Impact of ship-borne nitrogen deposition on the Gulf of Finland ecosystem: an evaluation*

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Urmas Raudsepp[1]
Jaan Laanemets[1]
Ilja Maljutenko[1]
Marke Hongisto[2]
Jukka-Pekka Jalkanen[2]

[1] Marine Systems Institute,
Tallinn University of Technology,
Akadeemia tee 15a, 12618 Tallinn, Estonia;

e-mail: urmas.raudsepp@msi.ttu.ee

e-mail: jaan.laanemets@msi.ttu.ee

e-mail: ilja.maljutenko@msi.ttu.ee

[2] Air Quality Research, Finnish Meteorological Institute,
P.O. Box 503, FI–00101 Helsinki, Finland;

e-mail: Marke.Hongisto@fmi.fi

e-mail: Jukka-Pekka.Jalkanen@fmi.fi

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Abstract

The degree of inter-annual variability in spring and summer phytoplankton blooms and nitrogen fixation in response to the deposition of oxidized nitrogen originating from ship emissions (hereafter nitrogen deposition) was evaluated in the Gulf of Finland (Baltic Sea) based on 10-year (1997–2006) simulation results using a coupled hydrodynamic (GETM) and ecological (ERGOM) model. Ship emissions were generated for 2008 using the Ship Traffic Emission Assessment Model, and ship nitrogen deposition was calculated using the Hilatar chemistry-transport model over the Baltic Sea. The annual ship nitrogen deposition in the Gulf of Finland was 1.6 kt N, about 12% of the annual atmospheric deposition, and increased in summer, up to 30% compared to the monthly atmospheric deposition. Ship nitrogen deposition caused an increase in spring and post-bloom primary production in two functional groups (diatoms and flagellates), at the same time reducing phosphate resources in the upper layer. Nitrogen fixation due to ship nitrogen deposition decreased by 1–1.6 kt N year^{-1} (2–6%). The effect of ship nitrogen deposition on nitrogen fixation was greater in the western and central Gulf of Finland. The additional ship nitrogen deposition to the Gulf was practically compensated for by a decrease in nitrogen fixation.

1. Introduction

Ship traffic in the Baltic Sea and Gulf of Finland increased to a remarkable extent during the 2000s and is expected to increase (e.g. Kalli et al. 2012). In 2009, vessels entered or left the Gulf 38 396 times (HELCOM 2010). A comprehensive inventory of ship traffic exhaust emissions in the Baltic Sea showed an increase of 7% in ship-emitted oxidized nitrogen (hereafter nitrogen) from 2006 to 2009 (Jalkanen et al. 2013). The contribution of ship emissions (119 Gg N) to the total nitrogen emissions (NO, NO_2 and NH_3) from the HELCOM contracting countries is around 2.9% of the values reported in Bartnicki et al. (2011).

The annual waterborne load of nitrogen to the Gulf of Finland is about 60 kt N (HELCOM 2009). The annual atmospheric nitrogen load is around 10 kt N (the reduced N load was not included) (Hongisto 2011). About 9% of the total airborne Baltic Sea nitrogen deposition comes from ships (Bartnicki et al. 2011), which comprises about 2% of the total annual nitrogen load to the Gulf of Finland. The fraction of ship nitrogen deposition is relatively small, but Stipa et al. (2007) showed that the spatio-temporal variability of ship nitrogen deposition is very high, e.g. in summer locally it can extend up to 50% of the total atmospheric deposition.

Spring phytoplankton growth and biomass in the Baltic Proper and Gulf of Finland are nitrogen-limited (Kivi et al. 1993, Lignell et al. 1993). After the spring bloom, the euphotic layer becomes depleted of dissolved inorganic nitrogen by the middle of May (HELCOM 2002). The dissolved inorganic phosphorus concentration usually reaches a minimum value (about 0.1 mmol m^{-3}) before the late summer cyanobacteria bloom, from the end of June to the middle of July (HELCOM 2002). During this period, primary production is maintained by the external nutrient load (atmospheric deposition and river runoff) into the Gulf surface layer with a clear excess of nitrogen compared to the Redfield ratio (Pitkänen et al. 2001, HELCOM 2002) and possibly by the utilization of dissolved organic nitrogen (e.g. Bronk et al. 2007).

Cyanobacteria capable of biologically fixing dissolved atmospheric dinitrogen gas (N_2-fixation) form extensive summer blooms, which are a major environmental problem for the whole Baltic Sea and for the Gulf of Finland in particular (Vahtera et al. 2007). The regular occurrence of N_2-fixing cyanobacteria blooms has been related to a low winter ratio of dissolved inorganic nitrogen to dissolved inorganic phosphorus (Niemi 1979, Laamanen & Kuosa 2005), resulting in excess phosphate left over from the spring bloom. In addition to this excess phosphate, summer upwelling events also transport nutrients from deeper layers into the surface layer with a clear excess of phosphate (compared to the Redfield ratio), thus promoting cyanobacteria blooms (e.g. Vahtera et al. 2005) and contributing to the inter-annual variability of nitrogen fixation (Kahru et al. 2007). Simulations by Zhurbas et al. (2008) showed that one upwelling event transported into the upper layer an amount of phosphorus roughly equal to one monthly external load of bioavailable phosphorus to the Gulf – approximately 380 tons. Water temperature is also a factor governing cyanobacteria blooms (Lehtimäki et al. 1997, Wasmund 1997).

Schneider et al. (2003) considered nitrogen fixation to be a major uncertainty in the Baltic Sea nitrogen budget. Existing estimates of nitrogen fixation rates in the Baltic Sea vary over a wide range, from 1 to 318 mmol m^{-2} $year^{-1}$, which corresponds to a basin-wide fixation of 3 to 1000 kt $year^{-1}$ (Rolff et al. 2007). The large variability of estimates can be explained by the high spatial patchiness of cyanobacteria blooms and differences in the methods used for quantification. Simulations by Neumann & Schernewski (2008) showed that the highest nitrogen fixation rates (about 300 mmol m^{-2} $year^{-1}$) in the Baltic Sea occurred in the western Gulf of Finland.

The dynamics of phytoplankton growth and biomass depend on the environmental conditions induced by biogeochemical and physical processes. To date, the influence of the additional atmospheric deposition of nitrogen due to shipping on the annual phytoplankton biomass and summer nitrogen-fixation by cyanobacteria has not been sufficiently investigated in the Gulf of Finland. In the present study we used the hydrodynamic model

GETM (General Estuarine Transport Model) coupled with the ecological model ERGOM (Ecological Regional Ocean Model) for the simulations. In order to evaluate the impact of ship nitrogen deposition originating from ship emissions on the Gulf of Finland ecosystem, we performed two 10-year (1997–2006) simulations: with and without ship originated nitrogen deposition over the whole model domain (Figure 1a). At the time of the simulations, the uniform whole-year ship nitrogen deposition was available only for 2008, so this atmospheric deposition of nitrogen (with and without ship deposition) was used repeatedly for the whole 10-year simulation period. The initial physical and nutrient fields as well as the atmospheric forcing and boundary conditions were kept the same for both simulations. Although the coupled hydrodynamic and ecological model domain covers the whole Baltic Sea, we focused our study on the Gulf of Finland.

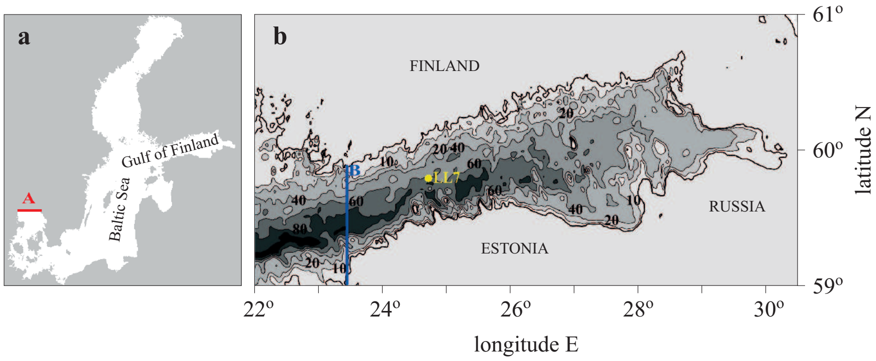

Figure 1. a) A map of the Baltic Sea. The red line A marks the open boundary of the model domain in the northern Kattegat. b) A close-up of the Gulf of Finland. The location of HELCOM monitoring station LL7 is shown. The blue line B along longitude 23°30′E marks the western boundary of the Gulf of Finland basin in the present study. The depth contours are drawn from the gridded topography (Seifert et al. 2001) in metres

The objective of the study was to evaluate, on the basis of two 10-year hindcast simulations, the degree of change of annual phytoplankton biomass and nitrogen fixation in response to ship nitrogen deposition.

2. Material and methods

2.1. Study area

The Gulf of Finland is an elongated (length 400 km) and relatively narrow (width 50–135 km) basin in the eastern part of the Baltic Sea. Its depth decreases from 80–100 m at the entrance area to 20–30 m in the eastern part. The salinity distribution in the Gulf is governed by the freshwater budget and water exchange with the open Baltic. The considerable inflow from the River Neva (77.6 km^3 year^{-1}, Bergström et al. 2001) causes the surface layer salinity to decrease from 6–7 g kg^{-1} at the entrance to about 1 g kg^{-1} in the Neva estuary. The near-bottom salinity may reach open sea values of 9–10 g kg^{-1} at the entrance to the Gulf. Typical of a wide estuary, flow in the Gulf is separated laterally into a cyclonic circulation pattern with the average surface water inflow along the southern coast and the outflow along the northern coast. The estuarine circulation of the Gulf results in a strong halocline at depths of 60–70 m (Alenius et al. 1998), hampering mixing between the surface and bottom water and leading at times to low oxygen conditions in the near-bottom water. The vertical thermal stratification has a highly seasonal character. Solar heating and wind mixing form a sharp seasonal thermocline at a depth of about 10–15 m, starting in May and becoming strongest in July–August, which restricts the mixing of nutrients from deeper layers into the surface layer during summer. The circulation in the Gulf is strongly influenced by synoptic variations in wind forcing. South-westerly winds generate a temporary reversal of the estuarine circulation, thereby weakening stratification (Elken et al. 2003) and thus improving near-bottom layer oxygen conditions, in particular during winter, when the seasonal thermocline decays. An important physical phenomenon in the Gulf is coastal upwelling, caused by transient alongshore wind forcing (e.g. Lehman & Myrberg 2008).

2.2. Ship emission model

Ship emissions were generated using the Ship Traffic Emission Assessment Model of Jalkanen et al. (2009, 2012). Automatic Identification System (AIS) position reports from each vessel sailing the Baltic Sea were collected for 2006–2009, describing over 800 million individual ship movements. Using this data collected by the national AIS networks in the Baltic Sea area, emission inventories for NO, NO_2, SOx, CO, CO_2 and particulate matter were generated. Ship emissions were allocated to a grid of 0.068° (grid cell size is around 7 km) with a temporal resolution of 15 minutes. The distribution of annual ship nitrogen emission over the Baltic Sea in 2008 is shown on Figure 2. The gridded emissions were directed as input to the chemistry transport model.

2.3. Chemistry-transport model

Nitrogen deposition over the Baltic Sea was calculated with the Hilatar nested chemistry-transport model (Hongisto 2003), using the forecasts of

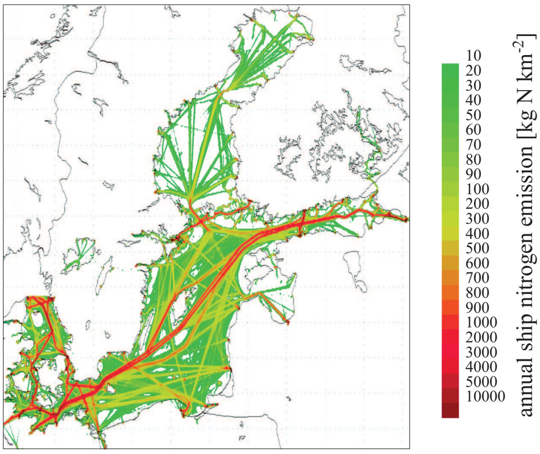

Figure 2. Distribution of annual nitrogen emissions [kg N km^{-2}] from Baltic Sea shipping in 2008

the HIRLAM (HIgh Resolution Limited Area Model) hydrostatic weather prediction model (Undén et al. 2002). The current European model has 60 vertical layers and a horizontal grid of 0.15° resolution; the model covering the Baltic Sea has a finer horizontal resolution, a grid of 0.068°. The chemistry module comprises the EMEP-MSC-W chemistry code with some modifications (Hongisto 2003). The model uses horizontally-rotated spherical coordinates and vertically hybrid sigma coordinates with selected (10–21) vertical layers up to 5–10 km in height. Dry deposition velocities calculated using the resistance analogy was used as the lower boundary condition of the vertical diffusion equation. The boundary-layer schemes of Lindfors et al. (1993) were used for calculating the marine boundary layer parameters for dry deposition velocities over sea areas. Wet deposition was calculated separately for in-cloud and below-cloud conditions for particles and gases.

Validation of the model through a comparison with EMEP network measurements was reported by Hongisto (2003) and Hongisto (2011). The Baltic Sea load was compared with other model estimates in Hongisto & Joffre (2005).

The model uses the 50-km EMEP-emission inventory for the European emissions, the Finnish Meteorological Institute inventory for Finnish and north-western Russian sources, and the above-described ship emission inventory for emissions over the Baltic Sea. The time variation is based on the GENEMIS project 1990 country-specific emissions and on the diurnal and weekly traffic indices. The initial vertical mixing was estimated from emission height profiles or using the plume rise algorithm.

2.4. Coupled hydrodynamic and ecological models

The hydrodynamic model applied is a 3D free surface GETM (www.getm.eu), described in detail by Burchard et al. (2004). GETM solves the primitive equations of water dynamics using the Boussinesq and hydrostatic approximations with a mode splitting technique on an Arakawa C-grid. Spherical coordinates were used in the horizontal plane, while a sigma coordinate system was applied in the vertical direction. Subgrid vertical mixing was resolved using a turbulence closure scheme of the k-ε type via the General Ocean Turbulence Model (GOTM, www.gotm.net) coupled with GETM (Umlauf & Burchard 2005). Subgrid lateral eddy viscosity was resolved using the Smagorinsky formulation (Smagorinsky 1963). GETM is used for simulations of water circulation in the Baltic Sea (e.g. Burchard et al. 2009, Gräwe & Burchard 2012).

Ecosystem processes were resolved by coupling the ERGOM ecological model (Neumann 2000, Neumann et al. 2002) with GETM. ERGOM is used for modelling the Baltic Sea ecosystem (e.g. Neumann 2010, Kuznetsov & Neumann 2013). Recent studies have shown that the ERGOM biogeochemical model performs well in the Baltic Sea (Eilola et al. 2011, Maar et al. 2011). Three nutrients (nitrate, ammonium and phosphate) taken up by phytoplankton are in ERGOM; the model uses nitrogen as the model currency. As a result of respiration and detritus mineralization, ammonium is produced, which in the presence of oxygen may be converted to nitrate via nitrification. Under anaerobic conditions nitrate is reduced to molecular nitrogen that leaves the system, and the released oxygen is used to mineralize detritus (denitrification). The model accounts for the oxygen-dependent dynamics of phosphate: under oxygenated conditions, part of the mineralized phosphate is stored in sediments in that iron-phosphate complexes are formed, while under anoxic conditions the previously stored phosphate is liberated to the overlying water (Neumann & Schernewski 2008). It is assumed that cyanobacteria are able to fix atmospheric nitrogen and are only limited by the availability of phosphate in the water (Neumann 2000). Therefore, low dissolved inorganic nitrogen to phosphorus ratios combined with high water temperatures promote the onset of cyanobacterial blooms. The current model version includes 10 pelagic variables (diatoms, flagellates, cyanobacteria, zooplankton, detritus, ammonium, nitrate, phosphate, oxygen and iron-bound phosphorus) and two benthic ones (sediment detritus and iron-bound phosphorus in sediments).

2.5. Coupled hydrodynamic and ecological model setup and forcing

The model domain includes the whole Baltic Sea with the open boundary in the northern Kattegat (Figure 1a). The horizontal resolution of the model grid is 2 nautical miles and there are 25 sigma layers in the vertical direction. The digital topography was taken from Seifert et al. (2001). The line (A) along longitude 23°30′E was treated as the western boundary of the Gulf of Finland basin in the present study (Figure 1b).

Initial temperature and salinity fields were constructed using the Data Assimilation System coupled with the Baltic Environmental Database at Stockholm University (http://nest.su.se/das). We used atmospheric forcing (wind velocity, solar radiation, air temperature, air pressure, cloudiness, precipitation, relative humidity) based on ERA40 re-analysis data dynamically downscaled with the RCAO (Rossby Centre Atmosphere Ocean) model (Döscher et al. 2002, 2010). Underestimated high wind speeds were corrected according to Höglund et al. (2009). For sea level elevations at the open boundary in the northern Kattegat, hourly averaged measurements in Smøgen (Sweden) were used. Salinity and temperature at the open boundary were adopted from Janssen et al. (1999) climatological mean fields. The values at the boundary were spatially relaxed to the nearby grid points using the sponge layer technique. Initial fields of biogeochemical variables for the simulation on 1 January 1997 were obtained from the MOM/ERGOM model (Baltic Sea Research Institute in Warnemünde) long-term run as the mean values of the preceding December. The initial winter surface layer nitrogen field was fitted to monitoring data in the Gulf of Finland area. Total river runoff and nutrient loads to the Baltic Sea were obtained from the HYPE hydrological model (Lindström et al. 2010). Two 10-year coupled model runs were performed using the atmospheric deposition of oxidized nitrogen in 2008 calculated with the Hilatar chemistry-transport model with and without ship nitrogen deposition for the whole Baltic Sea.

2.6. Measurement data and validation procedure

HELCOM monitoring data at station LL7 representing the central Gulf of Finland (Figure 1b) were used for the validation of simulated hydrodynamic (salinity and temperature) and biogeochemical (nitrate, phosphate and dissolved oxygen) parameters. To summarize the long-term statistical characteristics of model performance, we used Taylor diagrams and a cost function. The Taylor diagram shows the correlation between simulated and measured parameters and the ratio of their standard deviations (Taylor 2001). The cost function (Eilola et al. 2009) was calculated as CF = $|(M - D)/\mathrm{SD}|$, where the bias $(M - D)$ of the simulated mean (M) relative to the mean of observations (D) was normalized to the standard deviation (SD) of the observations. Cost function values of 0–1 indicate a good match between model results and measurements, values of 1–2 indicate a reasonable match and values > 2 indicate a poor match.

3. Results

3.1. Hydrodynamic and ecological model validation

The measured and simulated parameters are compared in Table 1 and Figure 3. The mean simulated surface layer temperature was slightly overestimated and salinity was underestimated. Both parameters followed the observed variability well. In the near-bottom layer temperature and salinity were slightly overestimated but again the observed variability was reproduced well.

Table 1. The 10-year mean, standard deviation (SD) and cost function (CF) values of temperature (T, °C), salinity (S, g kg^{-1}), dissolved oxygen (O, ml l^{-1}), nitrate (N, mmol m^{-3}), phosphate (P, mmol m^{-3}) for the surface (s) and near-bottom (b) layers at the location of monitoring station LL7. Cost function values 0–1 indicate a good result, 1–2 indicate a reasonable result and > 2 indicate a poor result. Note that D is mean of observations and M is mean of simulated data

	Mean		SD		CF
LL7	D	M	D	M	
T_s	7.9	9.0	6.1	6.3	0.2
S_s	5.4	4.6	0.4	0.6	1.8
T_b	3.5	4.6	1.1	1.2	1
S_b	7.4	7.8	0.7	0.8	0.6
O_s	8.4	8.4	1.5	1.1	0.0
P_s	0.4	0.3	0.4	0.2	0.3
N_s	3.8	2.3	3.7	2.6	0.4
O_b	2.7	3.8	2.2	1.4	0.5
P_b	2.9	2.1	1.3	0.6	0.7
N_b	7.9	10.6	2.3	3.6	1.2

Simulated nitrate was underestimated in the surface layer and overestimated in the near-bottom layer. The variability was reproduced well in the surface layer but in the near-bottom layer the correlation was poor. The mean levels of nitrate measured and simulated for the surface and near-bottom layer were well matched. Variability in surface layer phosphate was better reproduced by the model than near-bottom phosphate. Surface

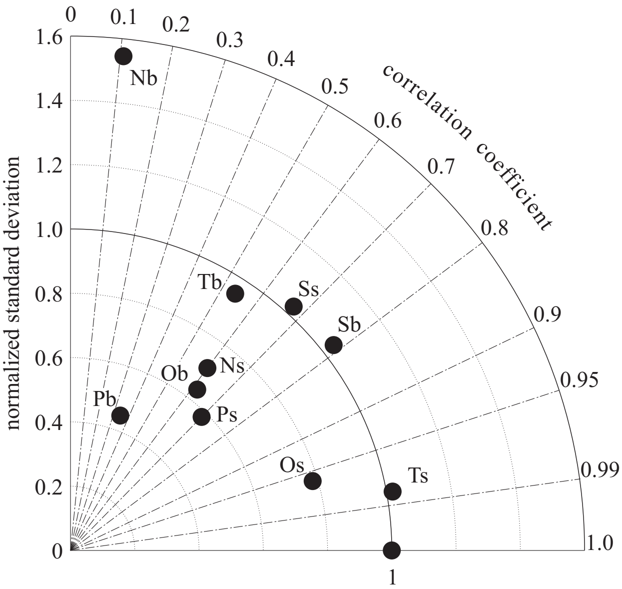

Figure 3. Taylor diagram of simulated and observed surface layer and near-bottom layer hydrographical and biogeochemical parameters at HELCOM monitoring station LL7 for the period 1997–2006. The parameters are temperature [°C], salinity [g kg^{-1}], nitrate (N, mmol m^{-3}), phosphate (P, mmol m^{-3}) and oxygen (O, ml l^{-1}). The normalized standard deviation is the standard deviation of the simulated data divided by the standard deviation of the observations. Observations are represented by 1 at the x-axis

layer oxygen was reproduced well. In the near-bottom layer, the oxygen concentration was overestimated but the variability was reproduced well. Generally, the cost function values for nutrients and oxygen were within the good range, except for near-bottom nitrate, which was in the reasonable category.

3.2. Atmospheric deposition of nitrogen in the Gulf of Finland

The month-on-month atmospheric deposition of oxidized nitrogen (without ship nitrogen deposition) and ship nitrogen deposition to the Gulf area was highly variable in 2008 (Figure 4). The deposition of atmospheric oxidized nitrogen was greater during the autumn and winter months (up to 1600 t N in January and October) than in the summer months (about 400 t N in July). The trend of monthly nitrogen deposition in the Gulf area caused by ship emission was the opposite: nitrogen deposition was greater in July–August (up to 220 t N month^{-1}) compared with the winter months (about 60 t N month^{-1}). The total annual atmospheric nitrogen deposition (including ship nitrogen deposition) in the Gulf area was 13.7 kt N. The

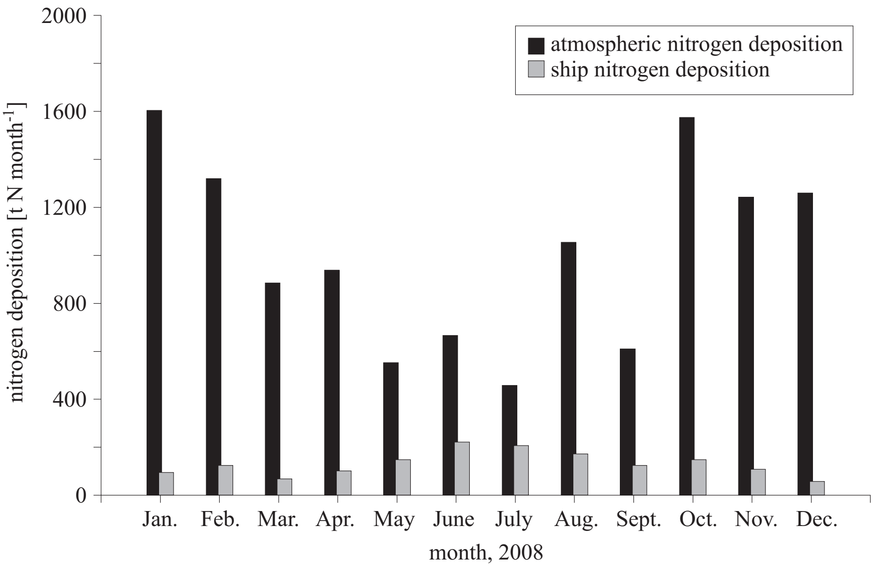

Figure 4. Monthly atmospheric nitrogen deposition [t N month^{-1}] without ship deposition (black bars) and monthly ship nitrogen deposition [t N month^{-1}] (shaded bars) in the Gulf of Finland area in 2008

annual ship deposition of nitrogen in the Gulf area was 1.6 kt N, i.e. about 12% of the total atmospheric deposition, which concurs with the results of Bartnicki et al. (2011). In May–August the proportion of ship nitrogen deposition increased, varying between 20–30% of the total atmospheric deposition of oxidized nitrogen. The annual deposition of ship nitrogen was greater in the western Gulf (up to 70 kg N km^{-2}) than in the eastern part (Figure 5).

3.3. Winter nutrient content in the upper layer

To estimate the impact of ship nitrogen deposition on winter nutrient conditions, we calculated the average dissolved inorganic nitrogen to phosphorus (DIN:DIP) ratio over the Gulf area and excess phosphate in the upper 10 m layer before the spring bloom (Figure 6). Values of the DIN:DIP ratio were relatively low, varying interannually from 8.5 to 11.5. The increase in the DIN:DIP ratio caused by ship nitrogen deposition was minor, and in almost all years was less than 1%. The average excess phosphate left over from the spring bloom (excessP = DIP–DIN/16) over the Gulf area varied interannually by more than two fold, between 0.17–0.4 mmol m^{-3}. The addition of ship nitrogen deposition reduced excess phosphate from 1 to 2.5%, depending on DIN and DIP resources in the upper layer.

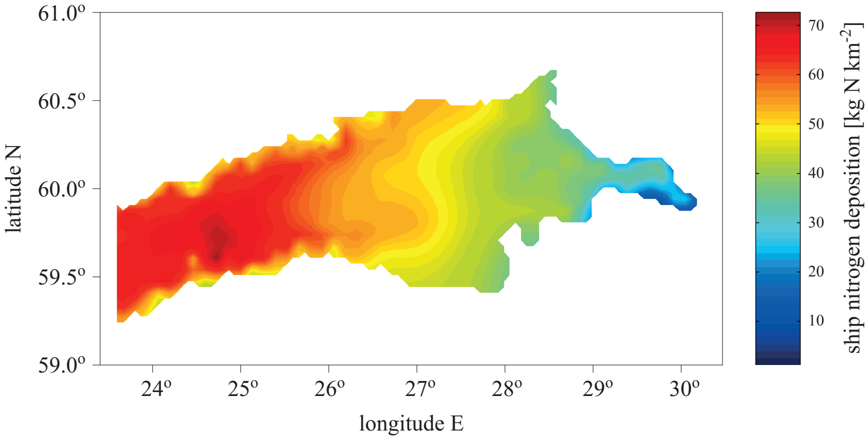

Figure 5. Distribution of annual ship nitrogen deposition [kg N km^{-2}] in the Gulf of Finland area in 2008

3.4. Impact of ship nitrogen deposition on phytoplankton primary production and nitrogen fixation by cyanobacteria

In the current version of the model, primary production is generated by three functional phytoplankton groups: diatoms, flagellates and nitrogen-fixing cyanobacteria. The annual primary production of diatoms and flagellates (spring bloom and post-bloom period) and late summer nitrogen fixation by cyanobacteria without ship nitrogen deposition was calculated for the Gulf of Finland water column (Figure 7). The total production (in nitrogen units) varied within the range of 220–264 kt N year^{-1}. The increase in primary production due to ship nitrogen deposition in the functional groups diatoms and flagellates varied within the range of 1–1.5 kt N year^{-1} (Figure 8), i.e. it did not exceed 0.7%.

The simulated nitrogen fixation for the Gulf water column without ship nitrogen deposition varied within a wide range, from 24.5 to 37.9 kt N year^{-1} (Figure 7) and the correlation with excess phosphate was relatively high, $r^2 = 0.4$. The inclusion of ship nitrogen deposition decreased the annual nitrogen fixation. The interannual decrease in nitrogen fixation due to ship nitrogen deposition varied within the range of 1–1.6 kt N year^{-1} (Figure 8). In some years, the relative decrease was as much as 6%. The calculated distribution of the 10-year mean differences in the nitrogen fixation rate (with ship nitrogen deposition minus without ship nitrogen deposition) in the Gulf of Finland showed the greatest decrease in the western and central Gulf (up to 65 kg km^{-2} year^{-1}), while in the eastern Gulf, the changes caused by ship nitrogen deposition were minor (Figure 9) owing to the high

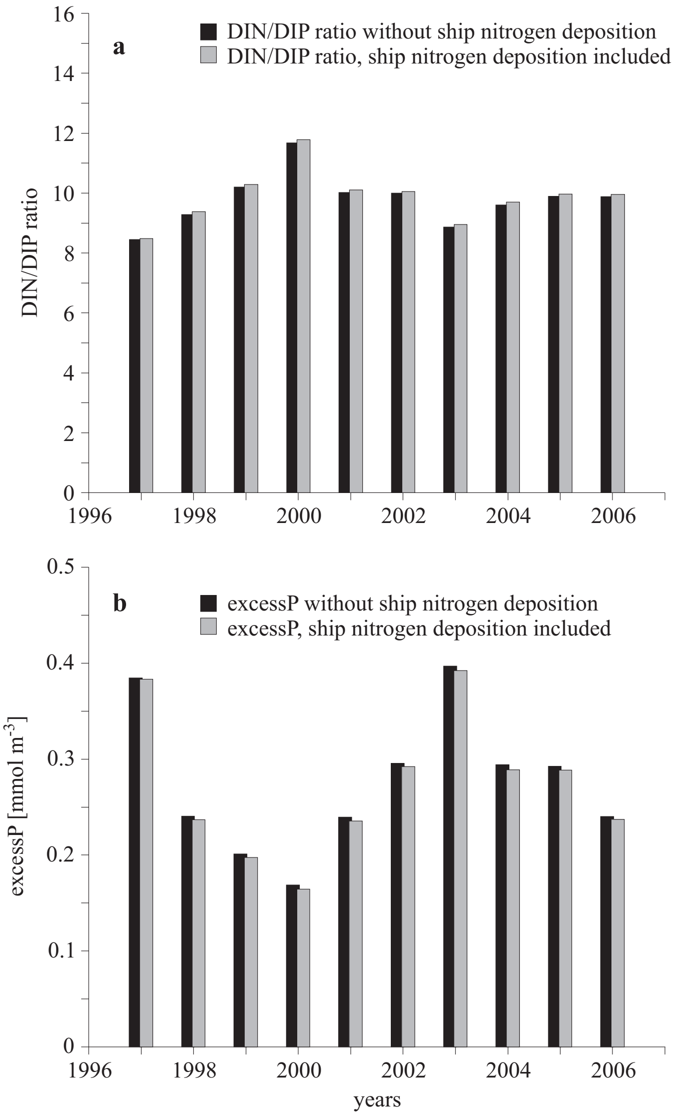

Figure 6. a) Mean winter ratio of dissolved inorganic nitrogen to phosphorus (DIN:DIP) and b) excess phosphate [mmol m^{-3}] in the upper 10 m water column in the Gulf of Finland. The black bars show the DIN:DIP ratio and excess phosphate without ship nitrogen deposition, the shaded bars show the DIN:DIP ratio and excess phosphate with ship nitrogen deposition included

DIN:DIP ratio of the riverine waters entering the Gulf of Finland in the east (e.g. HELCOM 2002). Also, the decrease in nitrogen fixation was less in the northern coastal zone of the Gulf than in the southern coastal zone.

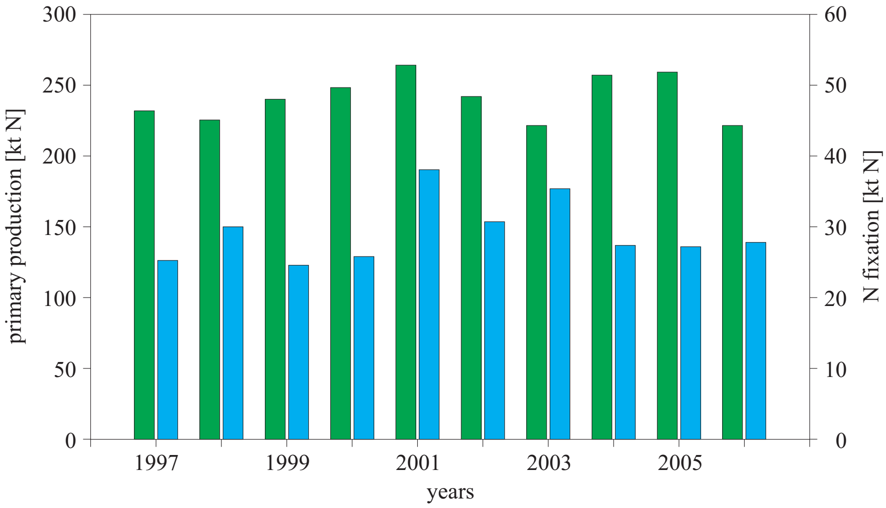

Figure 7. Annual primary production of diatoms and flagellates [kt N] and nitrogen fixation [kt N] by cyanobacteria without ship nitrogen deposition in the Gulf of Finland water column. The green bars indicate diatom and flagellate production, the blue bars indicate nitrogen fixation by cyanobacteria

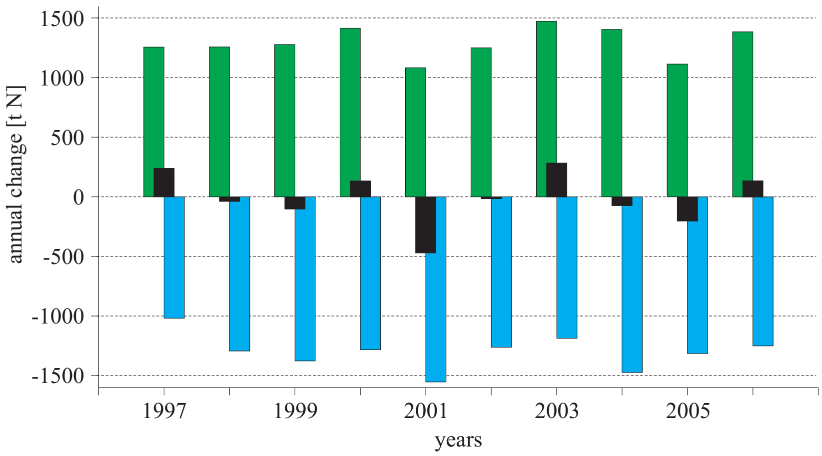

Figure 8. Changes in the annual primary production of diatoms and flagellates (green bars) and nitrogen fixation by cyanobacteria (blue bars) in the Gulf of Finland water column caused by ship nitrogen deposition. The black bars show the difference between the annual increase in primary production (diatoms and flagellates) and the decrease in nitrogen fixation by cyanobacteria

The difference between the annual increase in primary production (diatoms and flagellates) and the decrease in nitrogen fixation by cyanobacteria

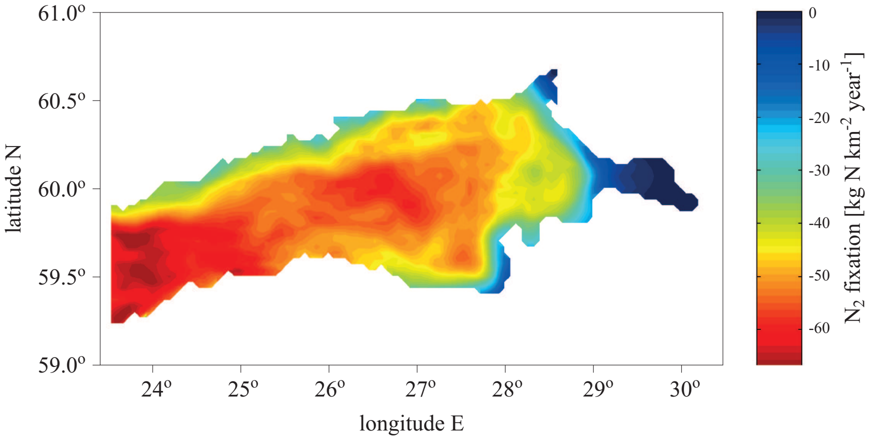

Figure 9. Distribution of 10-year mean differences of the nitrogen fixation rate (ship nitrogen deposition included minus ship nitrogen deposition excluded) in the Gulf of Finland

caused by the addition of ship nitrogen deposition was small (except in 2001) and with a variable sign (Figure 8).

4. Discussion

Ship nitrogen deposition during the winter months accumulates in the upper layer of the Gulf and is partly transported out of the Gulf as a result of the distinctly positive freshwater balance caused by the considerable river runoff. As expected, the physical and biogeochemical processes shaping the winter nutrient conditions in the upper layer of the Gulf and their interannual variability were clearly dominant, and ship nitrogen deposition changed the DIN:DIP ratio by less than 1% (Figure 6a). Starting in May, ship nitrogen deposition increased (Figure 4). Our simulations showed that the additional atmospheric nitrogen deposition due to shipping caused an increase in annual primary production in two functional groups – diatoms and flagellates – in the water column of the Gulf (Figure 7). However, the increase in annual primary production (up to 1.5 kt N year^{-1}) was minor compared to the natural level and variability ($< 1\%$).

Nitrogen fixation by cyanobacteria is an important source of new nitrogen in the Baltic Sea ecosystem. The initiation of cyanobacterial blooms in the Baltic Sea has been related to a low DIN:DIP ratio (e.g. Niemi 1979). Our simulations showed relatively low winter DIN:DIP ratios averaged over the Gulf area (compared to the Redfield ratio) varying interannually from 8.5 to 11.5 (Figure 6), which accords reasonably well with observations (HELCOM 2009). In the ERGOM ecological model, phosphate is assumed to be the only limiting nutrient for cyanobacteria (Neumann & Schernewski 2005). Therefore, the amount of excess phosphate is an important precondition for the summer cyanobacteria bloom. The annual nitrogen fixation correlated well with excess phosphate ($r^2 = 0.4$), which is comparable with the correlation between the peak cyanobacteria *Nodularia spumigena* biomass value and excess phosphate ($r^2 = 0.61$) estimated from field measurements (e.g. Laanemets et al. 2006). Thus, the interannual variability of winter nutrient conditions in the upper layer, sea surface temperature, nutrient transport into the upper layer by wind-induced mixing and upwelling events reproduced by the model all affect the interannual variability of the cyanobacteria bloom biomass. In addition to these major factors, the cyanobacterial bloom is slightly affected by ship nitrogen deposition. The small increase in primary production in two functional groups (diatoms and flagellates) due to additional nitrogen deposition reduced the already small available resources of phosphate in the upper layer for the summer cyanobacteria bloom. Simulations without ship nitrogen deposition showed that the interannual nitrogen fixation in the Gulf varied within the range of 24.5–37.9 kt N year^{-1} during the 10-year period (Figure 7), which is consistent with the simulations performed by Neumann & Schernewski (2008) in the Gulf of Finland area. The inclusion of ship nitrogen deposition decreased the nitrogen fixation to the range of 23.1–36.4 kt N year^{-1}. The maximum decrease was approximately 6%. No trend ($r^2 = 0.017$) was observed in the interannual changes of nitrogen fixation due to ship nitrogen deposition. Regionally, the effect of ship nitrogen deposition on the decrease in nitrogen fixation was greater in the western and central Gulf (Figure 9) where annual ship nitrogen deposition was also greater (Figure 5).

Thus, the simulations showed that the external input by ship nitrogen deposition was practically compensated for by the decrease in nitrogen fixation in the Gulf of Finland, where the species community consists of diatoms, flagellates and N_2-fixing cyanobacteria.

Finally, we present a possible future outlook. The use of after-treatment techniques, such as Selective Catalytic Reduction units, Exhaust Gas Recirculation and Water Emulsion equipment, will reduce NOx emissions from ships by over 80%. This limit is set as the minimum requirement of the NOx Emission Control Area (ECA) rules of the International Maritime Organization. Although the Baltic Sea is not yet declared as an ECA for nitrogen, it is very likely that an ECA will be established in the near future. So far, the only ECA for nitrogen exists in North American waters, extending 200 nautical miles from the coast. These limitations are likely to negate the increasing airborne nitrogen contribution from shipping because of annual traffic growth in the Baltic Sea. However, nitrogen reduction will only be applied to new ships and the full effect of ship nitrogen emission abatement is not expected to manifest itself until complete fleet renewal, which can take 25–30 years. Even so, this reduction requirement will affect just a small fraction of the total nitrogen emissions, because the contribution from shipping is less than 3% (Bartnicki et al. 2011).

5. Conclusions

Ten-year simulations with coupled hydrodynamic and ecological models showed changes in the annual phytoplankton biomass and nitrogen fixation by cyanobacteria as a result of neglecting or accounting for additional ship nitrogen deposition. Annual ship nitrogen deposition in the Gulf of Finland was 1.6 kt N, comprising about 12% of the total atmospheric deposition of oxidized nitrogen. The relative importance of ship nitrogen deposition was greater in summer, when it made up as much as 30% of the monthly atmospheric deposition of oxidized nitrogen. Ship nitrogen deposition caused an increase in the annual biomass of two functional groups (diatoms and flagellates), at the same time reducing phosphate resources. Annual nitrogen fixation fell as a result of ship nitrogen deposition by 1–1.6 kt N (2–6%). Thus, the additional ship nitrogen deposition was practically compensated for by a decrease in nitrogen fixation; this effect is insignificant compared with many other uncertainties. The effect of ship nitrogen deposition on nitrogen fixation by cyanobacteria was greater in the western and central Gulf of Finland. No trend in nitrogen fixation due to the possible accumulation of ship nitrogen deposition in the Gulf water column was observed.

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