Atmospheric forcing controlling inter-annual nutrient dynamics in the open Gulf of Finland

Jouni Lehtoranta, Oleg P. Savchuk, Jüri Elken, Kim Dahlbo, Harri Kuosa, Mika Raateoja, Pirkko Kauppila, Antti Räike, Heikki Pitkänen

A R T I C L E   I N F O

Article history:
Received 13 April 2016
Received in revised form 19 January 2017
Accepted 2 February 2017
Available online 8 February 2017

Keywords:
Baltic Sea
Wind
Atmospheric forcing
Hydrodynamics
Stratification
Salinity
Nitrogen
Phosphorus

A B S T R A C T

The loading of P into the Gulf of Finland has decreased markedly, but no overall trend in the concentration of P has been observed in the open Gulf, where the concentrations of both inorganic N and P still have a pronounced inter-annual variability. Our main aim was to study whether the internal processes driven by atmospheric forcing can explain the variation in the nutrient conditions in the Gulf during the period 1992–2014. We observed that the long-term salinity variation of the bottom water in the northern Baltic Proper controls that in the Gulf, and that the deep-water concentrations of oxygen and nutrients are significantly correlated between the basins. This imposes preconditions regarding how atmospheric forcing may influence deep water flows and stratification in the Gulf on a long-term scale. We found that over short timescales, winter winds in particular can control the in- and out-flows of water and the vertical stratification and mixing, which to a large extent explained the inter-annual variation in the DIN and TP pools in the Gulf. We conclude that the inter-annual variation in the amounts, ratios, and spatial distribution of nutrients sets variable preconditions for the spring and potential blue-green algae blooms, and that internal processes were able to mask the effects of the P load reductions implemented across the whole Gulf. The transportation of P along the bottom from the northern Baltic Proper and its evident uplift in the Gulf highlights the fact that the nutrient reductions are also needed in the entire catchment of the Baltic Sea to improve the trophic status of the open Gulf.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

A decrease in nutrient concentrations has been expected in the Gulf of Finland, as the loading of nitrogen (N) and phosphorus (P) into the basin has reduced markedly since the 1980s (Gustafsson et al., 2012; HELCOM, 2015b, Raateoja et al., 2016), but so far a decreasing trend in P concentrations has only been seen in the easternmost Gulf of Finland (Raateoja et al., 2016). In contrast to P, the concentrations of dissolved inorganic nitrogen (DIN) decreased in the open Gulf in the 1990s, which has been explained by the reduced loading of N in the late 1980s and early 1990s (Pitkänen et al., 2007; Raateoja et al., 2005). However, the reports show that the river and atmospheric loading of N into the Gulf have not decreased since the late 1990s (HELCOM, 2015a). We hypothesise that the discrepancy between the loads and nutrient status is explained by the changes in the internal factors controlling the transportation and behaviour of nutrients in the Gulf.

The shallow Gulf of Finland ecosystem captures a significant fraction of the available nutrients from the water column during spring bloom. The ‘fresh’ annually settled and ‘old’ accumulated organic matter mineralises in sediments. The settling matter controls the transportation of particulate organic carbon and nutrients into the sediments in the Gulf of Finland (Heiskanen, 1998; Lehtoranta et al., 2004). As a result, the sediments of the Gulf are rich in organic matter and nutrients (Lehtoranta and Pitkanen, 2003; Lukkari, 2008). Besides the high sediment concentrations, high benthic effluxes of dissolved inorganic carbon (DIC), DIN and dissolved inorganic phosphorus (DIP) have also been measured in the coastal and open Gulf (Lehtoranta, 2003; Lukkari et al., 2009; Viktorsson et al., 2012).

Sediment mineralisation processes such as denitrification and reduction of iron (Fe) and sulfate (SO4), coupled with cycling of P, have the potential to affect the amounts of nutrients in the water on a Gulf-wide scale (Hietanen and Kuparinne, 2008; Lehtoranta and Heiskanen, 2003; Lehtoranta and Pitkanen, 2003; Lukkari, 2008; Tuominen et al., 1998). The hydrodynamics controlling mixing and stratification strength may, in turn, affect the mineralisation and re-oxidation processes. The complete mixing of the water column...
keeps the dissolved oxygen \( (O_2) \) levels high, facilitating the coupled nitrification-denitrification process and re-oxidation of reduced Fe to P, binding Fe oxides. Therefore, the sediment under the non-stratified water column is capable of removing \( N_2 \) gas from the system and retaining P in sediments. In contrast, the strong vertical density stratification prevents the supply of \( O_2 \) to the bottom waters and leads to depletion of \( O_2 \) and \( NO_3 \) when sediment leaks \( NH_4 \) and P into the near-bottom water.

The Gulf of Finland is a dynamic system in terms of stratification characteristics. The lack of a sill between the Baltic Proper and the Gulf creates an open boundary facilitating the exchange of large volumes of water containing high levels of substances. The dependence of the exchange of water on wind conditions at the mouth of the Gulf is generally a known factor. The dominant winds from the west and south-west (hereafter WSW winds) push the surface water from the main basin into the Gulf in the coastal areas, and the compensating outflow is formed by the deep saline water flowing out through the halwag of the Gulf. Therefore, the stratification weakens or even collapses in a large part of the Gulf in winter (Elken et al., 2014; Lübliz et al., 2013). In the surface layers the upwelling of water is developed near the northern coast and downwelling near the southern coast (Haapala, 1994; Lehmann and Myrberg, 2008; Lehmann et al., 2012).

In contrast, the stratification is strengthened by the winds blowing from the east and north-east (ENE winds), which push the surface water out of the Gulf and the deep saline water in from the main basin. Upwelling occurs at the southern coast and downwelling at the northern coast (Lips et al., 2009). The easterly winds strengthen the estuarine stratification, which separates the surface and deep water layers from each other, hampering the downward transportation of \( O_2 \) and enabling the accumulation of substances in the deep water layers by preventing vertical mixing. Besides the dependence of the water exchange on wind, the fresh water inflow from the River Neva and the salinity (i.e. density) differences between the northern Baltic Proper (NBP) and the Gulf force an estuarine type of circulation in the mouth of the Gulf (Myrberg and Soomere, 2013). When density increases at the mouth, for example due to the Major Baltic Inflows (MBI), an inflow of deep water is also induced in the Gulf. The deepening of the halocline in the Baltic Proper, in turn, mediates the outflow of deep water from the Gulf. However, the formation of horizontal and vertical gradients of salinity, \( O_2 \) and nutrients in the main basin of the Baltic may take years, whereas in the Gulf the near-bottom salinity and the concentrations of \( O_2 \) vary considerably across much shorter time-scales, even within a day (Viktorsson et al., 2012).

Hence, atmospheric forcing has potential to regulate the formation and collapse of vertical density differences and, therefore, the availability of \( O_2 \) and nutrients in the Gulf (Lips et al., in press). A comprehensive study highlighting the atmospheric drivers behind the large variation in the salt, \( O_2 \) and N and P pools is lacking on the scale of the open Gulf.

The objective of this study is to shed light on how winter wind forcing may affect the hydrodynamics and the inter-annual behaviour of salt and nutrients, and how the variations in the amounts of nutrients may affect the ecosystem features in the Gulf. First, we demonstrate the variation in the concentrations of salt, \( O_2 \) and nutrients in the entire water column of the central Gulf and in the near-bottom waters at three monitoring stations along the east-west transect. We continue by looking into the correlations between the inputs of nutrients from the catchment and the nutrient pools in the Gulf. We then present the relationships between winter wind forcing and salinity, stratification strength and hypoxic area and investigate the correlations between the stratification strength and the nutrient pools. We highlight the importance of winter wind forcing in addition to the actual stratification at the boundary between the NBP and the Gulf by introducing two different time periods. Finally, we discuss the potential of the varying winter DIN and DIP pools in terms of affecting the fixation of carbon and nutrients in the Gulf.

2. Material and methods

2.1. Study area and description of monitoring stations

The Gulf of Finland is a sub-basin of the semi-enclosed Baltic Sea, with an area of c. 30,000 km², a mean depth of 37 m, a water volume of c. 1100 km³ and a maximum water residence time of c. 2 years (Andrejev et al., 2004). However, the residence time varies greatly in different parts of the Gulf, being the shortest at the entrance of the Gulf and the longest in the south-eastern area. The Gulf is influenced heavily by freshwater discharge, most notably from the River Neva, which accounts for almost 75% of the freshwater discharge into the Gulf, and by the saline water exchange between the Gulf and the NBP. The annual mean fresh water discharge is about 110 km³ a⁻¹, comprising about 10% of the total volume of the Gulf.

The site-specific data originated from three offshore stations, sampled mainly during R/V Aranda cruises four times a year. Station LL12 (82 m) is situated in the offshore area at the western brink of the Gulf, and in this context it serves as a baseline, i.e. as the station with the lowest nutrient content and representing a low direct land-based influence (Fig. 1). Stations LL7 (101 m) and F3 (80 m) are well placed to represent the middle parts of the Gulf. Station XN1 (64 m) is situated in the eastern Gulf at the brink of the offshore area and is more susceptible to vertical mixing than the deeper central and western stations LL7 and LL12. The data for the northern main basin was collected from the station BMB H2 (170 m). The winter surface values presented for the monitoring stations (see Fig. 11a-f below) include the period from December to March.

2.2. Analyses of salinity, oxygen and nutrients at reference stations

Water-column hydrography was investigated with an SBE 911plus conductivity, temperature and depth (CTD) system equipped with an SBE 13 Beckman \( O_2 \) sensor (Sea-Bird Electronics). The hysteresis effect of the sensor was compensated for in accordance with the manufacturer's instructions, and the output of the sensor was calibrated at one depth for each station against \( O_2 \) determination of the CTD’s rosette water sample. The \( O_2 \) concentration was determined by employing the Winkler technique with the Metrohm Titirin 702 SM (Metrohm AG) in accordance with Grasshoff et al. (1999), with the amendment that potentiometric endpoint recognition was used in the titration. Salinity was determined in accordance with Grasshoff et al. (1999) using a Guildline Autosal 8400B salinometer. The current measuring uncertainties (expanded uncertainty, U, including both sampling and analysis) of the wet-analytical methods are ±0.5% and ±6% for salinity and \( O_2 \), respectively.

The concentrations of \( PO_4 \), total P (TP) and \( NO_2 + NO_3 \) (henceforth NO) as the proportion of \( NO_3 \) was negligible were determined with a Skalar 5101 segmented flow analyser (1993–1999, Skalar Analytical), a Lachat QuickChem 8000 flow injection analyser (1999–2013, Lachat Instruments), and Seal Autoanalyser 3 continuous flow analyser (2014–, Seal Analytical). The outputs of the instruments were internally validated against each other and the concentration of \( NH_4 \) was determined using an indophenol method (Grasshoff et al., 1999). The current measuring uncertainties (expanded uncertainty, U, including both sampling and analysis) of the methods are ±15% for \( NO_3 \), ±21% for \( NH_4 \), ±23% for TP, and ±15% for \( PO_4 \). All the analytical methods above are internally accredited by the Finnish Environment Institute (SYKE, Marine Research Centre) in accordance with the requirements for an environmental testing laboratory, and inspected by the Finnish Accreditation Service (FINAS) in accordance with the SFS-EN ISO/IEC 17025 standard.
2.3. Calculations of the input of nutrients

Riverine export of nutrients was calculated by multiplying the mean monthly river flow by the mean monthly concentration in river water and summing up the monthly fluxes. In Finland and Estonia river flow is measured daily, whereas in Russia less data were available. Any missing monthly concentrations were substituted with mean seasonal or annual values. Estimations of point source loads were based on national regulations and vary by country and by point source load types (e.g., municipal, industrial or aquaculture). Annual loads of N originating from atmospheric deposition for the period 1995–2014 were modelled by the EMEP (The European Monitoring and Evaluation Programme). The version EMEP MSC-W was used for computations with a standard 50 × 50 km grid. A detailed description of different methodologies can be found in the HELCOM Guidelines for the annual and periodical compilation and reporting of waterborne pollution inputs to the Baltic Sea (HELCOM, 2015b).

2.4. Calculations of salt and nutrient pools

Marine data on salinity, O2 and nutrients available in the Baltic Environmental Database (BED, 2016) and in the Gulf of Finland Year 2014 dataset (GOF2014 dataset, 2015) were accessed using the Data Assimilation System DAS (DAS, 2016; Sokolov et al., 1997), and the ‘Marine distributed databases’ module of the Decision Support System Baltic Nest (Wulff et al., 2013). Integral annual pools and volume-weighted average concentrations for the entire Gulf of Finland and for the water volumes confined by O2 isosurfaces of 4 mL L\(^{-1}\) were computed from 3D gridded fields reconstructed with the DAS. The data extracted with the Nest tool for the entire Gulf of Finland marine area was pooled together within layers related to the standard sampling depths and averaged step-wise within a time window of 30 days. These average monthly vertical profiles were further used to plot the time-depth distribution of the parameters analysed, with the intervals between the profiles filled by interpolation. The winter DIN and DIP pools were calculated for the period January–April for 1995, 2001, 2004, 2007, and 2009 (see Fig. 13a – d below).

The peculiarities of DAS and Nest implementation are discussed in detail by Conley et al. (2002) and Savchuk (2010), and further facts, including time-specific data availability and distribution in the Gulf of Finland, can be found online with these tools. In the case of the Gulf, the most important are the uncertainties generated by year-to-year variations of the spatial and seasonal station distributions due to both modifications of monitoring programmes in surrounding countries and year-to-year variations in the number and programmes of the goal-oriented scientific cruises. For instance, the value of 4 mL O2 L\(^{-1}\) has been chosen as indicative for the oxygen-deficient conditions (‘hypoxic’) and corresponding nutrient distributions. Lower concentrations were experimentally found to be less reliable indicators of O2 deficit and nutrient pools for calculations performed on 3D fields built on a sparse and irregular station distribution over fairly irregular bottom topography. Generally, the total number of observations has increased from a few thousand horizons sampled annually in the 1970s to over ten thousand in the current century. Particularly well covered in the Gulf of Finland were the years 1996 and 2014, with samples taken from 27,166 and 24,835 horizons respectively. However, even in recent years data were not always available for all seasons, especially in the eastern Gulf of Finland. Furthermore, there was a high degree of variability in the quality of total N (TN) measurements between the analysing laboratories; therefore these measurements were not included in the pool calculations.

2.5. Calculations of mean wind speed and changes in stratification

Salinity, temperature and density fields were generated on the basis of HELCOM monitoring data downloaded from the International Council for the Exploration of the Seas database (ICES, Accessed Jan, 2016). Among the fixed monitoring stations, sampled in time at irregular intervals, we chose the station BMP F3 (water depth 80 m, <2 km from LL7, see Fig. 1) as representative of the central and western parts of the Gulf. Regarding the impacts from the outer northern Baltic Proper, we chose the station BMP H2. Due to the sparse datasets at exact locations during some periods, we extended the data search intervals as follows: from 24.0 E to 25.4 E and from 59.3 N to 60.3 N for station BMP F3 and from 20.4 E to 21.8 E and from 58.6 N to 59.6 N for BMP H2 (see Fig. 1). We added also some Estonian data from the research cruises, which had not yet been submitted to the public databases. Overall, this search procedure resulted in >12 oceanographic stations per year with the exception of 2006 and 2009, where late autumn data were lacking.
Irregular data, both in time and depth, were interpolated on a regular grid with the grid steps one month in time and 1 m in depth. For this procedure we used optimal interpolation (Toompuu and Wulff, 1995, 1996) using an exponentially decaying correlation function with e-folding scales of 0.65 years and 30 m. The number of nearest points was limited to 30 and a noise-to-signal dispersion ratio of 0.2 was used in order to allow some smoothing of data in the oversampled intervals. The stratification strength was calculated from the deep to surface density difference as in Laine et al. (2007) and Väli et al. (2013). Mean seasonal salinity, temperature and density characteristics were derived by averaging monthly gridded data over 3 appropriate months (December to February for winter and June to August for summer). The long-term trend (low-frequency variations) was determined by applying a cosine-type low-pass filter with length of 4 years (see Väli et al., 2013).

For the wind forcing analysis we used the data from 3-hourly observations provided by the Finnish Meteorological Institute from the Island of Utö meteorological station since 1961. The station is located in the entrance area to the Gulf. Regarding average wind fields, it also represents the western and central Gulf and the NBP. We calculated monthly mean zonal (westerly) and meridional (southerly) wind speed components as well as appropriate wind stress components using the common quadratic formulae. We found that monthly mean wind speed components correlated very well with wind stress components: $R^2 = 0.95$ for the zonal wind (westerly) and $R^2 = 0.90$ for the meridional (southerly) wind, and for the sake of intuitive reading we used wind speed in the analyses. The linear relation between the monthly mean values is probably caused by the particular wind statistics near the Gulf of Finland. The period December–January showed the best relation with winter density stratification when different options were tested.

We chose the time period 1992 to 2014 to study the relationships between wind forcing, hydrodynamics and salt and nutrient pools because a) there has been a marked decrease in the loading of P from the catchment, b) the spatial and temporal coverage of the salt and nutrient measurements is large enough for the pool calculations, and c) the period includes two different stratification regimes at the boundary between the NBP and the Gulf.

2.6. Potential of spring bloom to fix carbon and blue-green algae to fix nitrogen and carbon from the winter inorganic N (DIN) and P (DIP) pools

The potential for spring bloom and blue-green algae carbon fixation was based on estimates of new production by spring NO3 uptake and by summer N2 fixation (Dugdale and Goering, 1967). It was not possible to take the effects of advection or horizontal transfer of inorganic nutrients into account in the calculations. In our calculations we assumed that both carbon and N2 fixation occur according to the Redfield ratio C:N:P (106:16:1). The spring bloom estimate was based on limitation by the availability of inorganic nitrogen, the main source of which is NO3 that has accumulated in the water column during winter (Lignell et al., 1993). The water column data suggests that the consumption of DIN by spring bloom leads to its depletion from the surface down to 30 m (see Fig. 2c below), and the fixation of carbon can be calculated with the Redfield ratio given above for that water volume according to its total DIN content. As the wintertime DIN:DIP ratio is below the Redfield ratio, excess DIP is left in water column after spring bloom (Raateoja et al., 2011). The amount of excess DIP was calculated according to the Redfield ratio from winter inorganic nutrient concentrations, assuming DIN to be totally exhausted. Due to thermal stratification, available DIP is consumed mainly from the surface down to 15 m in the Gulf of Finland during summer. Thus, both N2 and carbon fixation were calculated with the Redfield ratio for that water volume according to its total DIP content.

3. Results

3.1. Variation of salinity, oxygen and nutrients in the water column

As demonstrated by the long-term evolution of the oceanographic conditions (Fig. 2a – d, left panels), the water freshening of the 1980s with improved oxygenation of deep layers has turned into an overall increase in salinity and decrease in O2 concentration with a simultaneous increase in the concentrations of DIP in the near-bottom water from the mid-1990s to 2014. Furthermore, near-bottom water salinity and the concentrations of O2 and nutrients have varied markedly over the years. Besides the decadal and the inter-annual variation, the following seasonal pattern is seen in salinity, O2, and nutrients. During winter near-bottom salinity was at its lowest and the water column was fairly well mixed (Fig. 2a). In spring NO3 was depleted and a large proportion of DIP was removed from the surface waters (Fig. 2c and d). In summer the deep water concentrations of O2 and NO3 decreased whereas those of DIN and NH4 increased. Early winter showed an increase in NO3 in the surface water (Fig. 2c) and the mixing that usually started in late January ventilated the deep water layers again (Fig. 2b).

In the near-bottom waters the lowered salinity was associated with high concentrations of O2 and NO3 and low concentrations of DIP and NH4 (see the a-line Fig. 3). In contrast, high near-bottom salinity in summer was reflected in reduced concentrations of O2 and NO3 and elevated concentrations of DIP and NH4 (the b-line in Fig. 3). Besides these two occasions, all of the concentrations were significantly and similarly correlated with each other at all three stations along the east-west transect, with the exception of salinity vs NO3 at station X VI (Table 1).

3.2. Variation in annually averaged salt and nutrient pools

The mean annual nutrient pools varied significantly from year to year in the Gulf (Table 2). The salt pool was more stable, but clear variations were still observed. The highest mean annual DIN pool was three times larger and those of TP and DIP about two times larger to their smallest annual pool (Table 2). The great variability in the N and P pools was seen in the molar DIN:DIP ratio which ranged from 4 to 16. The DIN pool varied more than that of DIP and the DIN pool explained 65% ($p < 0.0001$) and DIP 38% ($p < 0.0016$) of the variation in the DIN:DIP ratio.

The averages of year-to-year fluctuations calculated over the period 1992–2014 indicated that there were only minor long-term changes in the salt, DIN, TP, and DIP pools during the period (mean change for salt $–7 \times 10^2$ t; $–80$ t for DIN; $+150$ t for TP; and $+10$ t for DIP). In contrast, the inter-annual change calculated for consecutive years showed high negative and positive values, indicating the ability of the system to deplete and replete the pelagic DIN, TP and DIP pools within a period of one year. For example, the DIN pool increased by about 46,600 t from 2004 to 2005 but was diminished by an almost comparable amount of 47,200 t from 2006 to 2007. For TP, the maximum increase in the pool was 7700 t from 1996 to 1997 and the maximum decrease 4600 t from 2011 to 2012 (Table 2).

The changes in the overall salt and nutrient pools between the years (Fig. 4a, b, c) were parallel to those in the near-bottom water (Table 1, Fig. 3). The changes in the salt pool were positively correlated with the changes in the TP pool and negatively correlated with the DIN pool and molar DIN:DIP ratio. However, the correlations were not statistically significant due to the high variability. It was notable that the changes in the DIN and DIP pools were poorly correlated (Fig. 4d).

3.3. Inputs of nutrients and nitrogen and phosphorus pools in water

The annual input of TN varied between 91,600 and 134,000 t a$^{-1}$ and exceeded the size of the mean annual DIN pool consistently for the period 1993–2013 (Fig. 5a). The annual input from the catchment and atmosphere may thus significantly contribute to the DIN pool, which varied
between 32,600 and 96,000 t in the water of the Gulf. The input of TN was strongly correlated with the river discharge ($R^2 = 0.83$, $p < 0.0001$) linking climate controlled precipitation on the catchment to the input of N. However, the annual input of N could not explain the large variation in the mean annual DIN pool found in the Gulf ($r = -0.006$, $n = 20$).

In contrast to TN, the annual load of TP was lower by far than the TP and DIP pools in the water (Fig. 5b). The input varied between 5800 and 8150 t during 1994–2014. During the same period the TP pool varied between ~18,000 and 35,000 t and that of DIP between ~10,000 and 23,000 t. There was a large reduction in the municipal point-source loads of TP, from 1560 to 370 t a$^{-1}$ from 2004 to 2013, mostly due to improved waste water purification in St Petersburg (Räike et al., 2016). The total annual load of TP has decreased by 3500 t when the improved waste water treatment and improvements carried out at the fertiliser factory in the catchment of the Luga River are summed up (not shown in Fig. 5b, Räike et al., 2016). The input of TP was positively, but not significantly, correlated with the river discharge ($R^2 = 0.15$, $p > 0.09$). This indicated the uncertainties in the original P data from the Neva River (Pitkänen et al., 2007). Even after using elaborated inputs of P (Fig. 5b) the correlation between input of TP and the TP pool in the water of the Gulf was poor ($r = -0.047$, $n = 20$). Hence, the annual inputs of both TN and TP were not significantly correlated with the variation in the mean annual DIN and TP pools in the water column.

3.4. Stratification and mean winter wind speed in relation to variation in salt and nutrient pools

The river discharge into the Gulf varied considerably over the years in question, but it was poorly related to the long-term changes in stratification strength (Fig. 6a). The stratification strength, expressed here as density difference between the deep and surface water layers, revealed a distinct seasonal cycle: it always increased from winter towards summer and decreased during autumn (Fig. 6b). Furthermore, the stratification strength has increased since the mid-1990s due to a large MBI in 1993, which ended the long stagnation period that had formed in the 1980s in the main basin. The stratification strength in the Gulf reached the level observed in the 1970s (not shown). We found that the low stratification strength in winter created potential for its marked increase towards summer as indicated by their mutual correlation ($r = -0.512$, $p < 0.05$, Table 3). The increase in stratification strength also correlated very well with the increase in deep-water salinity ($r = 0.92$, not shown). Thus, the salinity created the main seasonal pattern in stratification strength, although the seasonal warming and cooling of surface water also plays a role in the Gulf.

The trends in the stratification strength were well correlated between the NBP and the Gulf (Fig. 6b and c), with the density and salinity of the deep water of the NBP also well correlated with those in the Gulf (Figs. 6c and 7a). There was a close relationship in the concentrations of $O_2$ between the deep waters of the NBP and the Gulf (Fig. 7b), and concentrations of phosphate were also correlated, but in general the deep-water concentrations were markedly higher in the Gulf than in the NBP (Fig. 7c). There was a significant, but rather poor correlation between the deep water concentrations of $NO_3$ and the concentration was commonly higher in the Gulf than in the NBP (Fig. 7d).

Wind forcing is one of the factors affecting stratification strength. Indeed, the mean wintertime WSW winds that usually cause weakening of estuarine stratification due to the topography of the Gulf decreased the stratification strength in winter ($r = -0.649$, $p < 0.01$, Table 3).
Furthermore, the high WSW wind speeds decreased the annual mean salt pool, whereas the winter ENE winds allowed the pool to increase in the Gulf ($r = -0.537, p < 0.01$, Fig. 8). The removal of years of large MBIs (see Fig. 6b) from the analysis changed the correlation between wind and salt only slightly ($r = -0.48, p < 0.04$, not shown). The significant correlations between wind and salt were maintained even after the removal of years 1 or 2 years after the MBIs ($r = -0.65, p < 0.001$ and $r = -0.49, p < 0.04$, respectively). The winter wind speed and direction explained the stratification strength well (Fig. 9a). Wind speed was positively correlated with the changes in DIN and negatively with those in DIP, but not significantly (Fig. 9b–c). The wind speed was positively correlated with changes in the DIN:DIP ratio (Fig. 9d).

Furthermore, the salt pool correlated positively with winter stratification strength and negatively with the increase in strength from winter to summer ($r = 0.430, p < 0.05$ and $r = -0.351, p < 0.01$, respectively). The extent of the annual mean hypoxic area correlated negatively with the winter wind speed ($r = -0.636, p < 0.05$, Fig. 10a) and positively with the winter stratification strength ($0.454, p < 0.05$, Table 3). The increase in the salt pool correlated negatively with both the DIN pool and the DIN:DIP ratio of the pools ($r = -0.482, p < 0.05$, and $r = -0.491, p < 0.05$, respectively), but it was not correlated with that of TP ($r = 0.283, p < 0.191$).

It was also notable that the variables correlated differently with the DIN and TP pools and pool changes from the previous year. The year 2007 was exceptional regarding DIN, therefore DIN data was excluded from the statistical analyses for the year and is discussed in Section 4.3. The change in the DIN pool was positively correlated with the change of stratification strength from winter to summer ($r = 0.483, p < 0.05$). The highest correlation was found between the winter-time deviation from the trend in stratification strength from its 4-year low-pass filtered values in the Gulf (stratification strength presented in Fig. 6b) and the change in the DIN pool (Fig. 9e). In contrast to DIN, the TP pool correlated positively with the winter stratification strength ($r = 0.439, p < 0.05$, Table 3) and with a confidence interval of slightly over 5%, covering the extent of the hypoxic area in the Gulf ($r = 0.410, p < 0.051$, Table 3, see Fig. 10b).

---

Fig. 3. Variation of a) salinity and concentrations of b) oxygen, c) phosphate, d) sum of nitrite and nitrate, and e) ammonium in near-bottom water along the east-west transect (stations XV1, LL7 and LL12). Vertical line a denotes heavy WSW winds caused by a storm event at the beginning of January 2005 and line b strong, long-lasting ENE winds in August 2006.
4. Discussion

4.1. Explanations for the behaviour of nutrients and correlations between salinity, oxygen, and nutrients

The change in stratification strength from winter to summer – which also correlated with DIN – was positively related to the DIN:DIP ratio ($r = 0.678$, $p < 0.01$). The winter stratification strength, which correlated with the TP pool, was, in turn, negatively related to the DIN:DIP ratio ($r = -0.480$, $p < 0.05$). However, the hypoxic area, which correlated with the TP pool, was associated poorly with the changes in the DIN:DIP ratio ($r = -0.173$, $p < 0.442$).

The winter surface concentration at the easternmost station, XVI, multiplied by the volume of the Gulf provided a good explanation for the stratification strength from winter to summer (see Fig. 11c and d). In contrast to DIP, the mean annual DIN pool was well explained by the winter surface concentrations of the station XL12, but not by those measured at the easternmost station, XVI (Fig. 11c–e). The best fit was found when the mean winter surface concentration of stations XL12, LL7 and XVI was used in calculations (Fig. 11f).

Table 1

Correlations between salinity, concentrations of oxygen ($O_2$), sum of nitrate-nitrite ($NO_3$), ammonium ($NH_4$) and phosphate ($PO_4$) in near-bottom water at monitoring stations XL12, LL7 and XVI. All station-specific data and sampling dates available for years 1994 to 2014 were used in analysis (all four parameters were measured for XL12 in 1994; LL7 in 48; XVI n = 260; statistical significance: *p < 0.01; **p < 0.001).

<table>
<thead>
<tr>
<th></th>
<th>$O_2$</th>
<th>$NO_3$</th>
<th>$NH_4$</th>
<th>$PO_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>XL12 salinity</td>
<td>$0.910^{**}$</td>
<td>$-0.490^{**}$</td>
<td>$0.435^{*}$</td>
<td>$0.820^{**}$</td>
</tr>
<tr>
<td>LL7 salinity</td>
<td>$0.316^{*}$</td>
<td>$-0.434^{*}$</td>
<td>$0.889^{**}$</td>
<td>$-0.899^{**}$</td>
</tr>
<tr>
<td>$NH_4$</td>
<td>$-0.622^{**}$</td>
<td>$-0.396^{**}$</td>
<td>$-0.363^{**}$</td>
<td>$0.636^{**}$</td>
</tr>
<tr>
<td>XVI salinity</td>
<td>$-0.690^{**}$</td>
<td>$0.006^{*}$</td>
<td>$0.418^{*}$</td>
<td>$0.620^{**}$</td>
</tr>
<tr>
<td>$O_2$</td>
<td>$0.223^{**}$</td>
<td>$-0.456^{**}$</td>
<td>$0.828^{**}$</td>
<td>$0.174^{**}$</td>
</tr>
<tr>
<td>$NO_3$</td>
<td>$-0.256^{**}$</td>
<td>$0.174^{**}$</td>
<td>$0.622^{*}$</td>
<td>$0.174^{**}$</td>
</tr>
</tbody>
</table>

The close simultaneity in the changes in the concentrations and the similarity in the correlations at the stations along the east-west transect of the Gulf since the temperature decrease from the surface to bottom from 15 to 5 °C yields density increase in ~1 kg m$^{-3}$ whereas typical change in salinity from 5 to 10 g kg$^{-1}$ results in about 4 times larger increase in density. Also, the stratification strength correlated very well with the deep-water salinity ($r = 0.92$, not shown). The stratification formed is unfavourable in the sense that it decreases the ventilation of $O_2$ from the surface to the bottom drastically. Dissolved $O_2$ in turn, exerts a significant degree of control over the re-oxidation of reduced substances such as $NH_4$, Fe$^{II}$, H$_2$S, CH$_4$ and thus on the mineralisation pathways of organic matter in sediments and in deep water through respiration of $O_2$, $NO_3$ and Fe(III) oxides. The negative correlation found between salt and $O_2$, and the positive one with $NH_4$ and DIP is established when the consumption and depletion of $O_2$ severely diminishes the re-oxidation of the reduced substances above. Subsequently, the concentrations of DIP and $NH_4$ in the bottom water increase (see Fig. 3).

Secondly, the correlations between salinity and nutrients can be established in the main basin on the basis of the physical and biogeochemical processes presented above. Therefore, the saline deep water flowing from the NBP into the Gulf may contain high concentrations of DIP and low concentrations of $O_2$ (see Fig. 7a–c). Furthermore, the bottom of the Gulf consumes $O_2$ and releases DIP into the water because, in general, the comparable deep-water salinity values result in lower $O_2$ and higher DIP values in the Gulf than in the NBP (Fig. 7b–c). The variation in the physical and biological processes regulating the concentrations of salt and $P$ means that salinity has only a transient ability to be used as a proxy for the concentration of $P$ in the deep water. Overall, the biogeochemical processes during the stratification in the Gulf itself and the import of salt and nutrients from the main basin explained the correlations found between salt and $NO_3$, $NH_4$, and DIP in long-term data.

However, the stratification strength fluctuates on a spatial, seasonal and inter-annual scales in the Gulf. The breakdown of stratification by storms occurring commonly in winter can change the nutrient conditions in bottom waters in short time scales. For example, winter storm Gudrun in January 2005 created heavy WSW winds (see mean winter wind speed in Fig. 8), which resulted in low near-bottom salinity and oxygen. The NO$_3$ produced in oxidation of NH$_4$ through improved O$_2$ conditions is largely mixed into the water column or removed as N$_2$ gas (Tuominen et al., 1998; Hietanen and Kuparinen, 2008). Additionally, the oxidation of the surface sediment may enhance the trapping of DIP in surface sediments in the Gulf (Ekeroth et al., 2016). Therefore, the improved O$_2$ conditions change the behaviour of inorganic N species and reconstitute the ability of the sediment to reload its pool. The oxidised sediment releases only minor amounts of P and relatively little P accumulates in the near-bottom water in the Gulf. In August 2006 the stratification was strengthened again by unusually strong and long-lasting ENE winds, which caused upwelling at the Estonian coast and led to low concentrations of O$_2$ and high concentrations of DIP and NH$_4$ (b-line in Fig. 3, see Lips et al., 2009).

Table 2

Mean, minimum (min), maximum (max), and standard deviation (SD) for pool of salt (as 10$^9$ t), and pools of DIN, TP and DIP (as tonnes) for study period 1992–2014. DIN:DIP is presented as mol:mol. The dSalt, dDIN, dDTP, dDIP and dDIN:DIP denote a change in pool as tonnes from year to year (for salt as 10$^9$ t).

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Salt</th>
<th>DIN</th>
<th>TP</th>
<th>DIP</th>
<th>DIN:DIP</th>
<th>dSalt</th>
<th>dDIN</th>
<th>dDTP</th>
<th>dDIP</th>
<th>dDIN:DIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>5490</td>
<td>64,000</td>
<td>27,600</td>
<td>16,200</td>
<td>9.2</td>
<td>-7</td>
<td>-80</td>
<td>150</td>
<td>10</td>
<td>-0.03</td>
</tr>
<tr>
<td>Min</td>
<td>5230</td>
<td>32,600</td>
<td>18,000</td>
<td>9600</td>
<td>4</td>
<td>-320</td>
<td>-47,200</td>
<td>-4590</td>
<td>-5270</td>
<td>-8</td>
</tr>
<tr>
<td>Max</td>
<td>5810</td>
<td>96,400</td>
<td>34,700</td>
<td>22,600</td>
<td>16</td>
<td>430</td>
<td>46,600</td>
<td>7750</td>
<td>8370</td>
<td>6</td>
</tr>
<tr>
<td>SD</td>
<td>180</td>
<td>18,800</td>
<td>4350</td>
<td>3600</td>
<td>3.4</td>
<td>222</td>
<td>25,000</td>
<td>3640</td>
<td>3890</td>
<td>3.3</td>
</tr>
</tbody>
</table>
(see Table 1, Fig. 3a–e) indicated that the imports from the main basin, stratification and processes influencing nutrients in sediments had a basin-wide impact on the salt and nutrient conditions in the bottom waters of the Gulf. The DIN pool controlled the DIN:DIP ratio more than DIP, i.e., an occasional low DIN pool may favour the excess of DIP potentially left for blue-green algae. Furthermore, the statistics of year-to-year changes over the study period (see Table 2) indicate that the variations in both DIN and P were reversible. In other words, there was no negative or positive bias in the DIN and TP pools and the pools only varied strongly round the mean value calculated for 1992–2014.

4.2. Input of nutrients and nutrient pools in water

The input of TN from the catchment and DIN pool in the water are not directly comparable. However, about 35–75% of the riverine export, 75% of the atmospheric deposition, and a large but variable proportion

Fig. 4. The relationships between the change in the mean annual salt pool and a) the TP pool, b) the DIN pool, c) the DIN:DIP ratio of the pools and d) the relationship between the change in DIN and DIP pools during the period 1992–2013.

Fig. 5. a) River, point source and atmospheric inputs of TN compared to the DIN pool and b) river and point source inputs of TP compared to TP and DIP pools in the water column of the Gulf of Finland.
of the point source loads of TN are in the form of DIN (HELCOM, 2011). Therefore, the large loads of TN from the catchment can explain a significant proportion of the DIN pool (see Fig. 5a). However, there was only poor correlation between inputs and pools. The renewal of the DIN pool, starting from the surface waters in early winter (Fig. 2c), suggests that the bulk of the replenishing can be explained by the input of N from the catchment and the atmosphere. Laukkanen et al. (2007) have calculated that for the Finnish coastal region of the Gulf the residual value for inorganic N from year-to-year was zero, which for N indicated that the DIN pool was completely depleted from the coastal waters in one year and the input from the catchment was needed to replenish the DIN pool. However, the release of DIN from the bottom is also likely to contribute markedly to the DIN pool annually. Based on a 9000 km² accumulation area and the flux measurements carried out by Lehtoranta (2003), the gross annual benthic efflux of DIN may vary between 35,000 to 76,000 t N a⁻¹ in the Gulf.

In contrast to N, the annual input of TP from the catchment is insufficient to control the inter-annual increase in the mean TP pool up to a maximum of ~8000 t in the water column (see Table 2, Fig. 5b). Furthermore, the renewal of the P pool starts from the deep water as early as the summer (see Fig. 2d). The renewal of the P pool is evidently explained by internal processes, i.e. (1) the re-release from the bottom.

Table 3
Pearson correlations for mean winter wind speed (Dec-Jan period) at Uti Island meteorological station, winter stratification strength, change in stratification strength from winter to summer, hypoxic area (bottom area covered by water with O₂ < 4 ml L⁻¹), mean annual pool of DIN, change in pool of DIN from previous year, mean annual pool of TP, change in pool of TP from previous year. The number of observations was 23 (i.e. years from 1992 to 2014, symbols denote ** p < 0.01 and * p < 0.05). The year 2007 was excluded from analysis for DIN (c.f. Section 4.3).

<table>
<thead>
<tr>
<th></th>
<th>Stratification strength (kg m⁻³)</th>
<th>Change in stratification strength (kg m⁻³)</th>
<th>Hypoxic area (km²)</th>
<th>DIN pool (tonnes)</th>
<th>Change in DIN pool (tonnes)</th>
<th>TP pool (tonnes)</th>
<th>Change in TP pool (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed (m s⁻¹)</td>
<td>−0.649**</td>
<td>0.359</td>
<td>−0.636*</td>
<td>0.019</td>
<td>−0.236</td>
<td>−0.236</td>
<td>−0.278</td>
</tr>
<tr>
<td>Stratification strength (kg m⁻³)</td>
<td>−0.512*</td>
<td>0.454*</td>
<td>0.387</td>
<td>−0.322</td>
<td>0.383</td>
<td>0.439*</td>
<td>0.012</td>
</tr>
<tr>
<td>Change in stratification strength (kg m⁻³)</td>
<td>−0.019</td>
<td>−0.241</td>
<td>−0.219</td>
<td></td>
<td></td>
<td>0.410*</td>
<td>0.278</td>
</tr>
<tr>
<td>Hypoxic area (km²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIN pool (tons)</td>
<td>0.576**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change in DIN pool (tons)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.283</td>
<td>0.168</td>
</tr>
<tr>
<td>TP pool (tons)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.395</td>
<td></td>
</tr>
</tbody>
</table>
of the Gulf and (2) the import of P-rich deep water from the NBP. These internal factors may explain the variation of the winter DIP pool from 19,000 to 37,000 t within a few years (see Fig. 13b) almost independently of the annual input from the catchment.

Our study was not able to distinguish between the proportions of P released from the bottom of the Gulf and that imported from the main basin to the Gulf, and this calls for further research. However, the correlation in deep-water P between the Gulf and the NBP indicated that a marked proportion of the P originates from the NBP (see also Lips et al., in press). The release from the bottom of the Gulf, in turn, can explain why the deep-water concentration of P with the same salinity was higher than that in the NBP. The studies published highlight that both release of P from the bottom and exchange of P with the main basin may have a marked effect on the P pool in the Gulf. For example, Lehtoranta (2003) has estimated that the gross release of DIP from sediments could vary between 4000 and 18,000 t a\(^{-1}\) depending on the oxygen conditions in the Gulf. Lukkari (2008) has estimated that the long-term average net release of P from the anoxic sediments could be 1900 t P a\(^{-1}\). Occasionally an annual enrichment of P up to 10,000 t a\(^{-1}\) can be explained by both the net release from the bottom and the net exchange with the Baltic Proper (Pitkänen et al., 2003). The estimate provided by Viktorsson et al. (2012) for the benthic efflux of P is up to 66,000 t P a\(^{-1}\) and is notably higher than the other estimates, and would require a marked sequestration of P to the shallow bottom of the Gulf or an export of P from the Gulf to the main basin. The nutrient budgeting approach, in turn, has suggested that the long-term import–export conditions may vary at the entrance of the Gulf. For example, in 1991–1999 the average net P import from the main basin was 1300 t P a\(^{-1}\) (Savchuk, 2005), but in 2001–2010 the Gulf exported 1600 t a\(^{-1}\) (Savchuk, unpubl.).

To summarise, there is great inter-annual variation in the DIN and TP pools and neither the inputs of TN nor TP from land are able to explain the variation. The discrepancy found between the inputs and pools suggests that the internal dynamics in the Gulf itself and the Baltic Proper exert a significant degree of control on the inter-annual variations in the nutrient pools.

4.3. Atmospheric forcing on stratification and salt and nutrient pools

The examination of the meteorological forcing opened a new avenue to study how wind forcing and large-scale hydrodynamics regulate the variation in the salt, N and P pools. It is known that westerly winds in the Baltic Sea region are positively correlated with the North Atlantic Oscillation index, representing the status of large-scale atmospheric circulation over the Northern Atlantic, especially during the winter, see e.g. Lehmann et al. (2011), Rutgersson et al. (2014), and Rutgersson et al. (2015). Our study proved the earlier concepts that strong winter WSW winds weaken and ENE winds strengthen the winter stratification in the Gulf (see Fig. 9a). The wind forcing did not explain the variation in the pools of nutrients directly (see Fig. 9b–c), but we were able to develop a general picture of the short-term winter wind forcing on the salt pool and stratification and subsequently link the stratification strength and hypoxic area to the inter-annual variation in the nutrient pools in the whole Gulf.

The MBIs (see Fig. 6b) affect the salinities in the NBP, but do so slowly. The strong correlation between the stratification strength (Fig. 6b)
Fig. 9. Mean winter wind speed for Utö meteorological station (positive values WSW winds and negative values ENE winds) and a) strength of stratification at the centre of the Gulf of Finland, b) change in the DIN pool, c) change in TP, d) change in the molar DIN:DIP ratio and e) wintertime deviation from the trend of stratification strength (shown in Fig. 6b) and change in the DIN pool for the period 1992–2013. The year 2007 is marked with asterisk beside the symbol.

Fig. 10. a) Mean winter wind speed and hypoxic area (O$_2$ < 4 mL L$^{-1}$) and b) hypoxic area and mean annual TP pool in the Gulf of Finland in 1992–2013.
and densities in the NBP and the Gulf (Fig. 6c) showed that the changes in the NBP affect density and stratification in the Gulf. However, despite this relationship the winter wind was estimated to be the main regulator of the stratification strength and the mean annual salt pool in the Gulf. Therefore, the signals of MBIs do not appear in the Gulf as distinct events as in the Gotland Deep, because there is a sequence of buffering basins along the route saline water takes into the Gulf. However, MBIs affect the salinity by demonstrating a delayed and smooth change of stratification strength and mean deep-water salinity in the Gulf.

The year-to-year control of salt by the winds across MBIs is created when the commonly occurring strong winter WSW winds push surface water from the NBP into the Gulf with salinity values close to those in the Gulf, and the salt wedge can be withdrawn and decrease the amount of salt in the Gulf (see negative correlation in the inner scatter plot in Fig. 8). In contrast, easterly ENE winds may push surface water out from the Gulf and the outflow can be compensated for by the inflowing deep and saline water which increases the amount of salt and enhances the stratification in the Gulf.

The winter wind forcing regulated the stratification strength (see Table 3). The high winter WSW wind speed was related to weak stratification, whereas the mild winter WSW winds were likely to maintain the stratification in the Gulf. Even the modest winter ENE wind speeds, in turn, seemed to increase the import of deep water from the main basin and simultaneously strengthen the stratification and extend the hypoxic area of the Gulf (see Fig. 10a). The ENE winds may, therefore, import P from the main basin into the Gulf and expand the hypoxic area, which increases the release of P from the bottom (see Fig. 10b). However, the ENE wind dominance seems to be exceptional and they only prevailed in the winters of 2010 and 2013.

The vertical mixing was indicated by the strong winter WSW winds, which lowered the stratification strength. The winter mixing brings O2 to the bottom waters and the deep nutrient-rich waters to the euphotic

Fig. 11. Calculated winter DIP pools based on winter surface concentrations from a) station LL12 west of the Gulf, b) the easternmost station, XV1, in comparison to the mean annual DIP pool. Corresponding winter pools of the sum of NO2 + NO3 from c) station LL12, d) central LL7, e) XV1, and f) as an average concentration value of all three stations in comparison to the mean annual DIN pool in the Gulf for 1992–2014. The mixing in winter 2003 was incomplete and was excluded from the analysis for DIP (black circle).
zone. The winter mixing oxygenated the bottom water at the easternmost station, XV1, throughout the study period, excluding 2003 (see Fig. 3b winter values). It was interesting that the winter surface DIN at the easternmost station, XVI (also XV1 and LL7), better explained the mean annual DIN pool in the entire water volume than the westernmost station, LL12, did (see Fig. 11b). The good correlation indicated that the shallower eastern and central area where winter mixing is likely to occur may act as a major location for delivering the P released from the bottom and imported from the main basin to the surface waters of the whole Gulf. Thus, the nutrients imported from the main basin and released from the sediments of the Gulf along the bottom of the Gulf may be lifted into the reach of algae until the deep water that has flowed in has reached the mixing areas. The model simulations by Eilola et al. (2014) also suggested that the mixing may uplift the P transported from the main basin into the Gulf of Finland, but that the uplift would occur mainly in the western Gulf.

There was occasional parallel behaviour in the DIN and DIP pools from year to year, but the overall correlation between the changes was poor during the study period (see Fig. 4d). The changes in the DIN pool could not, therefore, be explained by same factors as for P. In the Baltic Proper the decrease in the DIN pool has been linked to the increase in the hypoxic area (Savchuk, 2010a; Valterta et al., 2007). In our study, we also found a negative, but insignificant correlation between the extent of the hypoxic area and the mean annual DIN pool. The hypoxia may not affect the changes in the DIN pool in the Gulf as much as in the main basin because the rate of denitrification has been found to be somewhat similar inoxic and anoxic conditions when there is available NO3 (Hietanen and Lukkari, 2007). Bioturbation also enhance the denitrification rate inoxic conditions in the Gulf (see Tuominen et al., 1999).

Our study indicated that the changes in the DIN pool can be linked to the large annual input of N from land (see Fig. 5a) and the internal removal and reloading processes of N occurring in the Gulf. As an example of the removal processes, the DIN pool in the Gulf decreases to a low level for the entire 0 to 30 m water column through sedimentation of N fixed to organic matter in spring and summer (Figs. 2c and 12a). Additionally, the model studies have indicated that the total removal by N2 and bacterial removal may account for about 100,000 and 17,000 t N a−1, respectively (Savchuk et al., 2012). The denitrification measurements suggest removal of 39,000–45,000 t N a−1 (Tuominen et al., 1998; Hietanen and Kuparinne, 2008) and seem to underestimate the N removal in the Gulf compared to budgeting models. To summarise, the potential of the system to remove the winter DIN pool within one seasonal cycle is high due to biological uptake (Figs. 2c, 12a) preceding sedimentation of organic N, and formation of N2 and burial of N.

The Gulf was, interestingly, able to replenish the DIN pool every year (Fig. 2c) but there were large inter-annual variations in the reloading of the pool (see Fig. 5a). The reloading of the pool seems to occur in winter when the most notable increase in the concentration of NO3 in surface water occurs (Fig. 2c). Hence a considerable part of the replenishment may arise through mineralisation and photochemical transformation processes already in the water column when dissolved organic N is converted into DIN (Aarnos et al., 2012; Hoikkala et al., 2015) and through the inputs of N from land into the Gulf. However, in winter the mineralisation and photochemical transformations are likely to be low as the water temperature is close to 0 °C and the light intensity is low. Additionally, the input of TN from land alone could not explain the large inter-annual variation in the DIN pool (see Fig. 5a).

Our analyses indicated that the wind forcing and stratification were related to the variations in the DIN pool in the Gulf. For example, the strength of stratification in winter seemed to be related to the replenishment potential of DIN in the Gulf, because the wintertime deviations from the trend of stratification strength correlated well with the change in the DIN pool (see Fig. 9e). The result indicated that strong stratification led to a small DIN pool change from the previous year. In contrast, weak stratification resulted in large variation in the DIN pool. This indicated that the long-term variation in the DIN pool may be related to the filling-emptying of the Baltic Proper due to MBIs and long-term changes in WSW winds affecting bottom processes in the Gulf, in addition to the N inputs from the land. Additionally, the stronger the increase in the stratification strength from winter to summer, the larger the increase in the DIN pool size from that year to the next one (Table 3). This indicated that a rise in stratification strength from winter to summer enhances the removal of DIN during that specific year, but that the pool can be replenished during the next year.

To explain the relationship between the winter winds, stratification and variation in the DIN pools in the Gulf, we propose that the strong winter WSW wind may momentarily hamper the outflow of surface water containing high amounts DIN from the land, and mix it into a large water volume. Additionally, the mixing of water caused by WSW winds may uplift the bulk of DIN being released from the bottom to the upper water layers, beyond the reach of bacteria removing nitrogen as N2 gas in the winter. In contrast, weak WSW and especially ENE winds may maintain the large export of DIN out of the Gulf and retain the stratification that keeps the NO3 formed available for N2 removing bacteria in bottom-water layers. Therefore, the atmospheric forcing in winter may affect the DIN pool in large areas of the open Gulf by controlling the import and export of DIN from the catchment and by regulating the availability of NO3 for removal of N2. This type of mechanism may explain why the winter surface DIN values at three stations along the Gulf could be used as proxies for the mean annual DIN pools throughout the entire Gulf (see Fig. 11c–f).

To conclude, the changes in the atmospheric forcing and stratification can be linked to the variation in both the DIN and TP pools, but the variations can be explained by different mechanisms. Our study suggests that we should also focus on the internal mechanisms regulating the renewal of the DIN pool, in addition to those controlling the removal of N in the Gulf of Finland.

It seems that the replenishment of the DIN pool by the strong WSW winds was missed in 2007 because then there was an exceptionally large decrease of 47,200 t in the pool from the previous year, resulting in the lowest observed mean pool of ~35,000 t of DIN in the Gulf in 2007. In 2006 and 2007 the inputs of TN were 100,000 and 116,000 t (Fig. 5a), respectively, which were both moderately below the average input of 118,000 t N a−1. Therefore, it is possible that NO3 was efficiently removed as N2 from the bottom waters in poor O2 conditions during 2006, leaving little NO3 to be mixed into the water of the Gulf.

4.4. Episodes with different winter wind and stratification regimes

Two episodes with different winter wind and stratification regimes were chosen to highlight their effect on the O2 conditions and on the magnitude and location of the DIP pool in the Gulf (see Fig. 12a–c). The year 1992 represented a period when the halocline was deep at the entrance, the salinity stratification was weak, and strong westerly winds occurred for three subsequent winters in the Gulf (i.e. 1991–1993). In 1992 no oxygen concentrations below 4 mL L−1 were found in the near-bottom waters of the open Gulf of Finland. In less stratified and good oxygen conditions the total DIN pool was 85,000 t and DIP about 12,700 t. The DIN in the deep-water layers comprised only a small proportion of the total pool. The stratification strength increased after an inflow of saline water in 1995/96 and the O2 and DIP conditions worsened significantly (See Fig. 2).

In contrast, in 2003 there were only weak westerly winter winds in throughout the period 2001–2003 and the halocline was closer to the surface in the Gulf than in 1992. A permanent ice cover had already formed by December in 2002 (Fig. 2b) and ENE winds dominated in the summer of 2003. The stratification was strong and no efficient winter mixing occurred at stations LL7 and XVI in the winter of 2003 (see Figs. 2, 3 and 6b). As a result, the total volume of water with low O2 concentrations was about 110 km3 (11% of the total volume used in the calculation) and covered about 7700 km2 (27% of total area) of the bottom area of
the Gulf in 2003 (Fig. 12c and d). Large areas suffered from O₂ deficit and in these stratified poor O₂ conditions the mean annual DIN pool was 45,000 t and that of DIP 27700 t. A large proportion of DIP was found in the deep-water layers (9500 t, i.e. 35% of the total pool, Fig. 12g and h).

The strong stratification period, lasting over a year, was ended by a westerly winter storm in early 2004. After the storm event the concentrations of DIP increased substantially in the surface waters. The ability of the system to replenish the DIN pool after strong stratification was also highlighted by the pool of over 150,000 t found after the winter storm in 2004 (see Fig. 13a). The winter DIN pool in 2004 was comparable to those found in 1995 and 2001. Although the DIN pool recovered in 2004, the DIN:DIP ratio was low due to the high amount of DIP in the water.

4.5. Significance of atmospheric forcing on nutrient conditions and fixation of carbon and nutrients

The winds and stratification largely regulate the DIN and DIP pools by affecting the in- and outflows of water and by changing the conditions for the biological and chemical processes controlling the in- and outflux of nutrients in the bottom sediments of the Gulf. Therefore, the atmospheric forcing may drive the changes in the DIN and DIP pools and affect the fixation of C, N and P in surface water layers. The mean annual DIN:DIP ratio in the nutrient pools was almost invariably below the Redfield ratio of 16 (see Table 2), which suggested that the primary production in the pelagic system is predominantly limited by N (see also Tamminen and Andersen, 2007). Due to the N limitation, spring bloom depletes all of DIN and leaves an excess of DIP in the water (Lignell et al., 1993). The excess DIP pool has the potential to fuel blue-green algae blooms and N fixation in the summer. In our study spring bloom seems to commonly sequester DIN from a depth of 0 to 30 m (see Fig. 2c), comprising about 65% of the total water volume of the Gulf of Finland.

The large variation in the winter DIN pool revealed that the DIN-controlled C uptake may alter significantly inter-annually. The comparison of the calculated potential C uptake by spring bloom and blue-green algae with measurements from the Gulf itself is complex because monitoring does not cover the spring period properly and direct cyanobacterial biomass monitoring is rarely feasible. Therefore, we

![Fig. 12. Horizontal bottom and vertical distribution of a–d) oxygen (ml L⁻¹) and e–h) phosphate (µM P) for 1992 (strong WSW winds, weak stratification, reconstructed from 7552 sampling horizons taken at 232 stations) and 2003 (weak WSW winds, strong stratification, reconstructed from 9019 sampling horizons taken at 663 stations). The numbers in Figs b, d, f, and h are for water volume, where O₂ < 4 ml L⁻¹. The total bottom area and volume used in the DAS-calculations were 28,000 km² and 1000 km³, respectively.](image-url)
The changes in the annual inputs of N and P from the land into the Gulf of Finland could not explain the inter-annual variation in the DIN pools in the waters of the open Gulf. We conclude that the large-scale atmospheric forcing and stratification in the Gulf create potential for late summer blue-green algae blooms, which may fix significant amounts of C and N (N2 uptake by blue-green algae, Fig. 13c and d). Our calculations indicated that the potential for molecular N fixation varies greatly between years, but that values are reasonable in comparison to the modelled average amount of 27,000 t a\(^{-1}\) of fixed N by Lessim et al. (2014), and 35,000–70,000 t N a\(^{-1}\) by Savchuk (unpublished). Furthermore, the calculations indicated that a much larger proportion of DIN than DIN can be found in the deep water after the pelagic processes (42–57% of the total winter DIN pool and only 25–32% of the total winter DIN pool). The large reserve of DIN left in the deep water serves as a source of DIN through mixing, upwelling, diffusion, and erosion of pycnoclines, even without additional release from the sediment or inputs from the land during summer. In P-rich conditions as in 2004 there was no source large enough for DIN to raise the DIN pool and thus the DIN:DIP ratio fell clearly below Redfield ratio. However, whilst the dissolved organic nitrogen in the water may markedly increase the amount of bioavailable N, its role in the N cycle is not well quantified in the Gulf (Hoikkala et al., 2015).
the average long-term variation of the bottom water density and the stratification strength of the NBP. However, the wind forcing occurring within a comparatively small time window in winter explained the inter-annual variation in the salt pools, the stratification strength and the extent of the hypoxic area in the Gulf, despite the several MBIs that took place during the study period. So the control of atmospheric forcing over the nutrient pools emerges through winds governing the imports and exports of salt and nutrients at the boundary, stratification strength and the size of hypoxic area.

Regardless of the inter-annual relation of winds and hydrodynamics to nutrients presented, the actual stratification in the NBP provides the preconditions for the influence of winter wind forcing on the import-export dynamics and the stratification strength in the Gulf. The long-term changes in the stratification of the NBP and the short-term seasonal and annual hydrodynamical patterns driven by winds are likely to maintain a high degree of variability in the nutrient status of the Gulf also in the future. The alterations in the DIN and DIP pools lead to variable ecosystem features by creating different preconditions for the spring bloom community and highly variable potential for blue-green algal blooms.

The changes in the winter wind forcing, causing variation in the ability of bottom sediment to retain P and the amount of P imported from the main basin to the Gulf evidently masked the effect of the marked P reductions implemented on a Gulf-wide scale. Additionally, the potential of bottom sediment to retain P and the amount of P imported from algal blooms.

References


