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An overview of Atlantic forcing of the North Sea with focus on oceanography and biogeochemistry

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A R T I C L E I N F O

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A B S T R A C T

This paper provides an overview of the current knowledge of Atlantic forcing of the North Sea's hydro- and biogeochemical dynamics. The North Atlantic Oscillation (NAO) causes the largest short-term variations via common large scale atmospheric variations and the wind-driven exchange of water masses. On longer time scales the zonal shifts in the position of the subpolar front (SPF) in the eastern North Atlantic, also triggered by the NAO, determine the oceanic settings in the northern and central North Sea. The hydrodynamics of the southern North Sea are influenced more by local forcings. The influence of Atlantic forcing extends to the biogeochemistry of the northern North Sea, but its influence on primary production is still unclear. Climate change is expected to reinforce some of the forcing mechanisms but may reduce others, and further work is advised to firm up the projections available to date.

1. Introduction

The biogeochemistry and ecology of the North Sea are influenced by local and regional hydrodynamic conditions (temperature, salinity, stratification, currents, waves). These hydrodynamic conditions are, in turn, influenced by atmospheric and oceanographic conditions on the Atlantic Ocean, which also modulate biogeochemical exchanges between the North Sea and the Atlantic Ocean.

There is a long history of studies and reviews on North Sea hydrodynamics and Atlantic influences (e.g., Dickson, 1910; Lee and Ramster, 1968; Lee, 1980; Dickson et al., 1988; Otto et al., 1990; Sündermann and Pohlmann, 2011). At the most general level, Atlantic waters enter the North Sea through the English Channel in the south, around the north of Scotland in the north, as well as via the area east of the Shetland Islands. These waters follow a counter-clock-wise circulation around the North Sea, join the outflow from the Baltic Sea in the east, and leave the North Sea via the Norwegian Current in the northeast. There is considerable detail and seasonality in the interior current patterns (e.g., Hill et al., 2008), and interannual variability in response to atmospheric and oceanic forcing (see below). A prominent feature, visible in remote-sensing images due to high suspended sediment concentrations, is the Anglian Plume (e.g., Tiessen et al., 2017), where UK coastal waters from the north and south meet and flow eastward towards Denmark. In the 1990's, attention shifted from hydrodynamics towards associated nutrient fluxes into the North Sea (Laane et al., 1996a, 1996b), leading to a substantial number of publications providing information on this topic. Most recently, attention has shifted towards carbon fluxes and sequestration (e.g., Wakelin et al., 2012).

In this paper, we provide a compact review of the state of knowledge of Atlantic forcing of the North Sea's hydrodynamics and biogeochemistry. We conclude by identifying gaps in this knowledge.

2. Forcing mechanisms

2.1. Oceanic forcing

The sub-polar gyre is the dominant hydrographic structure in the north Atlantic Ocean influencing the north-west European continental shelf (see, e.g., Holliday et al., 2018 for recent observations). The Gulf Stream extension, the North Atlantic Current, forms the southern and eastern flank of this gyre, and transports warm, salty water towards and along the western and northern flanks of the continental shelf (e.g., Häkkinen et al., 2011), while a western branch of this North Atlantic Current, the Irminger Current, transports warm and salty waters towards Iceland. The northern and western flanks of the sub-polar gyre are formed by the East Greenland and Labrador Currents, respectively,

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which transport cold polar waters with reduced salinities southward (see, e.g., Sicre et al., 2014 for a recent study). This gyre system has distinct vertical structure, the North Atlantic thermohaline circulation (e.g., Hátún et al., 2005) or Atlantic Meridional Overturning Circulation (AMOC; e.g., Buckley and Marshall, 2016). The strength and size of the gyre are modulated by atmospheric conditions, notably anomalies in the wind-stress curl, which also drives decadal sea-level variations (Chafik et al., 2019). The size of the gyre, in turn, affects the penetration of the North Atlantic Current and associated temperature and salinity along the edge of the north-west European shelf (Häkkinen et al., 2011).

The European Slope Current or Shelf Edge Current serves as an interface between the North Atlantic and the North Sea (Marsh et al., 2017), and is mainly driven by meridional density gradients in the eastern subpolar gyre. Using a range of observations and models, they found a marked reduction in these density gradients in the mid- to late 1990s which reduced the slope-current transport. They estimated that 10–40% of slope-current waters passing west of Scotland enter the northern North Sea within six months.

At a more detailed level, geostrophic interactions with topography guide the ocean currents along the shelf edge, leaving exchange between ocean and shelf waters to secondary processes (Huthnance, 1995). Processes that exchange water and materials between the Atlantic Ocean and the north-west European continental shelf include: Ekman transport related to the along-slope current, eddies, wind-driven upwelling, upwelling-related filaments, and internal tides and associated mixing processes (see Huthnance et al., 2009 for an overview). Detailed observations of internal tides and mixing were carried out by Sharples et al. (2009). More recently, Porter et al. (2016) found canyon-related upwelling, during summer-time reversals of the along-slope current, leading to on-shelf transport of Atlantic waters. Graham et al. (2018) modelled down-welling in relation to carbon exchange. These processes are active to different degrees along the western shelf edge. Along the northern shelf edge exchange is more direct, as the Shelf Edge Current interacts with the topography, and two branches split off that penetrate the northern North Sea: the East Shetland Atlantic Inflow, and the Norwegian Trench Atlantic Inflow (Turrell, 1992).

After having exchanged water and materials with the Atlantic Ocean through these processes, further transport of outer shelf waters into and out of the North Sea is driven by currents on the shelf. Net inflows occur through the English Channel, and around the Orkney Islands by the Fair Isle Current (Turrell, 1992). Outflow is concentrated along the Norwegian coast (Furnes et al., 1986). These shelf currents are composed of contributions driven by density differences, wind stress and tidal rectification (Prandle, 1978; Turrell, 1992; Hill et al., 2008).

2.2. Atmospheric and oceanic modulation of North Atlantic forcing

2.2.1. Historical and recent situation

The North Atlantic Oscillation (NAO) is the dominant mode of atmospheric climate variability of the North Atlantic. Reintges et al. (2017) employed one of the first coupled atmosphere-ocean models reproducing the sub-decadal NAO mode. They described the corresponding variability as resulting from positive ocean-atmosphere feedback and a delayed negative ocean dynamical feedback. Using global model results, Koul et al. (2019) investigated the large-scale atmospheric variability (NAO) and the impact on the Northwest European Shelf (NWES) hydrodynamics. Positive NAO is associated with westerly winds leading to increased inflow of Atlantic water. The fresh Baltic outflow into the North Sea is restricted during westerly winds but may increase after the end of these winds due to the pressure gradient induced by the elevated sea surface height in the Baltic Sea during westerly winds. This direct influence of atmospheric winds on the North Sea salinity explains mainly short-term (interannual) variability of the salinity in the North Sea. Long-term (decadal) variations are explained by variations of the eastward extend of the subpolar gyre confirming the impact of oceanic variability. This study agrees with model studies by Huthnance et al. (2016) (their Fig. 3.21), who found variations in Atlantic water influx into the North Sea of 200–300% within the first six months of the year after the corresponding NAO winter index. At much shorter time scales (weeks to months), the weather can influence the hydrodynamics in the North Sea significantly, and to an extent that may affect exchange with the North Atlantic, as was recently illustrated with a drifter experiment and associated modelling during a period of prolonged easterly winds (Stanev et al., 2019).

Identifying similar mechanisms for biogeochemical tracers from these hydrodynamic results is difficult because nutrient concentrations and other biogeochemical tracers are not conservative like salinity. Nutrients are subject to seasonal cycles of biological consumption and remineralization. The supply of new nutrients from the deep ocean via vertical mixing in winter depends strongly on the mixed layer depth. So, the first step in investigating nutrient supply from the North Atlantic is inspection of nutrient variability in eastern North Atlantic surface waters. Oschlies (2001) assessed the nutrient supply to the surface for different regions of the North Atlantic during different NAO-phases. He found increased surface nutrient supply near the NWES-break during positive NAO-phases caused by vertical and horizontal advection. The consequences of these hydrodynamic and biogeochemical NAO-related variations differ by region: in the northern North Sea higher pH values occur during positive NAO-phases, while lower pH values prevail in the southern North Sea (Salt et al., 2013). The authors justify these findings from a larger supply of Baltic Sea water with low DIC concentrations and Alkalinity during positive NAO phases combined with limited mixing between the northern and southern North Sea. The investigations of Padin et al. (2011) were focused on the processes influencing the formation of the relevant water masses. They found NAO-related meridional shifts in the area separating the formation regions of subpolar (fresher, nutrient enriched) and subtropical (saltier, nutrient depleted) eastern North Atlantic water. Shifts in the position of this transition zone modulate the inflow of waters from these two respective sources, regulating both salinity concentrations and nutrient supply.

2.2.2. Climate change

Studies of past Northeast Atlantic and North Sea dynamics have shown that large-scale atmospheric variability drives ecosystem features within both regions simultaneously. de Winter et al. (2013) found indications of more frequent future annual extreme wind events from western directions in the North Sea. It is assumed that these and other atmospherically driven events will occur in parallel in the Northeast Atlantic and the North Sea in the future.

Model projections of climate change in the Northeast Atlantic show an ongoing heating of the surface ocean. Within the 21st century this will lead to stronger stratification and a shoaling of the mixed layer depth, which in turn reduces the nutrient supply to the surface ocean and consequently decreases the import of nutrients from the North Atlantic into the North Sea (Mathis and Pohlmann, 2014). Extending the simulations until 2150, Mathis et al. (2019) detected further surface heating and a further decrease of the mixed layer depth. Such situations allow shelf-break induced vertical mixing to catch nutrients from below the very shallow mixed layer in the North Atlantic and transport them into the surface layer where they are efficiently advected into the North Sea. This mechanism does not account for potential changes in the circulation patterns of the Northeast Atlantic that may alter the inflow of North Atlantic water into the North Sea as described by Holt et al. (2018). These authors project changes in ocean haline stratification and gyre structure resulting from climate-change induced changes in oceanic and atmospheric forcing, causing Atlantic waters to bypass the North Sea. The consequences are a reduced northern inflow from 1.2–1.3 Sv to 0.0–0.6 Sv, a freshening of the North Sea (1–2 PSU), and an accumulation of river-derived nutrients (up to 50% increase in winter DIN). A recent broad-scale and in-depth assessment of climate change in the North Sea region was given by Quante and Colijn (2016).

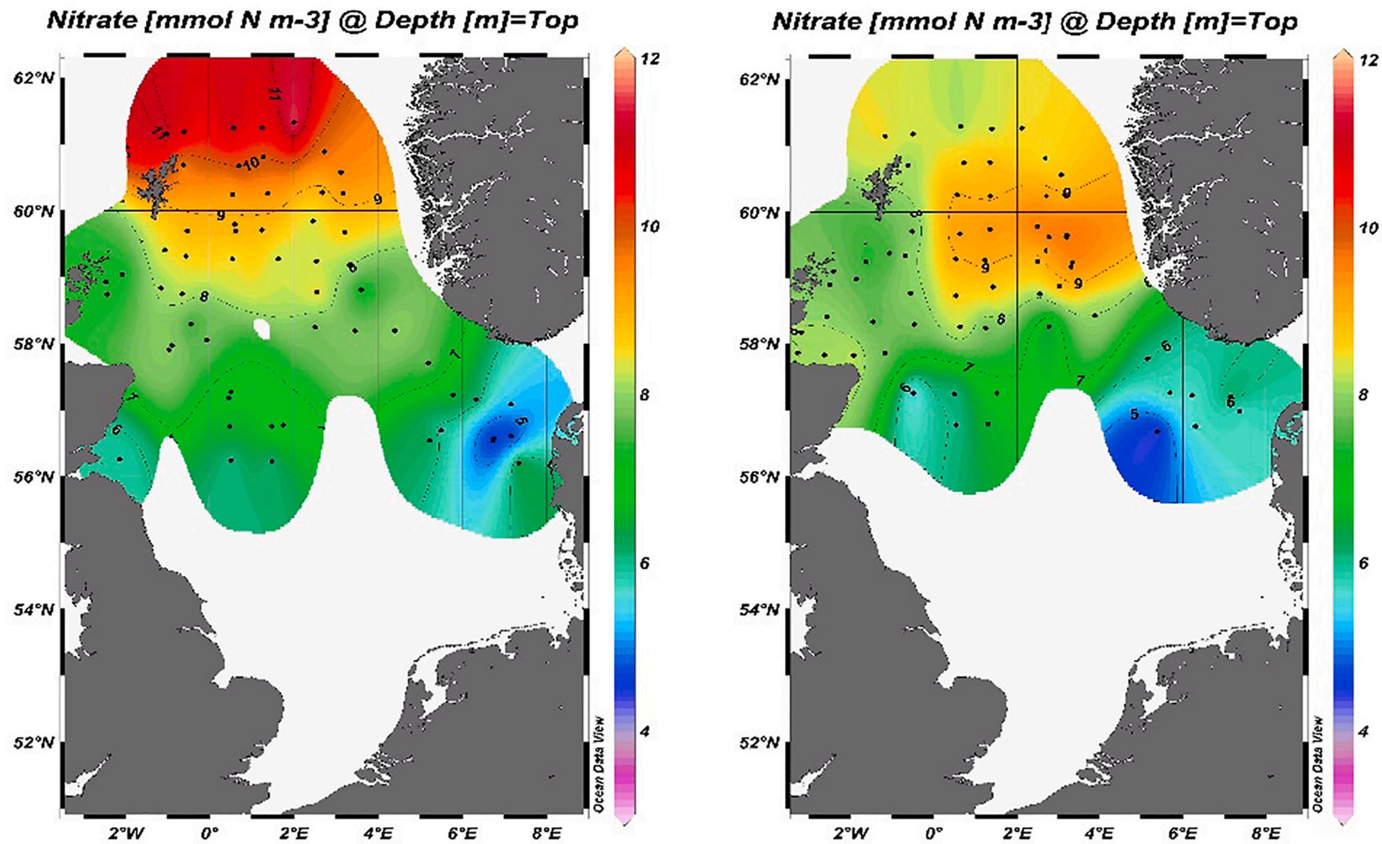

Fig. 1. Observed near-surface nitrate concentrations in a) winter 1995 (NAO+) and b) winter 1996 (NAO-). Samples were collected from 1984 to 2000 mostly during the Young- and Summer-Fish-Surveys with RV WALTHER HERWIG.

3. Modulations of North Sea oceanography and biogeochemistry

3.1. Waves

Surface waves contribute significantly to the vertical mixing, and storm events in spring and autumn influence the onset and breakdown of stratification. Moreover, waves are an important driver for sediment resuspension, and hence influence the under-water light climate (Van der Molen et al., 2017). In this way, they affect the primary production. A recent study of a wave model validated against wave data from the NWES found a correlation between extreme (100 year return period) and mean wave heights and NAO, with positive NAO resulting in higher waves, and other atmospheric modes contributing to a lesser extent (Santo et al., 2016). Mean wave heights also correlated in the northern to central North Sea, with less evidence for extreme wave heights, which decreased from north to south. The correlations allowed reconstruction of the extreme wave climate back to the 1600's. The study did not include wave stations in the southern North Sea. However, we expect this trend to continue into that area as wave fields in the North Sea tend to have substantial spatial coherence because weather patterns are typically larger than the North Sea.

3.2. Water fluxes and flow

The over-all water volume exchange between the Atlantic ocean and the NWES was recently re-calculated by Graham et al. (2018), using two models. They found an on-shelf flux across the shelf break of 1.7 to 2.0 Sv in surface and mid-waters, and an off-shelf downwelling flux of −0.7 to −0.8 Sv in bottom waters. The net on-shelf flux resulting from these two counter-acting contributions at the shelf break was balanced by an off-shelf flux of −1.1 to −1.2 Sv in the Norwegian Trench. These numbers compare well with the 1.2–1.3 Sv of northern inflow found by Holt et al. (2018) when considering that the inflow through the Strait of Dover is an order of magnitude smaller (0.1 Sv, Prandle et al., 1996). Huthnance et al. (2009) found slighly higher numbers: 2.5 Sv for the over-all shelf exchange, and −1.3 Sv for the outflow in the Norwegian Trench. Variations in the overall North Sea volume throughflow in winter have an amplitude of about 0.3 Sv and are driven by atmospheric forcing mostly correlated with NAO, with stronger NAO driving higher throughflow (Mathis et al., 2015).

3.3. Salinity

The North Atlantic Ocean typically has higher salinity than the North Sea, where waters are diluted by river runoff. The salinity of the North Atlantic Ocean is not constant, however, and various low 'salinity anomalies' have been identified (Dickson et al., 1988; Belkin et al., 1998; Belkin, 2004). Using data collected over >50 years, Sundby and Drinkwater (2007) concluded that salinity variability in the North Atlantic is driven by exchange with the Arctic Ocean, where they are generated by the formation and propagation of anomalies in sea-ice thickness (Haak et al., 2003). The North Atlantic Oscillation modulates the speed with which these variations propagate around the subpolar gyre, with higher NAO coinciding with higher speeds (Sundby and Drinkwater, 2007). These salinity anomalies propagate onto the shelf, but could not be traced in observations from the North Sea, presumably due to local modulation of salinity by riverine inputs (Dickson et al., 1988). Using observational data and model results Núñez-Riboni and Akimova (2017) were able to untangle the different sources of salinity variations. They found that remote variations of salinity in the northeastern Atlantic explain roughly 70% of the salinity variations in the northwestern North Sea.

3.4. Seawater temperature

Inter-annual variations in winter sea-water temperature in the North Sea, identified with EOF analysis of results from an ocean model, have an amplitude of up to 0.8 °C, driven mainly by variations in surface heat flux. Additional winter temperature variations induced by variations in Atlantic inflow have an amplitude of about 0.3 °C (Mathis et al., 2015). In summer, these authors report a wind-stress driven temperature variation in thermally stratified areas with an amplitude of about 0.2 °C, and a heat-flux driven temperature variation of 0.3 °C in vertically mixed areas, while variations due to Atlantic inflow were similar to those in winter. Mathis et al. (2015) found that these variations are partly forced by the NAO, with positive NAO resulting in higher temperatures, partly by more regional weather patterns, and partly by Atlantic inflow.

3.5. Nutrients

The amount of annual primary production within the central and northern North Sea is governed by winter nutrient concentrations (Pätsch and Kühn, 2008). The distribution of these nutrients in this area differs from year to year (Fig. 1) and is mainly determined by the nutrient concentrations in the areas where the influx of North Atlantic water is localized. Brockmann and Topcu (2002) found high nitrate concentrations in the winter of 1995 coinciding with a high NAO index. In the winter of 1996, with a low NAO index, the concentrations were significantly lower. The origin of these variations is still unknown. Are they driven by wind-forced upwelling of deeper water masses with higher nitrate concentrations, shifts of surface waters driven by meteorological forcing, or do they derive from water masses originating from subtropical nutrient-poor and subpolar nutrient-rich sources? In addition, a strong decrease in nutrient concentrations due to denitrification and primary production is expected along the main influx routes in the north-west of the North Sea in analogy with the Malin Shelf break (Hydes et al., 2004), which imports nutrients from the North Atlantic into the Celtic and Irish Seas. This very strong impact of North Atlantic nitrogen inflow reaches into the northern and central North Sea up to the 50 m depth contour in the south (Große et al., 2017). The nutrient concentrations in the southern part of the North Sea are governed by riverine nutrient inputs along the continental coasts of Belgium, the Netherlands and Germany. Radach and Pätsch (2007) presented different temporal variations for the western and the eastern continental riverine nutrient loads. Neither of these variations could be correlated with winter NAO-indices.

Model projections up to 2100 show increased stratification and a shoaling of the winter mixed layer depth (MLD) in the North Atlantic, leading to a reduction of nutrient imports into the North Sea (Holt et al., 2012; Mathis et al., 2018). The prolongation of the projection to 2150 revealed a subsequent increase in nutrient import due to enhanced shelf-break mixing (Mathis et al., 2018).

3.6. Carbon, pH and oxygen

The effective flushing of North Atlantic water through the North Sea dominates the carbon system of the North Sea (Huthnance et al., 2016). This mechanism does not imply large net effects but drives the different carbon sources and sinks (Thomas et al., 2005). Sources are rivers, the atmosphere and the Baltic inflow. The major sink of carbon is the deep outflow via the Norwegian Trench and the export via various shelf-break regions. For example, Painter et al. (2016) showed this for the Hebrides Shelf, west of Scotland. Variations in the carbon content are related to variations in temperature and nutrient availability because atmospheric CO2 exchange is strongly related to temperature (physical carbon pump) and to biological activities like primary production and respiration (biological carbon pump). In the southern part of the North Sea the CO2 system is mainly temperature-controlled, whereas in the deeper northern basin nutrients originating from the adjacent North Atlantic are a limiting factor for biological mediated fixation of atmospheric CO2 (Pätsch and Kühn, 2008). Summer observations in 2001, a year with a low NAOI (index), in 2005 with a medium NAOI, and in 2008 with a high NAOI revealed also a strong physical mechanism regulating CO2 and pH (Salt et al., 2013). In 2001 the lowest surface DIC concentrations and highest pH emerged, whereas in 2005 and 2008 higher DIC values and lower pH prevailed. These differences occurred because in low NAOI-years with weaker winds more metabolic carbon remained in deeper layers, and so was not effectively mixed into the surface layer. Salt et al. (2013) also observed that the general circulation pattern in the North Sea changes in relation to the NAO. During high NAO phases the counter-clockwise circulation prevailed, which in turn:

- increases DIC enriched water entering via the northwestern straits,
- increases the Baltic outflow in spring and summer,
- increases the outflow via the Norwegian Trench, and
- shifts the biogeochemical system to more autotrophy.

The downwelling circulation of the NWES was identified as the main mechanism for the removal of carbon from the shelf, called the carbon pump (Holt et al., 2009). Using a hydrodynamic model with tracers, they found that ~40% of the carbon sequestered by one growing season in the North Sea was removed in a year, of which 52% ended up below the pycnocline in the North Atlantic Ocean. These findings were supported by Wakelin et al. (2012), who found a net import into the North Sea in the upper 180 m and a strong export below.

Also the oxygen dynamics of the North Sea are basically defined by the effective flushing with oxygen-rich North Atlantic water. Hazardously low concentrations in the bottom mixed layer (BML) generally do not occur, but several areas have a higher risk of hypoxia due to stratification, in particular the Oyster Grounds and the Skagerrak (Topcu and Brockmann, 2015). Queste et al. (2012) found a trend of decreasing summer oxygen concentrations in the BML in the stratified central North Sea since 1990. They explained this by the strong negative correlation between temperature and oxygen concentration, which is caused by

- lower oxygen solubility with rising temperature, and
- increased oxygen consumption with temperature by benthic bacteria decomposing organic material.

The latter relation is also underlined by Provoost et al. (2013). Queste et al. (2012) also listed characteristics of regions with a potential risk of oxygen depletion: low advection, strong stratification, high organic matter production, and deep chlorophyll maxima. Große et al. (2016) concluded from their model studies that only areas between 54° - 57° N and 4.5° - 7° E show potential for oxygen deficiencies (< 6 mg O2 l^{-1}). They assign advection a less dominant role in oxygen variations. Authors who investigated smaller spatial scales identified near-coastal patterns of oxygen depletion at short time scales due to a rapid succession of vertical mixing and re-stratification (Topcu and Brockmann, 2015; Greenwood et al., 2010). Autonomous glider techniques allow investigation of processes with even smaller time scales. Queste et al. (2016) used this technique and found hot spots with astonishingly high rates of short term apparent oxygen utilization. The supply of oxygen for such strong consumption rates during stratification was explained by Rovelli et al. (2016) as caused by baroclinic near-inertial waves.

Many of these processes are influenced by direct anthropogenic loads of bio-reactive matter. On the other hand, it is evident that variations of meteorological parameters like wind and temperature driven by the NAO and other variations of large-scale fields determine the biogeochemistry of the North Sea.

3.7. Phytoplankton

Data on phytoplankton colour, a measure for phytoplankton

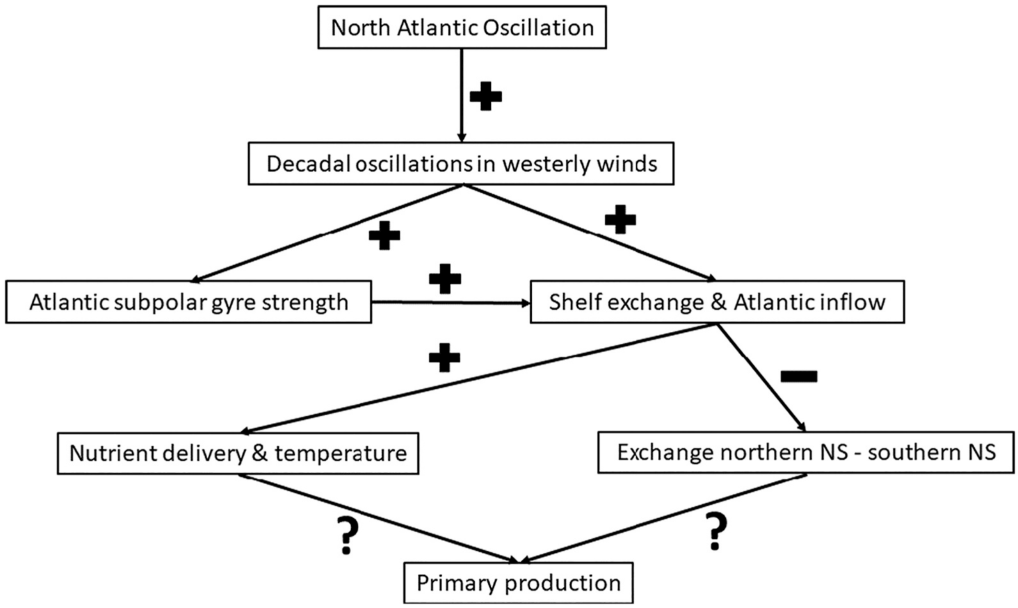

Fig. 2. Schematic summary of the main mechanisms of variations in Atlantic influence on the North Sea biogeochemistry.

biomass, from the Continuous Plankton Recorder (CPR) suggest an increase in the 1990's, the onset of which correlates with inflow of warm Atlantic waters caused by positive NAO conditions (Edwards et al., 2001; Reid et al., 2003). In a more recent analysis, Goberville et al. (2013) found correlations of ecosystem descriptors derived from the CPR observations in the Northeast Atlantic and the North Sea with the Atlantic Multidecadal Oscillation as well as the Northern Hemisphere Temperature anomalies. They did not find correlations with NAO.

Using a collection of various data sets, Capuzzo et al. (2018) found an overall decline in gross primary production in the North Sea from 1988 to 2013, with different trends in different hydrodynamic regions, and attributed this decline to increasing temperatures and decreased riverine inputs of nutrients. This was supported by an analysis of a 40-year data set of observations along the North Sea coasts of France, Belgium and the Netherlands (Desmit et al., 2019), which found a negative trend in Chlorophyll-a concentrations, and, at some locations, an earlier onset of the spring bloom in response to a rise in sea-water temperature and reductions in winter-nutrient concentrations. Other authors (van Beusekom and Diel-Christiansen, 2009) identified a top-down control mechanism, by which higher temperatures favour zooplankton growth and grazing during the spring bloom, thus leading to less intensive phytoplankton spring blooms.

Using a model, Holt et al. (2012) found that, under projected conditions of climate change up to 2100, the strength of stratification in the North Atlantic will increase, leading to a decrease of nutrients transported from the Atlantic into the North Sea, resulting in a reduction in nutrient concentrations and a corresponding reduction of up to 20% in primary production in outer-shelf waters. At the same time, primary production in inner-shelf waters was projected to increase by 5–10%. In response to the climate-change induced reduction in inflow of Atlantic water and the resulting increase in riverine influence, Holt et al. (2018) found an increase of primary production, in particular in coastal areas. This apparent contradiction to the classical picture that stronger stratification leads to a decrease of autochthonous primary production is also fueled by the discussion about diapycnal nutrient supplies to the upper ocean (Sharples and Zeldis, 2019; van Haren et al., 2021). Also, Xu et al. (2020) found a counter-intuitive relation between the negative trend of available nutrients and increasing autotroph biomass in the southern North Sea within the period 1961 to 2012. They explain this phenomenon by changed light availability and physiological acclimation of phytoplankton.

4. Summary and conclusions

Atlantic forcing of the North Sea hydrodynamics and biogeochemistry is mainly driven by oceanic and atmospheric variability of the Atlantic. Short-term variations in Atlantic inflows can be as large as 200–300% (Huthnance et al., 2016). The overall winter volume inflows from the North Atlantic typically vary inter-annually with an amplitude of slightly over 10% in response to a combination of Atlantic oceanographic and atmospheric variability (Mathis et al., 2015). The largest component in this variability is the North Atlantic Oscillation. These inflows carry nutrients and salt, the concentrations of which also vary at the boundary between the North Sea and the North Atlantic Ocean.

The main mechanism of variability is the following (Fig. 2). The atmospheric NAO includes variations in westerly winds, which are stronger under positive NAO conditions. These westerly winds enhance the strength of the Atlantic subpolar gyre. The combination of this wind forcing and the stronger gyre leads to enhanced shelf exchange and increased inflow of Atlantic waters into the northern North Sea. This leads to enhanced nutrient delivery, and the oceanic air masses carried by the westerly winds lead to higher sea-water temperatures. At the same time, Salt et al. (2013) report that these conditions reduce the exchange between the northern and southern North Sea, because of the stronger penetration of Baltic water into the northeastern North Sea. The subsequent enhanced flow from east to west along the 50 m depth contour line during the positive NAO phase reduces the mixing between the northern and southern North Sea. Reports on the influence of NAO on primary production focused on the southern North Sea, where riverine influences dominated the response, obscuring effects of NAO on the ecosystem. It may well be that correlations between NAO and primary production exist in the northern North Sea.

As the variability in nutrient concentrations at the inflow areas of the North Sea are smaller than the variability in water fluxes (Laane et al., 1996a, 1996b), it is still an open question whether long term variations in nutrient supply to the North Sea by oceanic variability can be detected in concentrations. Pätsch et al. (2020) found a strong negative correlation between shifts of the eastward extent of the subpolar gyre and nitrate and phosphate concentrations in the northern North Sea. In similarity with salinity the authors expected a time lag of 1–2 years for this phenomenon. This was not detected in the underlying data, as instead they found an immediate signal, which led to the conclusion that the large-scale atmospheric dynamics of the north-eastern North

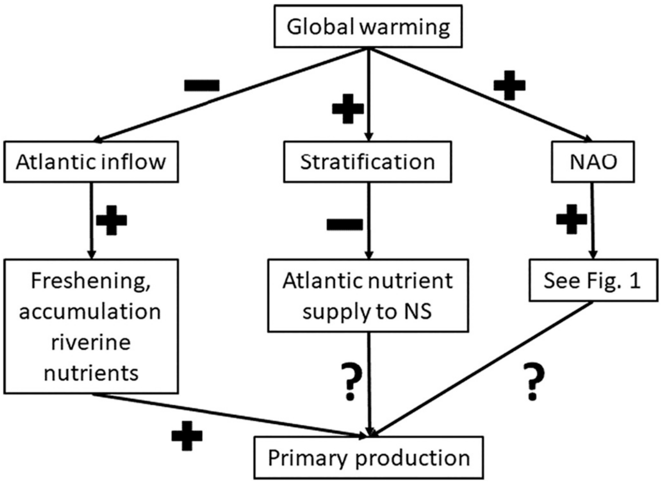

Fig. 3. Schematic summary of the main mechanisms of climate change on the North Sea biogeochemistry.

Atlantic were responsible for the concurrent variations. The long-term variability of the state of the ecosystems located in the North Sea and the Northeast Atlantic for 1958–2007 coincided with large-scale hydro-climatic forcings such as Northern Hemisphere Temperature anomalies, the Atlantic Multidecadal Oscillation index and the East Atlantic pattern (Goberville et al., 2013).

Model projections of changes in Atlantic forcing of the North Sea under climate-change conditions suggest three mechanisms (Fig. 3). At the most basic level, the warming will increase the strength and duration of stratification while reducing the depth of the surface mixed layer, leading to a reduction in the supply of Atlantic nutrients into the North Sea. This process is modulated by a strengthening of the NAO and its associated influences (above and Fig. 2). In addition, Holt et al. (2018) project that a possible shift of the Atlantic current patterns may reduce the Atlantic inflow and increase the relative importance of riverine loading of the North Sea with fresh water and nutrients. The overall combined effects of these three mechanisms on the primary production and wider ecosystem appear unclear and require further investigation.

Based on the overview presented here, a number of unclarities and issues related to the Atlantic forcing of the North Sea remain that are worthy of further investigation. The origins of the variations in winter nutrient concentrations in the North Atlantic are unclear, and may be a combination of variations in top-down and bottom-up ecosystem processes and oceanographic conditions in the subpolar gyre region. The influence of NAO on primary production in the northern North Sea can be further investigated, but needs to be separated from these variations in North Atlantic nutrient concentrations.

In relation to the effects of climate change on the Atlantic forcing of the North Sea, further work on confirming the potential reduction in Atlantic inflows, e.g. with different models, is desirable. At the same time, elucidating interactions of this process with the basic strengthening of stratification and expected increases in the strength of positive NAO conditions seems a viable avenue for further work, especially if such work could establish the combined potential effects on primary production and other ecosystem processes.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

The nutrient data were taken during the cruise 156 (1995) and 168 (1996) on board of Walther Herwig. The data are stored at the DOD, the German Ocenographic Data Center, with DOD reference numbers 19950062 and 19960056.

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