommended to take full profit from new scientific insights developed by this research by means of strong and frequent science-policy interactions (e.g., regular thematic meetings).

Legal regimes

The inscription of the Wadden Sea as a World Heritage was based on meeting three out of four natural heritage selection criteria, referring to its dynamic landscape (criterion xiii), the undisturbed ecological processes (criterion ix) and the important habitats for species' conservation (criterion x).

As a Wadden Sea community, we urgently need to explore how to get a grip on the tension between the "laissez faire" principle as it appears being incorporated into the first two criteria (dynamic landscape (criterion iiix) and the undisturbed ecological processes (criterion ix) and the Guiding Principle, and the "need to act" principle following from the third criterion (the important habitats for species' conservation (criterion x) and certain international and EU legal systems (Philippart et al., 2020).

The consequences of new legal obligations should be taken immediately in the options, consequences, and restrictions for nature conservations as well.

Action perspectives

Exploring action perspectives can be done, for example, by performing scenario analyses using Digital Twins (virtual research environments that give access to all existing data and models of the Wadden Sea) to allow for scientific understanding, historical reconstructions, and future predictions (scenarios) to managers, stakeholders, and the public.

The Wadden Sea Forum started to develop a digital hydro-morphological twin for the trilateral Wadden Sea ("TrilaWatt"), aiming to compile available datasets on sediment, geomorphology and hydrodynamics with respect to the trilateral Wadden Sea area (Bundesanstalt für Wasserbau, 2024). Next step to study impacts of climate change on the Wadden Sea ecosystem would be to include data and models on biota and human pressures. LTER-LIFE is a recently funded Large-Scale Research Infrastructure (20 MEuro; 2023-2033) that will provide a state-of-the-art 'digital twin' of the Wadden Sea to study and predict how changes in climate and other human-induced pressures affect ecosystems and biodiversity (LTER-LIFE, 2023).

5. Summary

Review

Since the previous overview of impacts of climate change as laid down in three QSR thematic reports ('Geomorphology and Climate', 'Climate Change' and 'Climate Ecosystems') in 2017, the **drivers** of climate change (concentrations of main greenhouse gasses due to ongoing human activities) further increased (Figure 10).

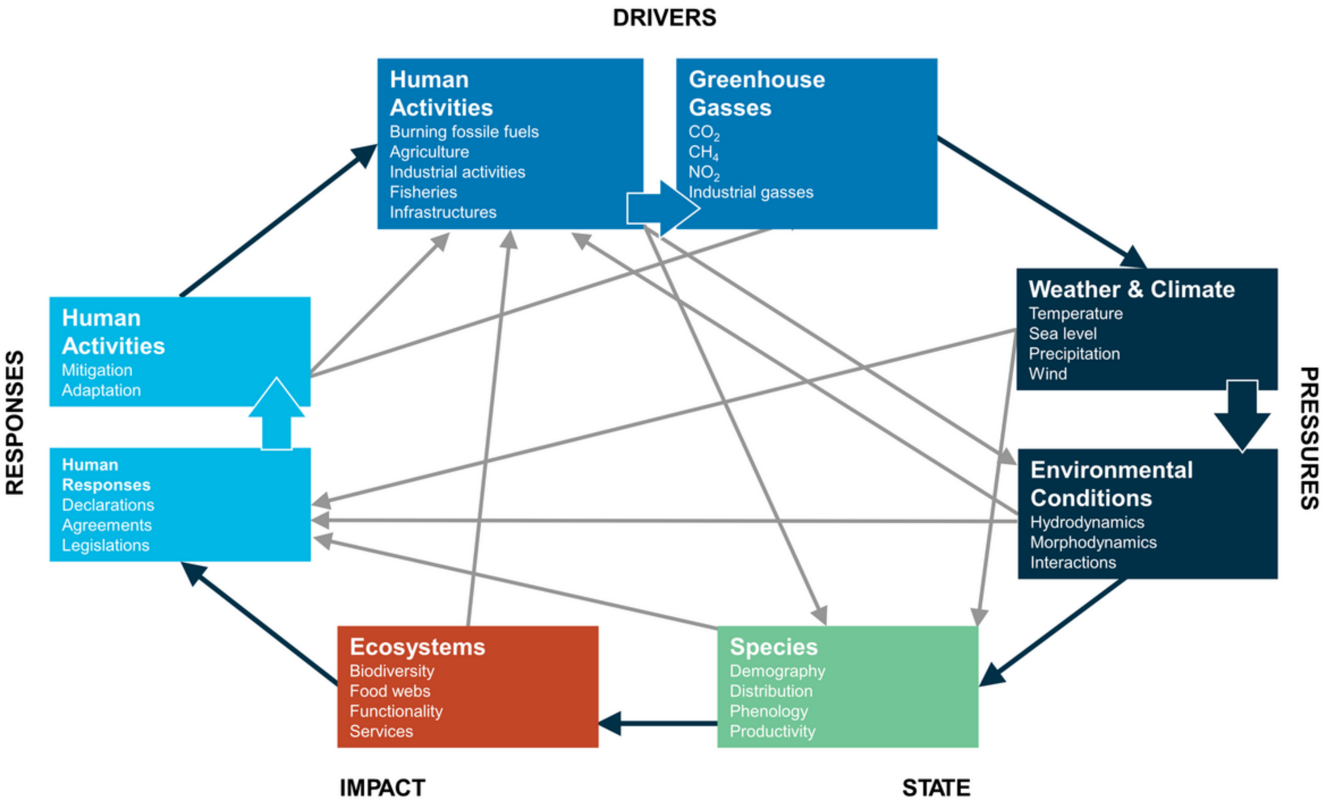

Figure 10. A Drivers-Pressures-State-Impacts-Responses (DPSIR) framework illustrating the impacts of climate change on the Wadden Sea ecosystem.

The increase in these gasses resulted in a further increase in temperatures (including heatwaves in 2018, 2019 and 2022) and in sea level, and in changes in patterns of precipitation (cloudbursts and droughts) and wind (summer storms). Changes in climatic conditions and in sediment and water dynamics have put increased **pressures** on the Wadden Sea ecosystem, a system that is already influenced by other human activities (e.g., fisheries, pollution, habitat destruction).

The **state** of species because of these pressures included shifts in their geographical distribution (mostly northward), in the timing of lifecycle events (mostly an advancement), and in recruitment and survival rates (e.g., mass mortality of cockles during heatwaves).

The **impacts** of these species' state shifts included shifts in biodiversity (e.g., northern bivalves being replaced by southern species), in food webs (e.g., mismatches between prey and predators), in functionality (e.g., decline in nursery function for juvenile flatfish), and in ecosystem services (e.g., possible decline in fisheries yields, and increase in tourism).

For the Wadden Sea, human **responses** to unwanted climate-driven changes included joint declarations, such as the Wadden Sea Plan (2010), the Climate Change Adaptation Strategy (2014) and setting a Trilateral Research Agenda (2018). Mitigation and adaptation measures are, however, still limited (with exception of coastal flood defence and coastal protection).

Recommendations

Addressing the increasing rates of climate change requires an increasing rate of the flow of information on changes in the state of the Wadden Sea, and on the effectiveness of mitigation and adaptation measures. With respect to **monitoring**, it is recommended to safeguard and strengthen existing long-term field observations, including a cost-effective increase in spatiotemporal resolutions (e.g., by means of new technologies, and involving citizen science approaches), and applying 'digital twins' to project consequences of scenarios of climate and management.

To increase the accuracy of predictive modelling capacity of the impacts of climate change on Wadden Sea communities, **research** to fill the knowledge gaps with respect to water and sediment budgets, dose-effect relationships, connectivity, and synergistic effects is essential. The Trilateral Research Programme is expected to cover at least part of these urgent research questions.

To ensure that the findings on monitoring and research are incorporated in **management** measures of the Wadden Sea, a much closer cooperation between science and policy is recommended (e.g., with respect to TMAP and the Trilateral Research Program). Furthermore, such a cooperation should include joint scenario building to explore legal regimes, action perspectives, and "climate endgame" scenarios.

Finally, to keep pace with the continuously increasing rate of climate change, it is strongly advised to develop and maintain a more frequent, more structural, and more intense exchange of data, information, and ideas on climate-change-related drivers, pressures, state, impact and responses within and between different stakeholder groups.

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