History and scenarios of future development of Baltic Sea eutrophication

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ABSTRACT

Nutrient loads from watersheds, atmospheric deposition, and cyanobacterial nitrogen fixation have led to eutrophication in the Baltic Sea. Here we give the historical evolution of this, detail some of the specific eutrophication features of the Baltic Sea, and examine future scenarios from climate related changes in the Baltic Sea region. We distinguish northern and southern regions of the Baltic Sea. The northern watersheds have sub-polar climate, are covered by boreal forest and wetlands, are sparsely populated, and the rivers drain into the Gulf of Bothnia. The southern watersheds have a marine influenced temperate climate, are more densely populated and are industrially highly developed. The southern areas are drained by several large rivers, including the representative Oder River. We compare these regions to better understand the present, and future changes in Baltic Sea eutrophication.

Comparing the future projections for the two regions, we suggest that in addition to changes in nutrient inputs, increased temperature and precipitation are likely to become important forcings. Rising temperature may increase release of dissolved organic matter (DOM) from soils and may alter the vegetation cover which may in turn lead to changed nutrient and organic matter input to the Baltic Sea. For the southern Oder River catchment a model study of nutrient input is evaluated, MONERIS (Modelling Nutrient Emissions in River Systems). The strong correlation between precipitation, flow and nutrient discharge indicates a likely increase in nutrient concentrations from diffuse sources in future. The nutrients from the Oder River are modified in a lagoon, where removal processes change the stoichiometry, but have only minor effects on the productivity. We suggest that the lagoon and other nearshore areas fulfill important ecological services, especially the removal of large quantities of riverine nitrogen but at the same time are threatened systems due to increasing coastal hypoxia.

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in the light of the political changes when the eastern block broke apart in 1989. Then there were nine states (Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia, and Sweden) that agreed on a politically updated convention that was only later ratified in 2000. The convention is supposed to foster a reduction of the land based pollution and, therefore, covers the whole of the Baltic Sea area, including inland waters. Many coastal point sources around the Baltic Sea had been successfully diverted by 2000 but non-point sources have remained a problem.

Even before the HELCOM agreement, the Baltic Sea was being surveyed on a regular basis by the individual countries, so that long-term water quality data exists. One of the longest records starts in 1900 for the oxygen concentrations from the Gotland Deep (Fonselius and Valderrama, 2003; Bernes, 2005). Based on these surveys, that were supported by funding from the EU and various nations, a detailed description of the history and evolution of the ecological status of the Baltic Sea is available (www://helcom.fi). The data includes information on nutrient concentrations, hazardous substances, marine diversity, maritime traffic, air pollution, and more.

The aim of this paper is to use existing data (Baltic Environmental Database, http://nest.su.se/models/bed.htm) and various published model results to show the regional differences in nutrient status and speculate about future developments of nutrient loads. Model results for climate change projections are used to predict future nutrient input. We select two regions representing different nutrient status and climate. The northern region experiences sub-polar climate and has hundreds of small catchments draining into the northern Gulf of Bothnia. The southern catchment with oceanic temperate climate mainly consists of four major rivers draining into the southern Baltic Proper (Fig. 2). One of the major rivers is the Oder River which will be discussed in detail.

Throughout the manuscript we will carefully distinguish between the coastal and the central Baltic Sea area. More specifically we will use the expression coastal area or coastal strip along the southern coastline where the water depth is shallower than 25 m. Baltic Proper is a synonym for the central Baltic Sea (Fig. 2) when no distinction between coastal and open areas are made. Therefore we will also use the word central Baltic Proper, when we talk about the area with a water depth above 25 m.

1.2. Climate and hydrology of the Baltic Sea

1.2.1. Climate zone

The Baltic region extends over two climate zones; in the south and south-west it is an oceanic temperate zone (Cf) and in the north and north east it is a humid sub-polar climate (Df) (Köppen and Geiger, 1960; Kottek et al., 2006). Rainfall occurs fairly evenly over all seasons in both climate zones and averages between 400 and 800 mm per year. Annual mean temperatures in the northern zone are lower than in the south. Precipitation in the catchment area is directly translated to changes in surface water runoff and river flow (Fisher and Oppenheimer, 1991) which has also been observed in the Baltic Sea catchment, where higher discharge in the rivers is strongly linked to precipitation and nitrogen inputs. Annual freshwater inputs are 300 km$^3$ in the Gulf of Bothnia and 180 km$^3$ in the rest of the Baltic Sea which is approximately 2% of the total volume of about 22,000 km$^3$.

1.2.2. Hydrography

Most of the freshwater inflow to the Baltic Sea of approximately 480 km$^3$ y$^{-1}$ goes into the Gulf of Bothnia with approximately 200 km$^3$ y$^{-1}$ and the Gulf of Finland with 100 km$^3$ y$^{-1}$. The freshwater input creates a strong gradient in the surface water salinity of the Baltic Sea from almost 0 in the north to over 20 in the entrance area of the Kattegat and Danish Straits (Fig. 1). Because the Baltic Sea is composed of a series of basins that are relics of the retreat of glaciers from the last ice age approximately twelve thousand years ago, a strong stratification occurs between 80 m and 100 m depth where fresh water lies above more saline water masses (Fig. 1). This is the case in all of the deep basins of the Baltic Proper. Moreover, sills between the basins restrict the deep water renewal with North Sea waters. Both these features (salinity gradient and sills) result in stagnating deep waters in the basins over periods of months to years. Water renewal and major inflows to the basins mainly take place during winter time and the intensity is strongly controlled by atmospheric forcing and the position of the salinity front in the Belt Sea, the transition area between North Sea and Baltic Sea (Stiebrandt, 2001). Those events may last days to weeks and deliver relatively saline (17–25) and oxygenated water to the deep basins; the inflows are infrequent and unpredictable because they rely on the large scale weather situation over Northern Europe. During the long lasting stagnation periods between inflow events, all of the oxygen in the deep waters may be consumed. The Gotland Basin is usually anoxic below 80–100 m depth, the Bornholm Basin and the Arkona Basin remain anoxic most of the time with short intermittent oxic periods. The longest well-studied stagnation phase of the eastern Gotland Basin lasted 9 years from 1983–1992 (Matthäus and Schinke, 1999). During a long stagnation period some freshening of the surface layer and continuous downward movement of the halocline and oxycline takes place (Gerlach, 1994; Conley et al., 2002). As a consequence oxygenated surface waters are mixed down to the halocline and the anoxic areas shrink in size.

1.2.3. Circulation

The circulation pattern of the Baltic Proper is characterised by an anti-clockwise circulation at the surface and few locations with a deep water exchange (Elken and Matthäus, 2008). An analysis of a model output (Neumann et al., 2002) by means of Empirical Orthogonal Functions (EOFs) shows an anti-clockwise circulation along closed streamlines in the Baltic Proper (Voss et al., 2005a) which has important consequences. The closed streamlines imply relatively long water residence time, 10 (Savchuk, 2005) to 30 (Fonselius, 1969) years, and function to largely separate the central basin of the Baltic Proper from the coastal areas. This means that the central basins accumulate and/or turn nutrients over on a longer timescale than the coastal areas. Moreover, this separation into coastal and central Baltic Sea suggests restricted mass transport of dissolved substances normal to streamlines. As a consequence river waters coming from the southern catchments (Oder,
Vistula, Nemunas Rivers) are transported alongshore, and terrestrial-derived nutrients and organic matter could be largely sequestered and transformed within the coastal strip and situated at a water depth below 25 m (Voss et al., 2005b).

1.2.4. Influence of the Northern European climate variability on the Baltic Sea

Climate variability acts on centennial and decadal scales and therefore, at least in the last 150 years, overlaps with the human activities in the drainage basin and the coastal zone. The interannual and inter-decadal variability of the Baltic Sea is forced by the North Atlantic Oscillation (NAO, Hurrell, 1995) and the inflow of Atlantic Water from the North Sea (Matthäus and Franck, 1992). The Arctic Oscillation (AO) describes comparable variations in the stratosphere of the northern hemisphere and it can be considered to be the dominant pattern of non-seasonal variations of upper layer pressure fields over Arctic zones (Thomson and Wallace, 1998). Consequently, the North Atlantic-European sector of the AO controls the NAO on a wide range of spatiotemporal scales including the decadal scale long-term changes. A high NAO index is associated with strong westerly winds and a low index with low westerly winds. During high NAO winters, the westerly winds over Europe are stronger than during low NAO winters and consequently, the moderating influence of the ocean during high NAO winters results in unusually warmer winter temperatures in Europe (Hurrell, 1995). Such a situation is connected with higher than normal precipitation which strongly influences the hydrological cycle and the river runoff (Dippner and Ikauniece, 2001). Moreover, atmospheric forcing influences the general circulation and the sea level and approximately 85% of the variability in sea level anomalies can be explained by the NAO and 10% by the Vb storm track (Heyen et al., 1996). The Vb storm track is the only persistent cyclone pathway in Europe which may cause extreme precipitation and huge flooding of central European rivers during summer time (Mudelsee et al., 2004).

A long-term analysis of 100 years of hydrographic data with focus on the freshwater budget (Winsor et al., 2001) indicates that freshwater supply to the Baltic Sea has large variations on time scales up to several decades. Analysis of a cumulative Baltic winter index (WIBIX) shows that during the last 350 years six regime shifts have occurred (Hagen and Feistel, 2005). Due to the fact that the Baltic Sea has decadal climate modes on the order of 30—60 years, it is rather problematic to clearly define “trends” or “regime shifts” on shorter time scales (Omstedt et al., 2004).

1.3. Nutrients in the Baltic Sea

1.3.1. Nutrient concentrations and riverine sources: Gulf of Bothnia vs. Baltic Proper

The major increase in the concentrations of nutrients appeared in the central Baltic Sea in the 1970s and 1980s (Fig. 3) (Larsson et al., 1985; Jonsson and Carman, 1994; Elmgren and Larsson, 2001a; Conley et al., 2009b) and may to a certain degree be fuelled by atmospheric deposition and nitrogen fixation while the importance of riverine loads for the open Baltic Sea is still debated (Voss et al., 2005a,b; Rolff et al., 2008). The Baltic Proper is surrounded by almost 50% of cultivated land and 20% forested land (Table 1, Fig. 2) resulting in higher anthropogenic inputs and higher nutrient delivery to the coastal waters. Therefore, the river sources of combined N (nitrate, nitrite, ammonia and organic nitrogen) come largely from agricultural land (Schernewski and Neumann, 2005; Deutsch et al., 2006; Voss et al., 2006), reaching in total approximately 750 kt y⁻¹ (HELCOM, 2004).

The five largest rivers draining into the Baltic Proper and Gulf of Finland are the Neva River (not discussed here) and the rivers Oder, Vistula, Nemunas, and Daugava located along the southern and southeastern coastlines of the Baltic Proper. Those river loads together deliver between 40 and 50% of the TN input (Table 2, Stalnacke et al., 1999; HELCOM, 2005). The decadal mean values show a high variation too, but no trend which only began in the 2000s. The loads of the individual years of TN vary quite considerably between 350 and over 600 kt y⁻¹ and show a weakly decreasing trend (Fig. 4). A high variation is seen in the NO₃ loads, and only the ammonia loads decrease clearly.

In contrast, the Gulf of Bothnia which is surrounded by forested land with over 50% and shrub areas with 20% (Table 1), and has experienced little or no nutrient enrichment with inorganic or organic substances since the 1970s. Concentrations of DIN remain around 5 μmol L⁻¹ and TN at approximately 20 μmol L⁻¹ in the open Gulf of Bothnia (Fig. 3a,b). The coastal zones, defined by water depths shallower than 25 m, show slightly higher inorganic and TN concentrations than the deeper parts (Fig. 3a,b).

An apparent decrease in DIN concentrations since 2000 was shown to result largely from changes in freshwater flows (Wulff et al., 2009). For the past 7 years from 2000 to 2006 precipitation was lower than average due to a climate shift (Swanson and Tsonis, 2005) leading to lower loads, however input in the catchment stayed rather constant or even increased. DON loads of the Baltic Proper show considerably higher concentrations than the ones further away from the coast and a trend towards slightly decreasing concentrations is suggested (HELCOM, 2007).

1.3.2. Atmospheric deposition

Atmospheric deposition estimates suggest dry plus wet deposition may be approximately 380 kt N y⁻¹ (Hertel et al., 2003) or within the lower range of nitrogen fixation by cyanobacteria. A sharp north-south gradient exists for the atmospheric deposition because the southern Baltic Proper receives much higher inputs than the north (Hertel et al., 2003). The amount of nitrogen deposited to the Baltic Sea may only enhance primary production and chlorophyll concentrations at times when nitrate is usually not present in surface waters like in summer (Spokes et al., 2006). The source of the DIN in the deposition may vary with season; combustion processes which release nitrogen containing oxides (NOₓ) seem more important in winter while manure fertilisation which releases ammonia to the atmosphere may be the dominant N-source in summer (Rolff et al., 2008).

1.3.3. Dissolved organic nitrogen

DON consists of a number of poorly characterised components. The bioavailable fraction includes proteins, urea, dissolved free and combined amino acids (DFAA and DCAA), nucleic acids (DNA, RNA), amino sugars and humic substances (Berman and Bronk, 2003) but most are still unidentified compounds. Only a few studies have focused on the bioavailability of these compounds, although DON is thought to contribute significantly to marine eutrophication (Berman, 1997; Seitzinger and Sanders, 1997).

Roughly half of all nitrogen entering the Baltic from the catchments is in the form of DON (Stalnacke et al., 1999), but there are substantial variations in the loads of inorganic and organic nitrogen sources among years (Fig. 4). The rivers draining into the Gulf of Bothnia carry about 2/3 of the TN as dissolved organic nitrogen (Fig. 4a), whereas the rivers draining into the Gulf of Riga and the Baltic Proper have 1/3 in form of DON (Fig. 4b). Stepanauskas et al. (2002) show that the Bothnian Bay and the Bothnian Sea receive a substantially higher proportion of DON than the Baltic Proper, even though the absolute concentrations of DON at the stations of the Bothnian Bay and Bothnian Sea are considerably higher than in the Gulf of Bothnia (Granell et al., 1990), we assume that riverine loads of DON may not enhance the productivity.
Autochthonous DON may be released during biological productivity in coastal zones (Bronk et al., 1994; Stedmon et al., 2006). Other sources of DON are from primary producers (e.g. cyanobacteria blooms in summer) and atmospheric input; the latter have been reported to be largely bioavailable (20–75%) (Timperley et al., 1985; Peierls and Paerl, 1997; Seitzinger and Sanders, 1999). How much DON from the rivers is sequestered along the coast is only vaguely quantified. In summer DON seems to become the dominant nitrogen source for phytoplankton communities when DIN is depleted (Stepanauskas et al., 1999; Berg et al., 2003). Both the bioavailability and the composition of DON may depend on the land use of the catchment areas being drained. Moreover, DON from anthropogenic sources is more bioavailable than DON exported from forested regions and wetlands (Seitzinger et al., 2002). But DON from pristine catchments tends to represent a relatively high proportion of the TN load whereas in anthropogenically less impacted regions the percentage of the DON (of the TN load) decreases with increasing TN concentrations (Seitzinger and Sanders, 1997; Stedmon et al., 2006; Wiegener et al., 2006; Agedah et al., 2009).

The bioavailability of terrestrially derived DON is variable at 2–70% (Seitzinger and Sanders, 1997; Stepanaukas et al., 2000; Veuger et al., 2004; Wiegener et al., 2006), but for the Baltic Sea this number seems to be around 30% (Stepanaukas et al., 2002). Only 8–14% was bioavailable in rivers situated in the Bothnian Bay drainage area, a similar amount in the in the Gulf of Riga (13% of the DON, Jorgensen et al., 1999). Higher values were found in two streams in northern Sweden, where 19%–55% of the DON was bioavailable in short-term bioassays (Stepanaukas et al., 2000).

1.3.4. Relationship between the riverine loads and the concentrations

In the first HELCOM report covering the environmental data from the 90s, the Baltic Sea was separated into sub-regions which stretched from the southern to northern coastlines covering areas like the Baltic Proper or the Gulf of Finland with no distinction between coastal and open areas of considerable depth (Fig. 1) (HELCOM., 1993). It was therefore implicitly assumed that the riverine loads can be directly linked to nutrient concentrations in the respective areas where a river entered the Baltic Sea. But recent evidence suggests that this may not be true, especially for nitrate. Nitrate input to the coastal zone seems to affect the coastal strip mainly. Consequently, a significant correlation between river loads of DIN or TN and the respective concentrations exists only for the coastal waters in the Baltic Proper (Fig. 5c,d). For the open sea stations in the Baltic Proper and the Gulf of Bothnia we found only weak or non-existent correlations (Fig. 5a,b). Moreover, concentrations of DIN and TN in the open (non-coastal) parts of the basins are always lower than for the stations closer to the coast. These findings suggest that the nutrient dynamics in the coastal area are quite different in comparison to the central parts of the Gulf of Bothnia or the Baltic Proper (Rahm and Danielsson, 2007). A similar conclusion was reached by a stable isotope study, where the δ15N in surface sediments along the southern coast are consistently higher compared to the open and northern Baltic Sea (Voss et al., 2005a). It was suggested that the riverine nitrate with a high δ15N (typical for eutrophied rivers) is fully consumed close to the coast and converted to organic matter, which is preserved in sediments together with the high δ15N signal (Voss et al., 2000, 2005a). Moreover, nitrate could be denitrified in coastal sediments, a process which does only leave...
a small imprint on the isotope signatures since fractionation is small (Brandes and Devol, 2002). Elimination of anthropogenic nitrogen along the coast and close to estuaries is a general typical feature (Seitzinger et al., 2006). Consequently, similar findings of elevated δ15N values in estuarine sediments and the North Sea were also related to riverine nutrients (Dahnke et al., 2008).

1.3.5. Nitrogen budget and processes

Recent estimates suggest that losses of nitrate by denitrification in the Baltic Proper potentially match the riverine NO3 input quite well (Deutsch et al., 2010). For the Gulf of Finland a similar conclusion was reached on the basis of rate measurements (Hietanen and Lukkari, 2007). These findings imply that most riverine nitrate can indeed be removed by the system. Moreover it explains the lacking relationships between river loads and concentrations in the central open Baltic Proper (Fig. 5). Moreover the rivers Oder, Nemunas and Daugava enter Szczecin Lagoon, Curonian Lagoon and the Gulf of Riga, respectively, where nutrients are consumed, removed etc. before the water enters the coastal zone (Pastuszak et al., 2005; Voss et al., 2010). We therefore address one lagoon example later in the text.

The increase in nitrate concentration in the 1970s and 1980s in the open Baltic Proper may instead be related to the two other major N-sources like are nitrogen fixation and atmospheric deposition. Both of these sources together match the overall river loads quite well and may theoretically lead to an increase by 5.25 mmol NO3 y−1 (Voss et al., 2005a). But since the 1980s no further increase in DIN concentrations in the surface waters of the open Baltic Proper has been found which can again only be explained by strong denitrification activity. Good estimates of water column denitrification are not yet available but few rate estimates suggest that a loss rate in the range of nitrogen fixation is possible (Hannig et al., 2007). It is interesting to note that a decrease in the oxygen supply leads to an increase in DIN and DIP in the Scheldt estuary in the 1970, after which a decline followed when the oxygen conditions were restored (Soetaert et al., 2006; Savchuk and Wulff, 2009).

Some minor transport of organic particles from the coast to the Baltic Proper normal to the streamlines may happen likely along the coast and close to estuaries is a general typical feature (Soetaert et al., 2006; Savchuk and Wulff, 2009).

### Table 1

Percentage of the land cover for the sub-catchments of the Baltic Sea. The most relevant areas are the Baltic Proper, Gulf of Riga which are compared to the Bothnian Bay and Bothnian Sea. Data source is the Baltic Environmental Database (http://nest.su.se/models/bed.htm).

<table>
<thead>
<tr>
<th>Basin name</th>
<th>Cultivated areas</th>
<th>Pasture</th>
<th>Shrub and/or Herb.</th>
<th>Bare areas</th>
<th>Inland water</th>
<th>Decid. forest</th>
<th>Mixed forest</th>
<th>Conif. forest</th>
<th>Inland wetlands</th>
<th>Snow and ice</th>
<th>Artificial surfaces</th>
<th>Maritime wetlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baltic Proper</td>
<td>45.7</td>
<td>6.6</td>
<td>5.6</td>
<td>0.1</td>
<td>2.8</td>
<td>4.8</td>
<td>7.9</td>
<td>21.1</td>
<td>0.6</td>
<td>0.0</td>
<td>3.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Bothnian Sea</td>
<td>7.5</td>
<td>0.1</td>
<td>18.0</td>
<td>0.5</td>
<td>6.8</td>
<td>2.4</td>
<td>8.7</td>
<td>49.1</td>
<td>5.8</td>
<td>0.0</td>
<td>1.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Bothnian Bay</td>
<td>3.2</td>
<td>0.1</td>
<td>22.5</td>
<td>3.4</td>
<td>5.8</td>
<td>4.8</td>
<td>16.5</td>
<td>31.6</td>
<td>11.3</td>
<td>0.1</td>
<td>0.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Gulf of Riga</td>
<td>23.6</td>
<td>6.0</td>
<td>16.6</td>
<td>0.0</td>
<td>1.4</td>
<td>15.6</td>
<td>19.4</td>
<td>14.5</td>
<td>1.9</td>
<td>0.0</td>
<td>0.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Gulf of Finland</td>
<td>6.1</td>
<td>0.6</td>
<td>8.7</td>
<td>0.0</td>
<td>14.1</td>
<td>10.2</td>
<td>28.5</td>
<td>28.6</td>
<td>2.6</td>
<td>0.0</td>
<td>0.7</td>
<td>0.0</td>
</tr>
</tbody>
</table>

### Table 2

Loads (decadal mean) in t y−1 to the Baltic Proper and Gulf of Riga (BP–GoR) and to the Bothnian Bay and Bothnian Sea (BB–BS) for the 1970s, 1980s, and 1990s. Please note, that the dissolved organic nitrogen (DON) concentrations were only calculated as the difference of TN (TN) minus ammonium and nitrate concentrations.

<table>
<thead>
<tr>
<th>BP–GoR</th>
<th>BB–BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH4</td>
<td>61,857</td>
</tr>
<tr>
<td>NO3</td>
<td>246,917</td>
</tr>
<tr>
<td>DON</td>
<td>167,359</td>
</tr>
<tr>
<td>TN</td>
<td>478,134</td>
</tr>
</tbody>
</table>

The increase in nitrate concentration in the 1970s and 1980s is likely the result of increased N-inputs. The most important site for N-input is nitrogen fixation. This process is not only important for the Baltic Sea, but also through increases in the sediment accumulation of BSI (Conley et al., 2009b). Sediment accumulation of biogenic silica (BSi) has increased by a factor of 1.9 due to increased diatom growth from eutrophication. Recent results indicate that the difference was about 36 μmol a century ago in the Baltic proper compared to about 13 μmol observed today (Conley et al., 2008). Long-term
trend analyses on DSi concentrations in the Baltic Sea have shown decreasing trends in the 1960s, 1970s and 1980s (0.3 μmol yr⁻¹), whereas similar analysis for the 1990s concluded that DSi concentrations were no longer decreasing, but rather levelling off (Humborg et al., 2008). In fact, DSi concentrations have changed much more dramatically compared to N and P regarding the total changes in the available nutrient stocks. Silica concentrations declined considerably over the past decades due to damming and other actions which reduced nutrients in the rivers. The Baltic Proper lost 0.3 μmol yr⁻¹ during the past three decades (Conley et al., 2008). Consequences are a declining diatom biomass in the spring bloom and the strengthening of the cyanobacteria bloom in summer (Wasmund and Uhlig, 2003; Schneider et al., 2009).

1.5. Biogeochemical models and nutrient budgets for the Baltic Sea

Since the Baltic Sea is a complex ecosystem, numerical models and budgets became an indispensable tool for evaluating the system’s response to external drivers. The interplay of physical transport of matter and biogeochemical processes can adequately be tackled only by numerical models. They have the potential to estimate a quantitative response of the ecosystem due to coupling of the involved processes.

Stigebrandt and Wulff (1987) first developed a biogeochemical model based on a simple physical model of the Baltic Sea with horizontally resolved basins and vertically resolved depth contours and stratifications. The main goal of the modelling was better
understanding of the oxygen – hydrogen sulfide interaction and distribution in the Baltic Sea. This model has been improved continuously over the years (e.g. Savchuk, 2005), and has been used in many management applications (e.g. Savchuk and Wulff, 2009). The advantage of this model type is the low demand of computer resources.

Another example is a box model with 7–8 boxes representing the major basins of the Baltic Sea, in which the water exchange between basins and the North Sea is considered (Savchuk, 2005, Savchuk and Wulff, 2009). The N input terms are river loads, atmospheric deposition and nitrogen fixation, while the losses are divided into burial, outflow to the North Sea, denitrification in the water column and denitrification in the sediments. Closed budgets are assumed so that ingoing and outgoing N- and P-compounds are balanced. The inputs were taken from HELCOM reports but also the model was used to evaluate unknown sinks and sources. Denitrification was one such unknown compartment.

Nitrogen cycling was evaluated with a fully three dimensional circulation model and a biogeochemical model (Neumann, 2000). Such spatially explicit three dimensional models have been used to consider changes in the biogeochemistry due to changing nutrient loads as well as changing meteorological forcing (Pitkänen et al., 2007; Eilola et al., 2009). Janssen et al. (2004) investigated the impact of meteorological forcing and demonstrated, that winter mixing depth was an important control of the intensity of cyanobacteria blooms in summer.

Most of these modelling approaches agree on a large uncertainty in nitrogen loss estimates. Moreover, it is assumed that inputs of nitrogen and losses are roughly balanced. This can be visualised by a simple budget where recent estimates of inputs and losses of nitrogen are summarised (Table 3). Sources are 1300 kt y\(^{-1}\) and sinks of 599–825 kt y\(^{-1}\) so that a discrepancy of 475–701 kt y\(^{-1}\) remains which may be lost via denitrification too (Table 3). The high losses may be plausible when compared to other studies where denitrification has been described for three systems with either diffusion, advection or periodic anoxia and nitrate supply (Seitzinger et al., 2006). All these system types exist in the Baltic Sea and together with the model results described above provide evidence for the possibility of high N-losses in the Baltic Sea.

2. The future of the Baltic Sea

2.1. General considerations of the changing climate

Recently the Baltic Sea Basin was subject of anthropogenic climate change studies using regional climate models (RCMs) used by IPCC (Giorgi et al., 2001). A number of simulations have been performed and compared for Northern European regions (Christensen et al., 2001; Rummukainen et al., 2003). Ten different RCMs were used to carry out more than 25 experiments (Déqué et al., 2007). Most of them were forced with global climate change models using dynamical downscaling techniques (BACC, 2008). Various time slice experiments have been performed mainly for IPCC scenario A2 and B2. These RCMs provide not only information on the projection of changes in air temperature, precipitation, sea level pressure, and wind. They are also used to drive hydrological models and circulation models for the projection of future changes in hydrology for the Baltic Sea (Graham et al., 2007; Hagemann and Jacob, 2007) and for the simulations and projection of future changes in sea ice (Omstedt et al., 2000), salinity (Meier and Kauker, 2003), sea surface temperature, and sea level (Meier, 2006). A detailed description of all projections is given in BACC (2008).

2.1.1. Temperature

Model simulations were specifically performed to evaluate the potential impact of climate change for the Baltic Sea and its catchment (BACC, 2008). They have the advantage over the global IPCC simulations in a higher spatial resolution and accuracy of regional climate models. Robust results of the scenarios for the Baltic Sea and the catchment area indicate an increase in temperature during all seasons with a pronounced peak in late winter/early spring and a mean annual warming of 3°–5° C in the atmosphere and 2°–4° C in the sea surface in the Baltic Sea by the end of the 21st century (BACC, 2008). Whether the temperature increase affects the soil chemistry and nutrient release is beyond the scope of this paper. One consequence is a decrease in sea ice extent by 50%–80% over the same period. The increase of temperature prevents late winter convection, which is essential for nutrient supply in the upper layer in the open Baltic Sea.

2.1.2. Precipitation

Projected changes in precipitation were more variable than temperature projections among different climate models. Winters will probably be wetter overall but in southern parts of the region, summers will likely be drier in many scenarios. As a consequence, winter flows of the rivers are expected to increase by up to 50% with the opposite pattern in summer. Floods caused by sea level rise may increase on southern and eastern coasts. Furthermore the increase in precipitation will result in higher river runoff, reduced salinity, higher nutrient input by rivers and enhanced eutrophication in near coastal areas (Dippner and Ilkäniemi, 2001).

2.2. The northern rivers to the Baltic Sea

2.2.1. The present situation

The population in the northern watersheds draining into the Bothnian Bay and Sea are generally low in density (1–30 inhabitants km\(^{-2}\)) and the waters are less eutrophic. The dominating land cover in the north is boreal forest (56%–97% of the land cover, Fig. 2, Table 1) and wetlands (0%–20% of the land cover, Fig. 2, Table 1). In general, the boreal northern watersheds have thin soil coverage of 5–10 m (Smedberg et al., 2009) dominated by till. The thin and

<table>
<thead>
<tr>
<th>Sink</th>
<th>Quantity sinks (kt y(^{-1}))</th>
<th>Source</th>
<th>Quantity sources (kt y(^{-1}))</th>
<th>Reference</th>
<th>Unexplained source (kt y(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water denitrification/</td>
<td>47</td>
<td>(Schafer and Rönner, 1984)</td>
<td>N from rivers and coastal point sources</td>
<td>686</td>
<td>(Wulff et al., 2009)</td>
</tr>
<tr>
<td>anammox</td>
<td>426–652</td>
<td>(Deutsch et al., 2010)</td>
<td>N from atmospheric deposition</td>
<td>201</td>
<td>(Wulff et al., 2009)</td>
</tr>
<tr>
<td>Sediment denitrification/</td>
<td>113</td>
<td>(Emeis et al., 2000)</td>
<td>Nitrogen fixation</td>
<td>370</td>
<td>(Wasmund et al., 2001)</td>
</tr>
<tr>
<td>anammox</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burial of N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outflow to North Sea</td>
<td>13</td>
<td>(Neumann, 2000)</td>
<td>Inflow from North Sea</td>
<td>43</td>
<td>(Neumann, 2000)</td>
</tr>
<tr>
<td>Sum</td>
<td>599–825</td>
<td></td>
<td></td>
<td>1300</td>
<td>475–701</td>
</tr>
</tbody>
</table>
unconsolidated structure of these soils may explain the short water residence times in boreal watersheds which are also caused by the high specific discharge (400–900 mm) and the relatively low evapotranspiration (10%–30% of the precipitation) due to low temperatures in these high-latitude watersheds. There are only rough estimates available on the water residence times in boreal watersheds. For small watersheds it is likely to be on the order of weeks to a few months (Laudon et al., 2007) whereas for the larger main Swedish watersheds the water residence times range from 2 to 27 months (Burgman et al., 1987) with an average of 11 months. The N loads to the Gulf of Bothnia varied between 80–140 kt y⁻¹ in the period 1970–2000 (Fig. 4a). The boreal river transport about 20% of the TN load to the Baltic Sea compared to the rivers draining into the Baltic Proper, although the annual water discharge is 20% of the TN load to the Baltic Sea. The increase in loads can be best described as a function of water discharge and therefore the increasing loads of TN and NO₃ observed during the late 90s (Fig. 4a) are due to extraordinary wet years. In contrast to the eutrophied rivers in the southeastern catchment of the Baltic Sea, the major part (65%) of the TN is in organic form and 35% of the TN is in dissolved inorganic form.

2.2.2. Nutrient sources, their dynamics, and future projections

The northern boreal watersheds of the Baltic Sea consist of taiga and tundra biomes that have been organic matter sinks since the last glaciations, but polar amplification of global warming (Graham, 2004) may defrost and turn these vast areas to carbon and nutrient sources due to enhanced degradation. Increased water percolation may also redistribute DOC and POC. The very northern watersheds can be characterised as sub-arctic and are very similar in their hydrological and biogeochemical conditions to the large Siberian and Canadian rivers (Smedberg et al., 2006). A change in climate and hydrology in these high-latitude regions could liberate large amounts of previously inactive soil organic matter (Freeman et al., 2001a, 2001b; Tranvik and Jansson, 2002) as dissolved organic carbon and nitrogen. In fact, as indicated by the relatively unper- turbated rivers Kalixälven, Torneälven and Kemijoki (Fig. 1 for location of rivers, Fig. 6), the seasonal patterns of total organic carbon (TOC) and TN (note that >90% of carbon and nitrogen are in dis- solved organic form) are essentially the same, indicating similar sources. TOC and TN are associated with the upper 0–5 cm soil layer (the O-horizon of the predominating podzols) that has an unconsolidated structure that determines their high hydraulic conductivities and low water storage. TOC and TN respond fast to precipitation events and, thus, follow the elevated spring flow peak due to snowmelt characteristic of the hydrology of boreal and arctic river systems (Smedberg et al., 2006).

Model results of the regional Swedish climate model SWECLIM (Rummukainen et al., 2004) indicate that temperature and precipitation will increase in average by about 2.6–5.0 °C and by 9–17% respectively (BACC, 2008). Even more pronounced changes in precipitation are expected for the northern Baltic Sea watersheds (2.6–5.1 °C and 13–33% in precipitation) that are connected to expected global warming (Graham, 2004). Model results have shown that this will alter the entire discharge patterns of these boreal and sub arctic watersheds with significantly higher runoff and a much prolonged spring flow starting much earlier in the season, but with a less pronounced peak flow (Graham, 2004). Currently, roughly half of the runoff in boreal and sub arctic rivers is generated within a few weeks in May and June (Fig. 6), flushing especially topsoils that are rich in organic matter. The pathways may change together with changes in the water chemistry and DON transport. An increase in runoff may either flush even more of the topsoils leading to a massive release of DOC and DON or percolate deeper into soils and increasing weathering due to deeper thawing of permafrost areas. The significance of both processes for the overall C and nutrient budgets is not yet known. Evidence for the latter hypothesis, a decrease in DOC and DON export relative to water discharge during summer through autumn has been noted in the Yukon River and is believed to result from increased flow through deeper soil layers as well as longer water residence times and microbial mineralisation of DOC and DON in the active soil layer (Striegl et al., 2007). Moreover, a general upstream trend in the groundwater contribution has been recorded for the Yukon River as a result of changed hydrological flow paths due to permafrost thawing and this alteration of flow paths is believed to further decrease DON exports (Walvoord and Striegl, 2007).
A further unresolved question is how organic nitrogen concentration in the boreal rivers will change when the vegetation cover will lead to an increase in forested areas (Kullman and Kjallgren, 2006; Kullman, 2007) and changes in vegetation belts in the northern parts of the Baltic Sea catchments towards wetlands, taiga (boreal coniferous forests) and more broad-leaved forest (Smith et al., 2008). A working hypothesis would be that DON composition will change towards younger and more bioavailable organic material as a function of increased vegetation biomass and production, since trees exude a large amount of dissolved organic matter (Giesler et al., 2007). Even the observed increasing DOC trends as seen in southern and central watersheds of Sweden could be partly a result of increased forest production (Humborg et al., 2007; Smith et al., 2008). Whether additional DON or DOC is bioavailable or refractory is unclear. Only one available experimental study from the Gulf of Alaska region suggests that changing DOM and nutrient concentrations may affect the productivity of coastal seas (Hood and Scott, 2008). The same authors assume that early successional plants after a retreat of glaciers may increase N-release and positively influence the production. For the Baltic Sea region we can only tentative assume that similar processes may affect the polar areas.

2.3. The southern rivers of the Baltic Sea region exemplified by the Oder River

2.3.1. Present situation of the Oder River and Szczecin Lagoon

In the southern Baltic region, an oceanic temperate climate and productive soils on glacial sediments support intensive agriculture. The catchment has been densely populated since centuries and industries are highly developed, leading to high N- and P loads along the southern coastline of the Baltic Sea including Germany, Poland, the Russian Enclave and the Baltic States (HELCOM, 2005). One of the major rivers of this region is the Oder River. The river basin is 118,000 km² large (Fig. 2), the length of the Oder is 854 km and the average discharge is about 550 m³ s⁻¹. The river drains into Szczecin Lagoon and from there flows into the coastal sea, the Pomeranian Bay. The lagoon is located at the German/Polish border and has a size of 687 km² and an average depth of 3.8 m. Poland is with 89% the largest country by area in the catchment (Czech Republic 6%, Germany 5%) with a mean population density of 136 km². 66% are agricultural land and 32% forests (Voss et al., 2006) while the whole catchment of the Baltic Proper has only 46% of cultivated land (Table 1) resulting in an export of <4 to >32 kg N ha⁻¹ y⁻¹ (Fig. 7).
annual loads of 47 kt y⁻¹ DIN, 73 kt y⁻¹ TN and 1.6 kt y⁻¹ PO₄⁻⁻ (Pastuszak et al., 2005).

The MONERIS model was used to estimate nutrient fluxes for the Oder River basin based on a geographical information system (GIS), and to allocate sources and pathways of nutrients; from 500 sub-catchments (Behrendt and Dannowski, 2005; Behrendt et al., 2008) (see Fig. 7). Model results are in good agreement with observations with only small maximal deviations of 12% from actual measurements as demonstrated for Warnow river (located 200 km west of the Oder) (Deutsch et al., 2006; Behrendt et al., 2008). The nutrient loads in the Oder depend largely on precipitation effects were excluded for the last 20 years and loads were instead based on a mean discharge year of 2005 (Fig. 8a), we observed a slight decrease of the total loads during the last 5 years which is in agreement of the study by Savchuk and Wulff (2009).

The Oder River does not directly flow into the southern Baltic Proper but enters the Szczecin Lagoon first. The Szczecin Lagoon is a recipient and “treatment plant” of the Oder River nutrients where the nutrient concentrations and rates directly follow changes in riverine loads without time lag. The model ERGOM was used to simulate lagoon processes and extended to cover the lagoon with a horizontal resolution of 1 N.m. and a vertical resolution of 2–3 m. The biogeochemical model has nine state variables. The nutrient state variables include dissolved ammonium, nitrate, and phosphate. Primary production is provided by three functional phytoplankton groups: diatoms, flagellates, and cyanobacteria (blue-green algae) (Neumann, 2000). Modelled chlorophyll levels in the lagoon reach up to 50 mg L⁻¹, demonstrating its high eutrophication level. However, much seems to be removed too since denitrification rates of 10 mmol m⁻² d⁻¹ (15 times higher than other coastal rates from the Gulf of Finland (Hietanen and Kuparinen, 2008) were estimated. Consequently nitrogen fixation rates are negligible in the model (Fig. 9).

The ratio of N:P in the river water has always been above the Redfield ratio (Fig. 10) and suggest P-limitation. But concentrations are so high throughout the year that almost never a nutrient limitation was observed (Voss et al., 2010). Since the loads of DIN are positively correlated to the discharge the ratio may further increase in future when the amount of DIN increases — a climate change scenario likely to occur under higher precipitation during winter (see chapter 2.1.2.).

2.3.2. Oder River: N- and P dynamics in the future

Since most of the Oder river basin is located on Polish territory changes in Polish agricultural practices and life style are most important for the nutrient input. In 2004, Poland joined the European Union (EU) and after a transition period, the Polish laws have to be adjusted to the EU legal requirements until 2015 to meet e.g. the thresholds of the Urban Waste Water Directive (UWWD) specific concentrations like total phosphorus (TP) = 2 mg L⁻¹, TN = 15 mg L⁻¹ for municipalities with a population between 10,000 and 100,000 and 1 mg TP L⁻¹ and 10 mg TN L⁻¹ for municipalities with more than 100,000 inhabitants. Together with the full introduction of phosphorus free detergents, these measures would reduce the phosphorus and nitrogen inputs from point sources and urban areas by 50% and more, when compared to the period 1998–2002 (Hirschfeld et al., 2009).

The fertiliser consumption in Poland is today still lower compared to Germany, but it is likely that Poland will reach similar fertiliser consumption in the near future. In the Polish part of the Oder River basin the N-fertiliser application already increased by 16% from 6.1 tN km⁻² to 7.1 tN km⁻² in only five years (2002–2006) while northern Germany uses about 17 tN km⁻² of fertiliser. During the same period the application of P-fertiliser increased by 40% in Poland (Hirschfeld et al., 2009). Future development may result in a surplus of 6.1–6.4 tN km⁻² on the Polish territory until 2020 (Hirschfeld et al., 2009). This is close to the

![Fig. 8. TN loads between 1983 and 2005 of the Oder River before entering the lagoon according to the model MONERIS. The loads are separated into load from point and diffuse (mainly agricultural) sources. a) TN loads and water discharge b) TN loads calculated with a constant river discharge of the year 2005 to eliminate discharge effects on nutrient loads.](image-url)
present surplus in Germany, but higher than the surplus in the mid 1980s in Poland (Behrendt et al., 2008). The nitrogen inputs from diffuse sources in the entire river basin will presumably increase to a level close to the mid 1980s. Phosphorus inputs will very likely decrease during the next decade. At the same time the increasing nitrogen loads will cause the already mentioned increase in the N/P ratios in the river (Fig. 10). This may not only be true for the Oder river basin but for most river basins in the southern Baltic region where countries with transitional economies are located.

3. How successful is the eutrophication management in the Baltic region?

According to the Baltic Sea Action Plan (BSAP) (HELCOM, 2007), “eutrophication is a major problem in the Baltic Sea, caused by excessive inputs of nitrogen and phosphorus which mainly originate from inadequately treated sewage, agricultural runoff and airborne inputs from shipping and combustion processes”. Goals have been defined to combat eutrophication. Among these are to lower the N and P input by 135 kt and 15 kt, respectively, to reach a good environmental status. However, what is not considered are the different nutrient sequestration capacities of rivers, lagoons, coastal systems, and the open Baltic Proper.

For a good ecological status it is necessary to consider inner and outer coastal waters separately especially in the southern Baltic Sea region, where the large rivers drain. The interactions between these systems and their different vulnerability towards pollution have to be taken into account. The example of the Szczecin Lagoon shows that coastal waters benefit from a reduction of nutrient loads. A lower primary production rate yields less organic matter and potentially reduces the risk of anoxia. Under these conditions denitrification can take place and reduce nitrate concentrations.

In the open Baltic Sea nitrogen is the limiting element for primary production in summer while in spring and in some coastal waters phosphorus is the element with the least availability. This is but one reason why there is an ongoing discussion whether management should focus on nitrogen or phosphorus reduction or on both (Elmgren and Larsson, 2001a,b). Currently, the reduction of both nitrogen and phosphorus loads is strongly considered to be necessary to reduce eutrophication in Baltic coastal water (Conley et al., 2009b). A vicious, self-sustaining circle, which maintains the cyanobacteria blooms for decades through a coupled process mobilising internal P-loading, nitrogen removal, and nitrogen-fixing cyanobacteria (Vahtera et al., 2007) may otherwise be a risk.

For coastal waters, not the nutrient concentrations in river water but the nutrient loads entering the coastal region are important. The example from the Oder River shows that a good riverine water quality does not necessarily result in a good water quality in the coastal waters. This may be true for other coupled river-lagoon-coastal systems too. Our example from the Oder River further shows that water quality objectives in a river, lagoon, or coastal water system cannot be determined independently for each subsystem. Rather the objectives should be defined according to the needs of the most sensitive system.

There are several lessons learnt for Baltic Sea eutrophication management. 1. Estuaries and coastal waters linked to large rivers
cannot be managed independently from the wider river basin. 2. Coastal ecosystems depend on processes, utilisation, structure and management in the river basin. Nutrient loads in these rivers are a mirror of activities in the river basin. 3. The close dependencies between river basin – river – coastal waters and the sea are well known and, with respect to water quality, reflected in the European Water Framework Directive (WFD). The Directive, published in December 2000, recognised for the first time the importance of aquatic biota in assessing the quality of European fresh and marine waters likewise. Specific objectives of the Directive are to prevent further deterioration and protect and enhance the status of aquatic ecosystems. It is unique in setting ecological targets for surface waters and, managing three components of aquatic habitats simultaneously, which are water quality, water quantity and physical structure. The WFD directive suggests a complex procedure to define concrete thresholds for a good ecological status, based on “reference conditions”. Reference conditions equal a high ecological status but do not necessarily reflect pristine conditions.

A good ecological status shows low levels of distortion from human activity and deviates only slightly from reference conditions (Fig. 11). Although good conditions are reached in the case of the Oder River under present nutrient concentrations this status may not ensure an improvement of the ecological conditions in the Baltic Proper. Therefore, a better understanding of the linkages between the waters is necessary and presumably a further nutrient load reduction in most rivers. The WFD is the major legal instrument to fight eutrophication in European waters during the next decades but it may be questioned whether it will be successful at all places.

The WFD still has weaknesses. Water quality objectives are largely defined separately for lakes, rivers, and coastal waters and do not take into account the continuum for the river to the coast and the differing vulnerabilities of rivers, lakes, and coastal waters towards pollution. This is especially critical for the catchment of the Baltic Sea which is about four times larger than the sea itself. One may assume that there is a high risk that, as soon as the water quality objectives in rivers and lakes have been met, the pressure to reduce nutrient inputs further in order to meet the requirements of the Baltic Sea will diminish.

In this scenario, the Baltic Proper might be left polluted while watersheds meet criteria for good ecological status. This situation would be unfortunate and carries a risk of increasing hypoxia and anoxia of coastal waters. In turn the denitrification capacity would
be lost in these important systems. Riverine nutrient reduction will remain an important challenge in future! The Nordic Rivers’ managements may need stronger focus on dissolved organic compounds and how these materials are produced and exported to the sea. But this field of scientific research is just emerging and we need more results before actual management ideas can be developed.

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