Simulation of nutrient transport from different depths during an upwelling event in the Gulf of Finland*

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Abstract

Numerical simulation experiments with a high-resolution circulation model were carried out to study nutrient transport from different depths to the surface 10-m layer during an upwelling event along the northern coast of the Gulf of Finland in July 1999. The initial nutrient distribution is based on field measurements performed in the north-western part of the Gulf. Wind forcing covering the period of the upwelling along the northern coast was turned through 180° to simulate an upwelling along the southern coast. The simulation results showed that the main phosphorus transport to the upper 10-m layer occurred from depths shallower than 30 m for the upwelling events along both the northern and the southern

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coasts. Nitrogen transport to the upper 10-m layer was the largest from depths of 40–55 m for the upwelling along the northern and 40–65 m for the upwelling along the southern coast. Simulated cumulative volume transports to the upper 10-m layer from different depths showed that the contribution from deeper layers was larger in the case of the upwelling along the southern coast. The reduction of wind stress had a bigger influence on water transport from the deeper layers.

1. Introduction

Wind-driven coastal upwelling is a typical phenomenon in the Baltic Sea (Gidhagen 1987, Myrberg & Andrejev 2003) with strong upwelling events occurring with an annual average frequency of up to 30% in some parts of the Baltic (Kowalewski & Ostrowski 2005).

In the Gulf of Finland, a sub-basin of the Baltic Sea oriented from west to east, wind-driven coastal upwelling events are caused by either westerly or easterly wind forcing, which must have been operating for at least 60 h to generate an upwelling in the Gulf (Haapala et al. 1994). Upwellings and related mesoscale structures (meanders, filaments and eddies) in the region have been studied with different methods – field observations (e.g. Haapala et al. 1994, Lips et al. 2009, Kuvaldina et al. 2010), remote sensing (Kahru et al. 1995, Uiboupin & Laanemets 2008) and model simulations (Myrberg & Andrejev 2003, Zhurbas et al. 2008, Laanemets et al. 2009). Because the prevailing wind in the region blows from the south-west (e.g. Soomere & Keevallik 2003), upwelling events along the northern coast are more frequent.

Coastal upwelling typically transports nutrient-rich deeper water to the surface euphotic layer. Simulations with the ecohydrodynamic model by Kowalewski (2005) in the Hel region (the Baltic Sea) during an upwelling event showed an elevation of nutrient concentrations and an increase of phytoplankton biomass in the surface layers, especially during the spring bloom. Owing to the difference in vertical locations of the summer nutriclines in the thermocline (the phosphacline is shallower than the nitracline in the Gulf of Finland, as shown by Laanemets et al. (2004)), nutrients may be transported with an excess of phosphorus, compared with nitrogen according to the Redfield ratio. During the nutrient-depleted summer period, an upwelling is probably one of the main phosphorus sources for the formation of nitrogen-fixing cyanobacteria blooms (Vahtera et al. 2005).

Comprehensive reviews of upwelling in the Baltic Sea, its dynamics and effects on the ecosystem have been presented by Lehmann & Myrberg (2008) and Myrberg et al. (2008).

Previous numerical studies showed that the instability of longshore baroclinic jets and related thermohaline fronts caused by coupled upwelling and downwelling events lead to the development of cold and warm filaments and eddies contributing to a coastal offshore exchange (Zhurbas et al. 2008). During coastal upwelling, nutrients are transported into the upper 10-m layer with a clear excess of phosphorus. In addition, the amount of transported phosphorus by one upwelling event is roughly equal to the monthly external bioavailable phosphorus load to the Gulf (Zhurbas et al. 2008). There is an asymmetry in upwelling response patterns owing to the cross-gulf topography: the southern half of this elongated basin is deeper and has steeper bottom slopes. Thus the amount of nutrients transported into the upper 10-m layer depends on whether upwelling occurs along the northern or the southern coast of the Gulf (Laanemets et al. 2009). Also, in the shallower eastern part of the open Gulf, the content of upwelled nutrients is low. With respect to the geographical distribution of upwelling effects, upwelled nutrients are transported more intensively from the coastal zone to the open sea by filaments and eddies in the narrow western and central part of the Gulf, as can be judged from the maps of mean eddy kinetic energy and phosphorus and nitrogen content in the surface layer (Laanemets et al. 2011).

During upwelling, waters from different layers are both advected and mixed. Lips et al. (2009) showed on the basis of field observations that during a strong upwelling event in summer 2006, the cold intermediate layer water and the upper mixed layer water were mixed in proportions of 85% to 15%. One may assume that the vertical clines separating the water masses and nutrient pools make a major contribution as sources of 'foreign' water upwelled to the surface layer. Nevertheless, the exact contribution of the different layers in the water column to the transport of nutrients is hard to detect from direct measurements, but this is possible from model-based estimates. In topographically asymmetrical regions, like the Gulf of Finland, one may assume a different contribution at different shores under upwelling-favourable wind conditions with the same magnitude.

The objective of this paper was to study and estimate the nutrient transport from different depths to the surface layer during coastal upwelling events along opposite coasts of an elongated basin such as the Gulf of Finland. For this purpose we used a series of numerical experiments in which the initial tracer (simulating short-term nutrient behaviour) source is put at different depths for each experiment. The results of the experiments are summarized as time and depth maps of cumulative nutrient mass transported to the upper layer from a layer of unit thickness at a certain depth in the Gulf of Finland.

2. Material and methods

2.1. Model setup

We applied the Princeton Ocean Model (POM), which is a primitive equation, σ-coordinate, free surface, hydrostatic model with a 2.5 moment turbulence closure sub-model embedded (Mellor & Yamada 1982, Blumberg & Mellor 1983, 1987). The model domain included the whole Baltic Sea closed at the Danish Straits. The digital topography of the sea bottom was taken from Seifert et al. (2001). We used a horizontal resolution of 0.5 nautical miles within the Gulf of Finland and 2 nautical miles in the rest of the Baltic Sea (Figure 1); in the vertical direction we used 41 equally spaced σ-layers, which in the Gulf gave the lowest vertical resolution of $\Delta z = 3$ m at a point of depth 120 m. A model resolution of 0.5 nautical miles allows good resolution of mesoscale phenomena, including upwelling filaments/squirts (Zhurbas et al. 2008) controlled by the internal baroclinic Rossby radius, which in the Gulf of Finland varies within 2–5 km (Alenius et al. 2003).

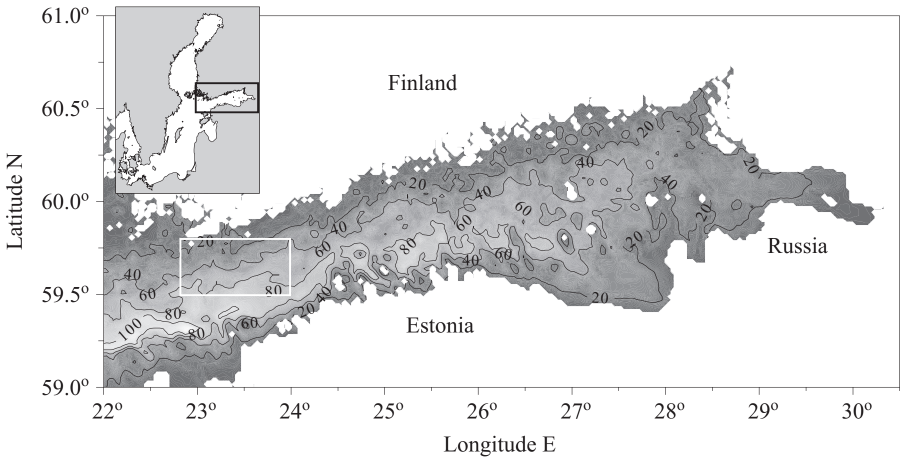

Figure 1. The model domain was the whole Baltic Sea with the model grid refined to 0.5 nautical miles in the Gulf of Finland. The white box indicates the area of the measurements performed on board r/v 'Aranda' in July 1999. The depth contours are given in metres

We chose the simulation period from 20 to 29 July 1999, which represents an intensive upwelling event along the northern coast and is well covered by high-resolution observations including CTD, biological and chemical measurements along with the SST from satellite imagery (Vahtera et al. 2005).

Atmospheric forcing (wind stress and heat flux components) for the simulation period was calculated from a meteorological data set of the Swedish Meteorological and Hydrological Institute (SMHI). The 10 m wind components were calculated from the SMHI geostrophic wind vectors by turning the latter 15° counterclockwise and multiplying by a factor of 0.6. The components and other meteorological parameters obtained were afterwards interpolated in space from the 1° resolution to our 2 and 0.5 nautical mile model grid. Since the winds calculated from the geostrophic gridded winds were lower compared with the wind measurements performed on board r/v 'Aranda' (within the study area of 22°50′–24°00′E, 59°30′ –59°48′N, see Figure 1), the gridded wind stress field was multiplied by a correction factor of 2.04. The comparison of the corrected along-gulf wind stress τ_0 (positive eastward) with the wind stress component calculated from the measured wind on board r/v 'Aranda' is presented in Figure 2.

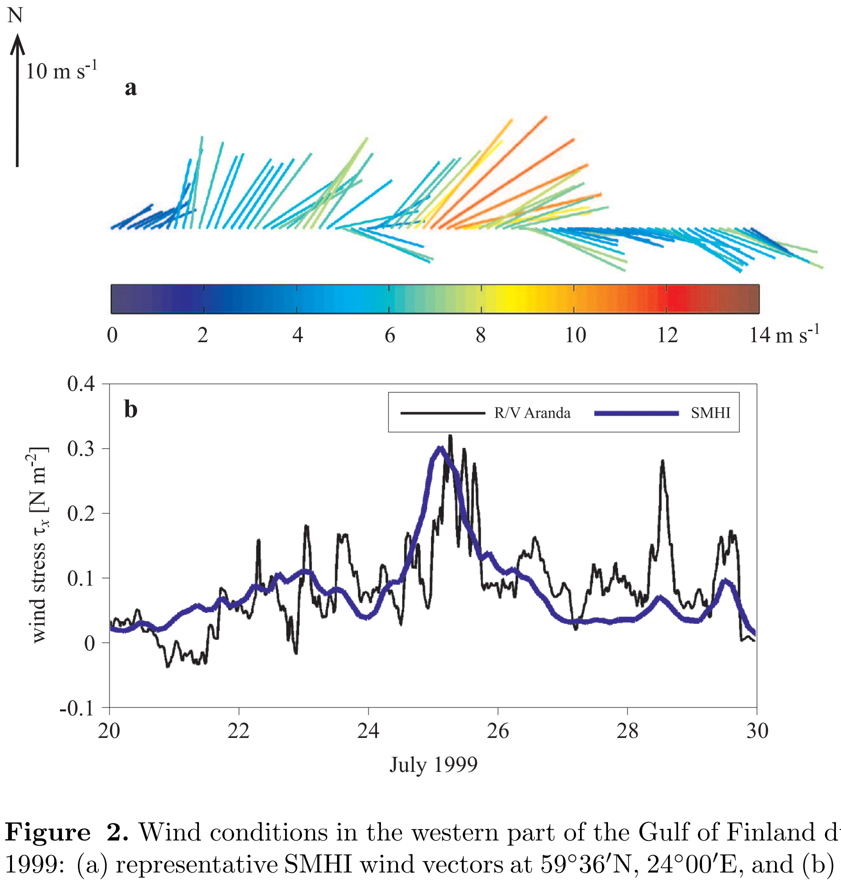

Figure 2. Wind conditions in the western part of the Gulf of Finland during July 1999: (a) representative SMHI wind vectors at 59°36′N, 24°00′E, and (b) the along-gulf wind stress calculated from measurements performed on board r/v 'Aranda' (solid black line) and SMHI gridded meteorological data set (solid blue line)

During the period from 21 to 25 July, westerly winds prevailed (Figure 2a) and the along-gulf wind stress component increased more or less steadily up to about 0.3 N m^{-2} (Figure 2b, SMHI data), causing the development of upwelling along the northern coast of the Gulf. From the peak onwards, the along-gulf wind stress decreased steadily. In order to model the upwelling along the southern coast, the wind vectors were turned through 180° and a wind stress of $\tau = -\tau_0$ was applied.

The initial thermohaline fields were constructed with the help of the Data Assimilation System coupled with the Baltic Environmental Database established and maintained by Alexander Sokolov and Fredrik Wulff at Stockholm University (see http://nest.su.se/das), using the climatological data from July to capture the main large-scale features of temperature and salinity, including the along-gulf salinity gradient. Interpolation of DAS data on 20 July yielded approximately an upper mixed layer temperature of 16°C in the Gulf, which was 3°C less than that measured on board r/v 'Aranda' on 20–21 July 1999 (Vahtera et. al 2005); therefore, the initial temperature field obtained from DAS was increased in the upper 10-m layer of the whole Baltic Sea by the difference. For more details on both factors, see Zhurbas et al. (2008) and Laanemets et al. (2009).

Owing to the smooth climatological density field and weakness of the related geostrophic currents, a windless model adjustment period was not found necessary to study the wind-forced upwelling events. We started the model run from zero currents and sea level and 'switched' the wind forcing on at the beginning of the run as used by Zhurbas et al. (2008). One justification for such an approach is that the Baltic Sea currents respond to changing wind in topographically controlled regions within approximately a day (Krauss & Brügge 1991). However, for seasonal and climatic circulation studies (not the purpose of our investigation), the 'warm-up' period of the model may be much longer than several months. In the present study, we do not present validation against measurements, but refer the reader to the studies by Zhurbas et al. (2008) and Laanemets et al. (2009), who demonstrated very good agreement of their model results with the observations. We note that closing the Danish Straits was of minor importance to the simulated upwelling events, since the mean sea level as observed at Landsort increased only by 10^{-7} m s^{-1}.

Phosphate and nitrate transport were simulated by introducing two equations describing passive tracer balance. During the short upwelling event, nutrients were considered to be conservative passive tracers, although the posterior behaviour of nutrients in the upper layer is not conservative. The equations were solved numerically within the POM code using the central leapfrog advection scheme, as used originally for temperature and

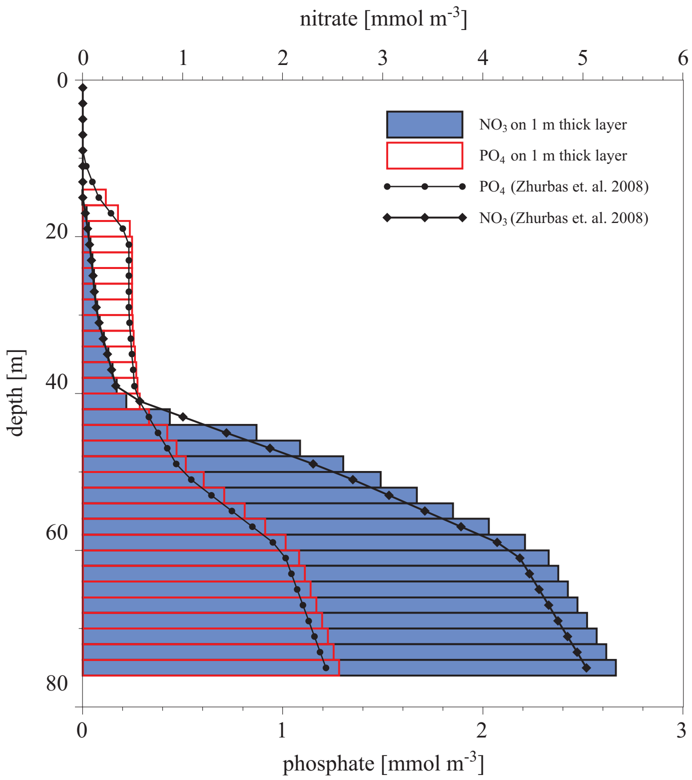

Figure 3. The initial nutrient concentration of different layers at 59°37.5′N, 23°46′E compared with the profiles based on measurements performed onboard r/v 'Aranda' on 20 July 1999 (Zhurbas et al. 2008)

salinity. Initial nutrient fields based on the field measurements on board r/v 'Aranda' in July 1999 and the measured nutrient profiles (see Zhurbas et al. 2008, Figure 3) were extended uniformly to the whole Baltic Sea.

2.2. Experiment setup

We studied the depth-origin vertical transport of nutrients (due to three-dimensional advection and mixing) by a series of numerical experiments in which the tracers had initial non-zero values only in a specific layer $z - \Delta z/2$, $z + \Delta z/2$ of thickness Δz (the values are taken from the initial nutrient profile, see Figure 3) and concentrations were zero elsewhere. Because of the σ-coordinate formulation of the POM, the initial nutrient concentrations were introduced only into one σ-layer closest to a given depth z (i.e. $-\sigma H \approx z$), where H is the sea depth. To leave the total initial nutrient mass unchanged, the nutrient concentration in z-coordinates, $C(z)$ is related to that of σ-coordinates, $C(\sigma)$, as $C(\sigma) = C(z)\,\Delta z/(\Delta\sigma\, H)$ (Figure 3).

Nutrient transport simulations started at 00:00 hrs on 22 July 1999 and lasted for 7 days in every model run, with the tracer source at a different individual depth layer.

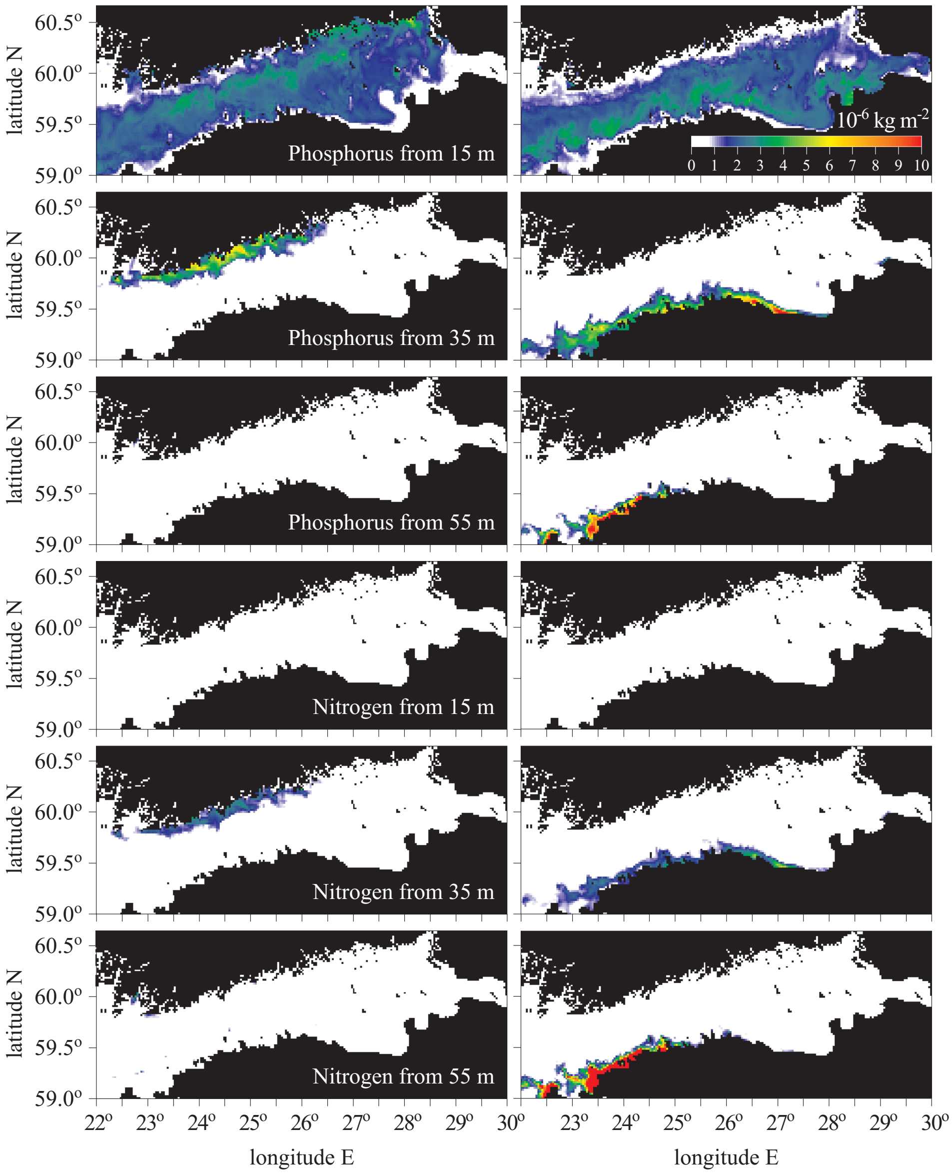

Figure 4. Maps showing the amounts of phosphorus and nitrogen in the upper 10-m water column with unit cross section transported from a layer 2 m thick at depths of 15, 35 and 55 m during the upwelling event along the northern (right panels) and southern coast (right panels) at $t = 6.3$ days

In the further analysis we use plots of nutrient content and water volume, integrated within the upper 10-m layer over the whole Gulf, transported from different depths during the upwelling event. To illustrate the background to the numerical experiments and the spatial distribution of upwelled nutrients along the northern and the southern coasts, the maps of the cumulative amounts of nutrients transported to the upper 10-m water column of unit cross section after 6.3 days simulation, with a source layer of 2 m thickness at 15, 35 and 55 m depth, are shown in Figure 4.

3. Results

3.1. Nutrient transport to the surface from different depths

Within the framework of the experiments, the horizontally integrated cumulative amount of nutrients in the upper 10-m layer over the whole Gulf was calculated as a function of time and initial depth of 2 m thick nutrient layers. Upwelled horizontally integrated cumulative amounts of nutrients

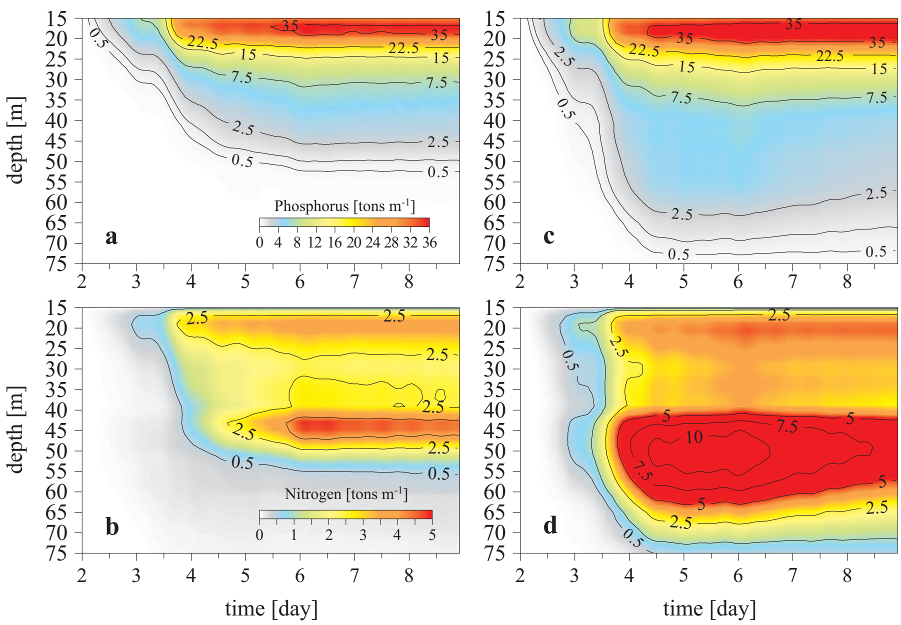

Figure 5. The plots of differential nutrient transport to the upper 10-m layer of the Gulf of Finland (in tons m^{-1}) versus the depth and time obtained from the simulations. The time is from 20 July 1999 onwards and the depth is the one where the nutrients were located in a layer with unit thickness as the initial source and from where they were brought to the surface layer. The results for the upwelling along the northern coast are on the left hand side, those for the upwelling along the southern coast are on the right hand side

in the upper 10-m layer were divided by the nutrient layer thickness Δz, and the plots obtained of the nutrient mass carried up to the top 10-m layer from a layer of unit thickness located at different depths during the upwelling (Figure 5) showed that the main source of phosphorus was between 17–41 m for the upwelling along both coasts of the Gulf – it was slightly deeper, though, along the southern coast. Transport was greatest from 17 m depth during the northern coast upwelling (Figure 5a) and from depths of 17–19 m during the southern coast upwelling (Figure 5c). More than 35 tons m^{-1} of phosphorus were brought to the surface layer from that depth range. With the increase in 'source' depth, the transport of phosphorus was reduced to 2.5 tons m^{-1} at 45 m depth for the upwelling off the northern coast and at 65 m depth off the southern coast. In the case of nitrogen the behaviour was slightly different. The greatest transport was from the depth interval of 40–65 m off the southern coast (Figure 5d) and 43–49 m in the case of the opposite coast (Figure 5b). The regional upwelling response pattern differs more than 2.5 times – during the southern coast upwelling more than 10 tons m^{-1} of nitrogen was brought to the surface layer from depths of 45–55 m, while off the northern coast the highest values were no more than 4 tons m^{-1} from depths of 40–45 m. The deeper layers were quite inefficient as nutrient sources for the euphotic layer during short-term upwelling events. Less than 1 ton m^{-1} of nitrogen was brought to the surface layer from depths

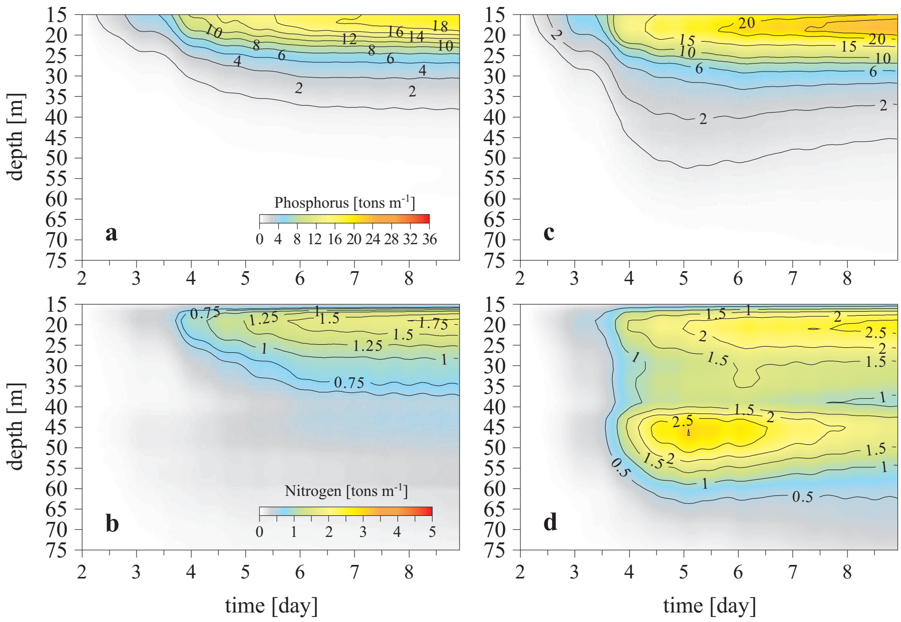

Figure 6. As for Figure 5 but with a 50% smaller wind stress $\tau = 0.5\,\tau_0$

of over 53 m and 73 m during the upwelling events along the northern and the southern coasts respectively.

The results of a similar nutrient transport simulation with a 50% smaller wind stress ($\tau = 0.5\,\tau_0$) are shown in Figure 6. The reduction in wind stress results in the overall decrease of amounts of upwelled nutrients. In particular, the largest transport of phosphorus remained in the upper 15–25 m layer off both coasts, whereas nitrogen transport from deeper layers was vanishingly small for the upwelling along the northern coast (< 0.75 tons m^{-1} from depths greater than 35 m). As regards the southern coast, the largest transport of nitrogen remained in the depth range of 40–55 m with the maximum at 45 m.

3.2. Volume of water transported to the surface

Nutrients are considered to be conservative passive tracers, and it is therefore possible to transform the cumulative amount of nutrients per metre $\Delta \mathrm{m}_{10}/\Delta z$ to a volume of water V_{10}, which is cumulatively transported to the upper 10-m layer from a 1 m thick layer at a certain depth z:

$$V_{10} = \frac{1}{C(z)} \frac{\Delta \mathrm{m}_{10}}{\Delta z}, \tag{1}$$

where $C(z)$ is the initial nutrient concentration at depth z (Figure 3). The cumulative volume transports per unit source layer thickness to the upper 10-m layer during the upwelling along the northern and the southern coasts with different wind stresses are shown in Figure 7, and the snapshot of upwelled volumes during the maxima of nutrient amounts on the 6th simulation day in Figure 8. It is seen in both Figure 7 and Figure 8 that the total volume of water transported to the upper 10-m layer from the top depth interval of 15–19 m was almost the same for the upwelling events off the northern and the southern coasts of the Gulf, with the maximum of 6.7×10^9 m^2 (Figure 8). Such equality of upwelled volumes is achieved as a result of the predominance of vertical turbulent diffusion (vertical mixing) over vertical advection, as the intensity of turbulent mixing in the upper sea is governed by wind force rather than wind direction. The cumulative transport due to vertical mixing is therefore expected to be more or less uniformly distributed within the Gulf area (see Figure 4, the source depth of 15 m for phosphorus), having the same total value for the upwelling events off the northern and the southern coasts. During the upwelling along the southern coast, the volume of water transported to the upper layer was larger than that off the northern coast, and the water mass was brought up from depths greater than 60 m (see Figures 7a, 7b and Figure 8). During the upwelling event along the northern coast, water was

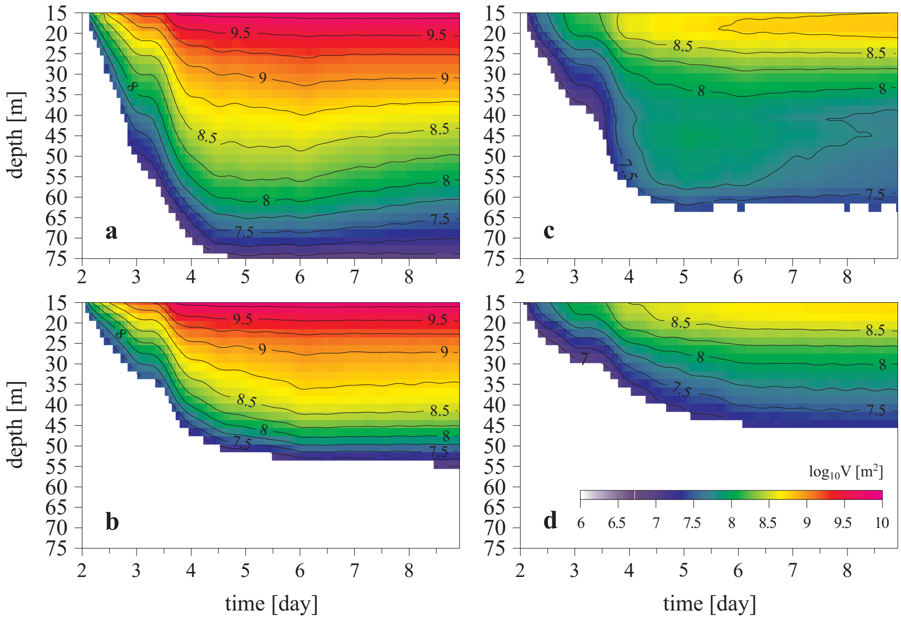

Figure 7. The cumulative volume transports per unit layer thickness to the upper 10-m layer from different depths during the upwelling along the southern (a, c) and the northern (b, d) coast. Cumulative volume transports were calculated for wind stress $\tau = \tau_0$ (a, b) and for wind stress $\tau = 0.5\,\tau_0$ (c, d). Note the logarithmic scale of the volume transports

transported to the surface mainly from the depth range of 21–41 m. There was a remarkable decrease from 3.7×10^8 m^2 to 1.08×10^7 m^2 in the amount of water transported to the surface from the 41–55 m depth range; hence, the maximum depth influenced by the upwelling along the northern coast was about 55 m. In the case of the upwelling along the southern coast, such a depth interval with a rapid decrease of upwelled water volume was not detected; the volume of upwelled water decreased more or less uniformly with depth.

The contribution from deeper layers during the upwelling with reduced wind stress ($\tau = 0.5\,\tau_0$) was lower for the upwelling events along both the northern and the southern coasts (see Figures 7b, 7d and Figure 8). The maximum depth influenced by the upwelling also fell to 45 m for the northern and 65 m for the southern coast. In Figure 8 the shapes of the curves of transported water volume have been transformed into straight lines for both upwelling cases. Comparison of the changes in transported volumes during the upwelling along the northern coast with reduced wind stress from depths of 15–45 m with the results for the upwelling along the southern coast with reduced wind stress shows that transport from intermediate layers was

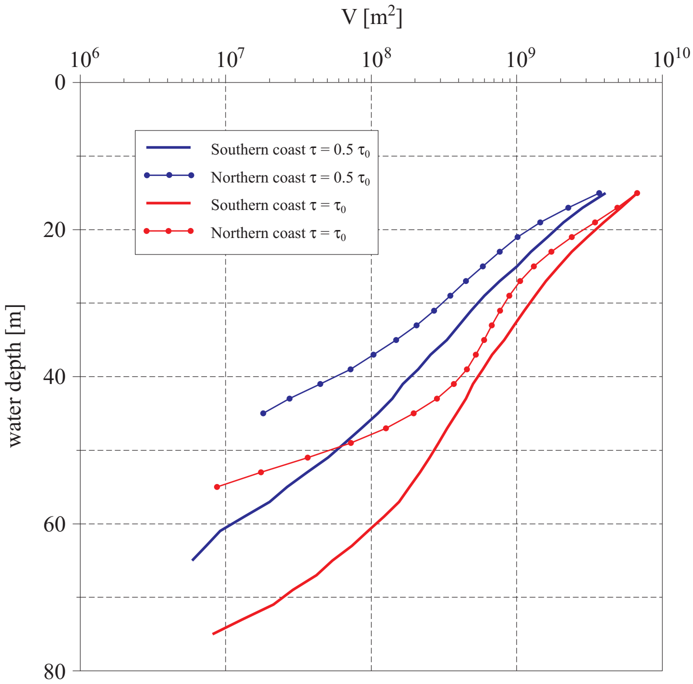

Figure 8. The volumes of water transported to the upper 10-m layer within the Gulf during the upwelling event along either the northern or the southern coast of the Gulf with wind stress $\tau = \tau_0$ and $\tau = 0.5\,\tau_0$ by day 6 of simulation

reduced remarkably: the volume of water transported from 21 m depth was more than 50% smaller, but for the deepest layers, the decrease was 10 times larger.

4. Discussion

According to Lentz & Chapman (2004), the vertical position of the onshore return flow that balances the offshore Ekman transport in an idealized case of stationary 2D upwelling is controlled by the Burger number $S = \alpha N/f$, where α is the bottom slope, N is the buoyancy frequency and f is the Coriolis parameter. For $<< 1$ (weak stratification), bottom stress balances wind stress, and the onshore return flow is primarily in the bottom boundary layer. For $S \approx 1$ or more (strong stratification), the cross-shelf momentum flux divergence balances wind stress and the onshore return flow is in the interior. Despite the fact that real upwelling events in the Gulf of Finland are neither stationary nor two-dimensional, the finding by Lentz & Chapman (2004) may be used for the qualitative interpretation of the results obtained in this study. The estimates of the Burger number retrieved from the simulations were found to vary within the respective ranges of $S = 0.3$–1.2 and $S = 0.2$–0.9 for the upwellings along the southern and the northern coasts. Both upwelling regimes, $S << 1$ and $S \approx 1$, are therefore likely to be encountered in the Gulf, so there is no rigid restriction for the vertical position of the onshore return flow. As a result, we do not observe an abrupt decease of the volume transport at a certain depth, but a gradual decrease instead (see Figures 7 and 8).

The model results described above showed that the main transport of phosphorus into the upper 10-m layer was from depths less than 30 m for the upwelling along both coasts, whereas for nitrogen transport it was from layers deeper than 40 m. This is explained by the difference of nutricline depths and shape: there is a remarkable increase in nitrate concentration starting from 40 m depth, whereas for phosphate there is no such increase (Laanemets et al. 2004). Along the southern coast, where the depths are greater, nitrogen is more easily transported to the surface than off the northern coast, where the seabed is shallower and the amount of nitrogen in the offshore water column is correspondingly lower.

The total amounts of nutrients transported to the surface are larger during the upwelling along the southern coast. Laanemets et al. (2009) explained these larger amounts by the shorter distance that water particles carrying nutrients have to cover in order to reach the surface.

Lips et al. (2009) showed that during the upwelling event along the southern coast, observed during the summer 2006 measuring campaign, 85% of the upwelled water was from the intermediate layer and the remaining 15% from the surface layer. The plots of the ratios of depth-accumulated amounts of nutrients transported to the upper 10-m layer in the Gulf from a depth range [75 m – given depth z] to the total amount of nutrients transported to the surface (Figure 9) show that for the northern coast the main phosphorus transport is confined within the upper 40-m layer: 95% of nutrients are transported from there (Figure 9a). During the upwelling along the southern coast 95% of phosphorus was transported from the upper 55-m layer and 85% from the upper 40-m layer (Figure 9c). On the other hand, the behaviour of nitrogen was different: 95% of the nitrogen found in the upper 10-m layer by day 6 came from depths shallower than 55 m off the northern (Figure 9b) and 65 m off the southern coast (Figure 9d). 40% of the surface layer nitrogen was from depths shallower than 33 m and 45 m for the northern and the southern coasts respectively. Simulations showed that off the southern coast the upwelled water was transported to the surface mostly from the intermediate layer, as suggested by Lips et al. (2009), whereas off the northern coast transport from the shallower layers has a larger impact.

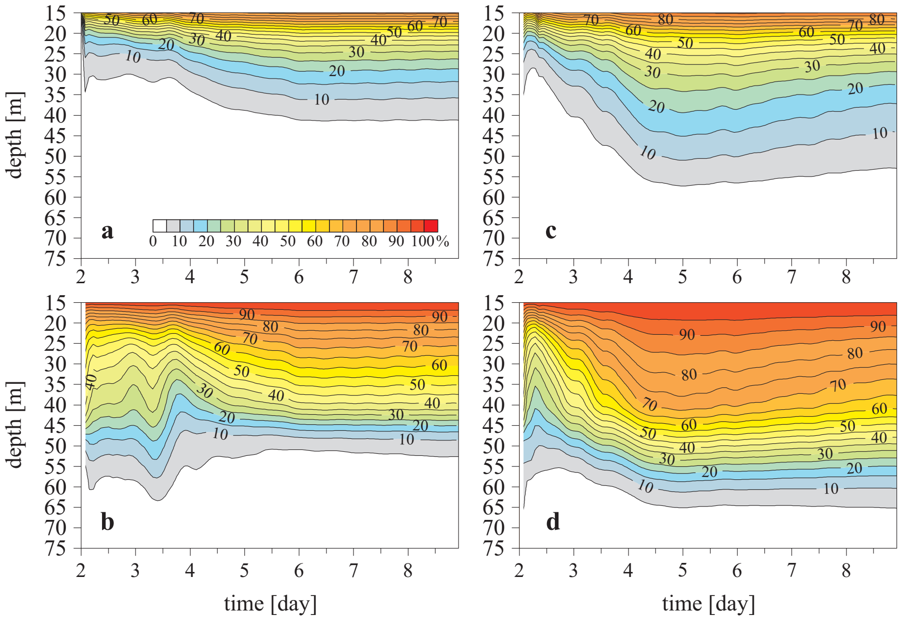

Figure 9. Maps showing the ratios of depth-cumulative nutrient amounts from 75 m to depth z to the total amount of nutrients in the water column as a percentage at a given time for the upwellings off the northern (left) and southern (right) coasts for phosphorus (upper panel) and nitrogen (lower panel)

The intensity of nutrient transport from the middle layers was greater during the upwelling along the southern coast for the same wind forcing magnitude, because the water from the depths of 35–45 m reached the surface layer more quickly, at least in the course of one day (Figure 7, cf. a and b). In addition, as the deeper layers have an earlier impact on the transport of nutrients during the upwelling along the southern coast, the total amounts of nutrients transported to the upper 10-m layer were larger during the upwelling along the southern coast. During the upwelling along the northern coast, water masses from depths of > 50 m reached the upper 10-m layer at least 1.5 days later and the total amount of nutrients transported to the surface layer were therefore lower compared than that off the southern coast.

5. Conclusions

The aim of this paper was to describe nutrient transport from different depths to the surface layer during an upwelling event in the Gulf of Finland. Modelling results showed that during upwelling events off either the northern or the southern coast of the Gulf, the highest phosphorus transport to the upper 10-m layer was from depths shallower than 35 m. The largest amounts of nitrogen were transported to the surface layer from depths of 40–50 m off the northern and 40–60 m off the southern coast.

The volume of water transported to the upper 10-m layer from the deeper layers is greater during the upwelling along the southern coast – there was a clear decrease in the water volume reaching the surface layer from depths greater than 50 m during the upwelling along the northern coast.

The impact of the upwelling wind impulse was higher on the southern coast; the transport of water from deeper layers started earlier than on the northern coast. Owing to the earlier transport from the bottom layers during the upwelling along the southern coast, the total amount of nutrients transported to the upper 10-m layer at the culmination of the event are larger during the upwelling along the southern coast.

Although the reduction in wind stress lowered the amounts of nutrients transported to the upper 10-m layer during the upwelling event on both coasts, the main transport of phosphorus remained at the depths of 15–25 m. Nitrogen transport from the deeper layers was vanishingly small for the upwelling along the northern coast, whereas for the southern coast, the largest transport remained in the depth range of 40–55 m.

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