The influence of the Hel upwelling (Baltic Sea) on nutrient concentrations and primary production – the results of an ecohydrodynamic model*

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Abstract

An ecohydrodynamic model was used to investigate the effect of the Hel upwelling on nutrient concentrations, primary production and phytoplankton biomass. The model covered the whole Baltic Sea with a 5 NM grid spacing and the Gulf of Gdańsk with a 1 NM grid spacing. Validation indicated good agreement between model results and measurements in the Gdańsk Deep, and slightly weaker concord for the Hel upwelling area. The vertical nutrient fluxes associated with up- and downwelling in the Hel region were simulated for two 30-day periods in 2000. The nutrient input resulting from long-term upwelling is comparable to the load carried into the Gulf of Gdańsk by the Vistula (Wisła), the largest river in the vicinity. Performed at times when upwelling was almost permanent, the simulations showed elevated nutrient concentrations in surface waters. This was especially distinct in spring when primary production and phytoplankton biomass were both higher. In late summer, however, upwelling caused primary production to decrease, despite the elevated nutrient levels.

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1. Introduction

Previous papers on coastal upwelling in the Baltic Sea have usually focused on descriptions of its occurrence and the conditions of its generation. Satellite observations provide detailed information on such events (Horstman 1983, 1987, Gidhagen 1984, 1987, Bychkova & Viktorov 1987, Bychkova et al. 1988, Urbański 1995, Krężel 1997a, Siegel et al. 1999). In recent years some attempts at modelling upwelling have also been undertaken. Lass et al. (1994) and Fennel & Seifert (1995) studied the dynamics of the upwelling that took place northwest of Rügen. A three-dimensional hydrodynamic model (Kowalewski 1998) was used to examine the areas where upwelling occurs, the meteorological preconditions for such events in the Baltic Sea and their frequency (Kowalewski & Ostrowski 2005, this volume). Upwelling along the Polish coast has been simulated by Jankowski (2002). Myrberg & Andreyev (2003) determined an upwelling index for different parts of the Baltic, based on a ten-year model simulation.

Surface water nutrients are usually consumed or even depleted as a result of the life functions of phytoplankton. Upwelling could make that deficit good, since it raises nutrients from deeper waters. One could put forward the hypothesis that since upwelling fertilises the surface water, it should contribute to an increase in primary production and consequently, in the biomass of phytoplankton and zooplankton. Studies of the chemical and biological effects of upwelling in the Baltic Sea began not long ago, but they have often yielded contradictory results. Nômmann et al. (1991) reported an increase in primary production near Hiiumaa Island within some days of an upwelling event. The raising of nutrients by upwelling along the Hanko Peninsula, lying between the Gulf of Finland and the Baltic Proper, was described by Haapala (1994). Uitto et al. (1997) noted that this process was accompanied by a decrease in primary production. Siegel et al. (1999) found from satellite observations and ecological modelling that after the first spring phytoplankton bloom, when surface nutrient salts were depleted, coastal upwelling sufficed to support the bloom. However, satellite images indicated a lower chlorophyll *a* concentration during spring upwelling events (Semovski et al. 1999, Krężel et al. 2005, this volume). Cold waters raised to the surface prevented cyanobacteria blooms in summer (Siegel et al. 1999) and increased the chlorophyll *a* concentration in the Hel upwelling area in early autumn (Krężel et al. 2005, this volume). Ennet et al. (2000) used an ecohydrodynamic model to study the influence of upwelling on phytoplankton blooms in the Gulf of Riga. Kostrichkina & Yurkovskis (1986) noted an increase in zooplankton biomass in the open sea 2–3 weeks after an upwelling occurrence, off the eastern shores of the Baltic Proper.

The present work investigated the vertical transport of nutrients as a result of upwelling along the Hel Peninsula (Gulf of Gdańsk). The ProDeMo ecohydrodynamic model (Jędrasik 1997, Ołdakowski & Renk 1997, Ołdakowski et al. 2005, this volume) describes the dynamics of organic matter production and decomposition in terms of nutrient cycles in the sea. It was applied here to determine nutrient fluxes and to study the effect of the Hel upwelling on primary production and phytoplankton biomass.

2. The ProDeMo model

Any study of coastal upwelling in the Baltic Sea is fraught with difficulties owing to the small extent and irregular occurrence of such events. They take place when winds blow from certain directions; the Hel upwelling, for example, makes its appearance when winds are from the east, south-east and south. The poor reliability of long-term wind forecasts is a further obstacle to the efficient planning of research cruises. Moreover, since upwelling occurs in a narrow coastal zone, it is rarely reported during routine monitoing. It is therefore satellite detection methods, and recently also numerical modelling, that are mostly used nowadays for investigating upwelling.

Developed at the Institute of Oceanography, University of Gdańsk, the ProDeMo ecohydrodynamic model was used in the present work (Ołdakowski & Renk 1997, Ołdakowski et al. 2005, this volume). A three-dimensional numerical model describing biogeochemical processes in the sea, it is integrated with a hydrodynamic model (Kowalewski 1997) and allows the horizontal and vertical transport due to advection and diffusion to be calculated. The latter model had been used in earlier studies of upwelling dynamics in the Baltic, and the validated model results showed good agreement with satellite observations (Kowalewski 1998, Kowalewski & Ostrowski 2005, this volume).

The two models cover the Baltic Sea and the Gulf of Gdańsk with respective numerical grids of c. 5 and 1 NM (Fig. 1). A numerical grid with a sigma-transformation enabled the vertical profile at any point in the sea, irrespective of depth, to be divided into the same number of layers – in this case, 18 layers of different thickness. Thinner layers were adopted to obtain a better representation of the surface and bottom boundary layers.

The ProDeMo model addresses 15 state variables that can be classified into a number of functional groups: nutrients, phytoplankton, zooplankton, organic detritus and dissolved oxygen. Nutrients include nitrate nitrogen (N-NO_3), ammonium nitrogen (N-NH_4), phosphate phosphorus (P-PO_4) and silicate silicon (Si-SiO_4). The nitrogen, phosphorus and silicon cycles are much the same with respect to exchange with the bottom sediments and the air. The nitrogen cycle involves mineralisation, nitrification,

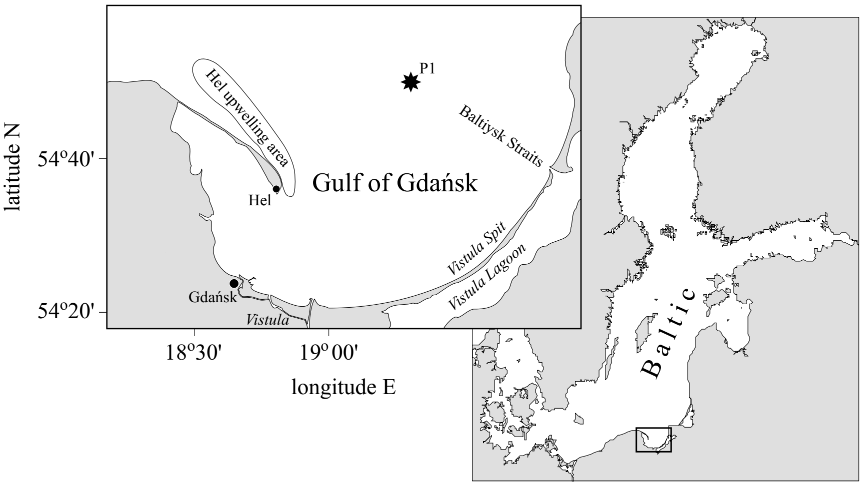

Fig. 1. The modelled areas – the Baltic Sea and the Gulf of Gdańsk

denitrification and uptake by phytoplankton, the changes in phosphorus concentration are described by mineralisation, uptake by phytoplankton, and absorption-desorption on suspension, and the silicon cycle includes mineralisation and uptake by phytoplankton (Ołdakowski et al. 2005, this volume).

The phytoplankton was divided into two groups – diatoms and other forms. The biomass changes in these groups were due to phytoplankton growth (in relation to temperature and light intensity), respiration, zooplankton grazing, death, and sinking. Zooplankton was limited to phytoplankton feeders, and the zooplankton balance took nutrition, respiration, excretion and death into account. Detritus included dead phyto- and zooplankton and mineralised faeces. The mass balance of dissolved oxygen included deep-sea processes, consumption of oxygen for bottom sediment mineralisation, and exchange across the air-sea interface. The ProDeMo model parameterises light penetration into deep water in relation to phytoplankton and detritus concentrations (Ołdakowski et al. 2005, this volume).

Carried out for the year 2000, the model simulations took the water entering the Baltic Sea from the 125 largest rivers into account. For the Vistula (Wisła), the largest river entering the Gulf of Gdańsk, the data included daily flow-rates and temperatures, and twice-monthly concentrations of nitrates, ammonia, total nitrogen, total phosphorus and dissolved oxygen. Daily concentrations of these nutrients were obtained by interpolation. The daily flow-rates and temperatures for the other rivers were calculated from multi-annual trigonometric series describing the seasonal variability of river inflows (Cyberski 1997). On the basis of the available data (Stålnacke 1996), nutrient and oxygen concentrations were assumed constant in all the rivers, except the Vistula. The influx of nitrogen and phosphorus compounds from the atmosphere was estimated from literature data (Falkowska 1985).

Solar energy fluxes were calculated for every time step on the basis of solar zenith angles and weather records (Krężel 1977b). The other elements of the sea-surface heat balance were estimated from meteorological data and simulated sea-surface temperatures (Jędrasik 1997). The meteorological data – wind field, air temperature, atmospheric pressure and water vapour pressure – were obtained from the UMPL mesoscale operational weather forecast model (Herman-Iżycki et al. 2002). The initial conditions for the hydrological and nutrient fields were adopted in accordance with their climatic distributions. The 3D distributions of water temperature, salinity and nutrient concentrations were prepared using the Data Assimilation System (Sokolov et al. 1997), founded on the Baltic Environmental Database (http://data.ecology.su.se/models/bed.htm). When the model was implemented, the changes in state variables were affected only by time-variable meteorological conditions and river inflows; no data assimilation was performed.

3. Comparison of model results with measurements

The data collected during two research cruises in the Hel upwelling region in April (28.04.2000) and September (18.09.2000) were used for validating the model results. During each cruise three stations were set up based on preliminary measurements of surface water temperature, and biological and chemical investigations were carried out at each one. The first station was situated at the site of the lowest surface water temperature, i.e. at the upwelling centre, the second one on the border of the upwelling region (in the vicinity of the hydrological front); the third station was located beyond the cooler water zone. The following measurements were performed at the stations: water temperature and salinity, nutrient concentration (nitrates, ammonia, and phosphates), dissolved oxygen (Burska & Szymelfenig, in press), and phytoplankton and zooplankton biomass (Gromisz & Szymelfenig, in press). The measurements at 0.5 m depth were used for testing the model, and the simulated *in situ* primary production (Renk et al. 2000) was calculated on the basis of potential primary production at 2.5, 5, 10 and 15 m depth (Zalewski et al., in press)

Monitoring data from station P1[1] (Gdańsk Deep) were used for validating the model results in the open sea. Specifically, the measurements

[1]The data were obtained from the Institute of Meteorology and Water Management, Maritime Branch, Gdynia.

made during the Hel upwellings on 16.04.2000 and 28.09.2000 were chosen. This included water temperature and salinity, concentrations of nutrients (nitrates, ammonia, phosphates and silicates) and dissolved oxygen at 1, 3, 5, 10, 15 and 20 m depth, and thence down to 110 m at 10 m intervals. Total nitrogen and phosphorus were also available for 16.04.2000.

Fig. 2 presents the spatial distributions of the physical, chemical and biological parameters in the surface layer, obtained from model simulations and measurements (28.04.2000). The effect of upwelling on the modelled water temperature field was a significant drop in temperature along the Hel Peninsula. Temperatures were 4.5°C at the upwelling centre, 6.5°C in the transition zone and 9°C in the surrounding waters. The measured temperature range was similar: 5.3–9.3°C. Greater discrepancies between the observations and the model results were linked with their spatial distribution, and are due to field 'blurring', an artifact typical of the model. The use of a numerical grid with a relatively long spacing (1 NM) in comparison to the width of the upwelling zone permitted the smoothing of steep gradients. In consequence, the modelled upwelling zone is broader than the actual one, and the station where the measured temperature (9.3°C) was typical of the surrounding waters was found in the modelled upwelling zone where the temperature was c. 5°C. The salinity validation yielded similar results. The ranges of modelled (6–6.8 PSU) and measured (6.1–7.0 PSU) values displayed substantial conformity, and gradients were smoothed. Low salinities (< 6 PSU) to the north of the Hel

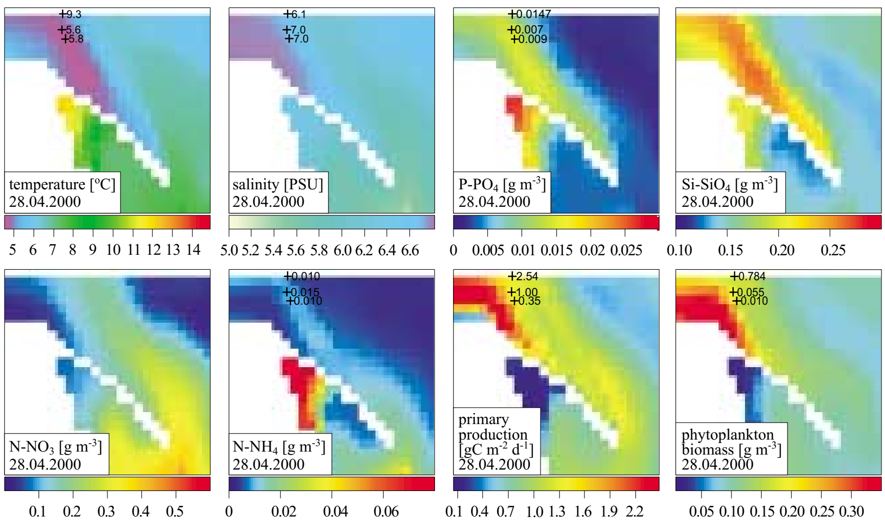

Fig. 2. Modelled spatial distributions and point data of physical, chemical and biological parameters for the surface layer in the Hel upwelling area on 28.04.2000

Peninsula revealed the rare situation when fresh waters from the Vistula are transported to beyond Hel. As a result, large amounts of nutrients, nitrogen compounds in particular, reached the upwelling area with the Vistula waters. The reported concentrations of ammonia and phosphates were consistent with the modelled ones.

The measurements showed a fall in primary production near the upwelling centre, whereas the modelled data indicated the opposite tendency. The zone of enhanced primary production was shifted in relation to the area where the increase in nutrient concentrations occurred. This could be explained by the time interval between the appearance of the nutrients at the sea surface and their consumption in primary production. Sea currents transport the upwelled waters towards the north-west, and this is exactly where the zone of increased primary production had shifted to (Fig. 2). The situation was the same with respect to the phytoplankton biomass distribution. As a result of the shift, all the measuring stations found themselves on the border of this increased production zone; it is this that may have given rise to the discrepancies between measurements and modelled results. In order to record the effect of elevated nutrient levels on primary production and phytoplankton biomass, the measuring stations should have been sited considerably farther to the west. The low phytoplankton biomass measured in the zone of rising currents was the direct consequence of upwelling. The lack of such effects in the modelled data was probably due to the smoothing of the numerical solutions and to the rather too rapid adaptation of the modelled phytoplankton to the cold upwelled water. On 16.04.2000 the vertical distributions of the modelled physical and chemical parameters in the Gdańsk Deep (Fig. 3) showed a high correlation with the observations, especially in the 0–60 m layer, although there were some discrepancies regarding nitrates and silicates. According to the simulations, surface nitrates should already have been depleted, whereas the measured concentration was c. 2 g m^{-3}. The simulated silicate concentrations were also underestimated as compared to the observations.

In September, as in April, the model results indicated the occurrence of an upwelling plume, since cold waters had been raised to the surface (Fig. 4). Moreover, at the centre of the upwelling plume, the measured temperature was markedly lower (4.6°C) than that yielded by the model simulation (c. 10.5°C). The simulation produced similar results for all the nutrient salts; their concentrations were relatively high to the north of the Hel Peninsula. This may have been due partly to the influence of upwelling (in the near-shore zone), and partly to an inflow of water from the Gulf of Gdańsk (at a greater distance from the shore). The measured nutrient concentrations tended to increase near the upwelling centre, which was in

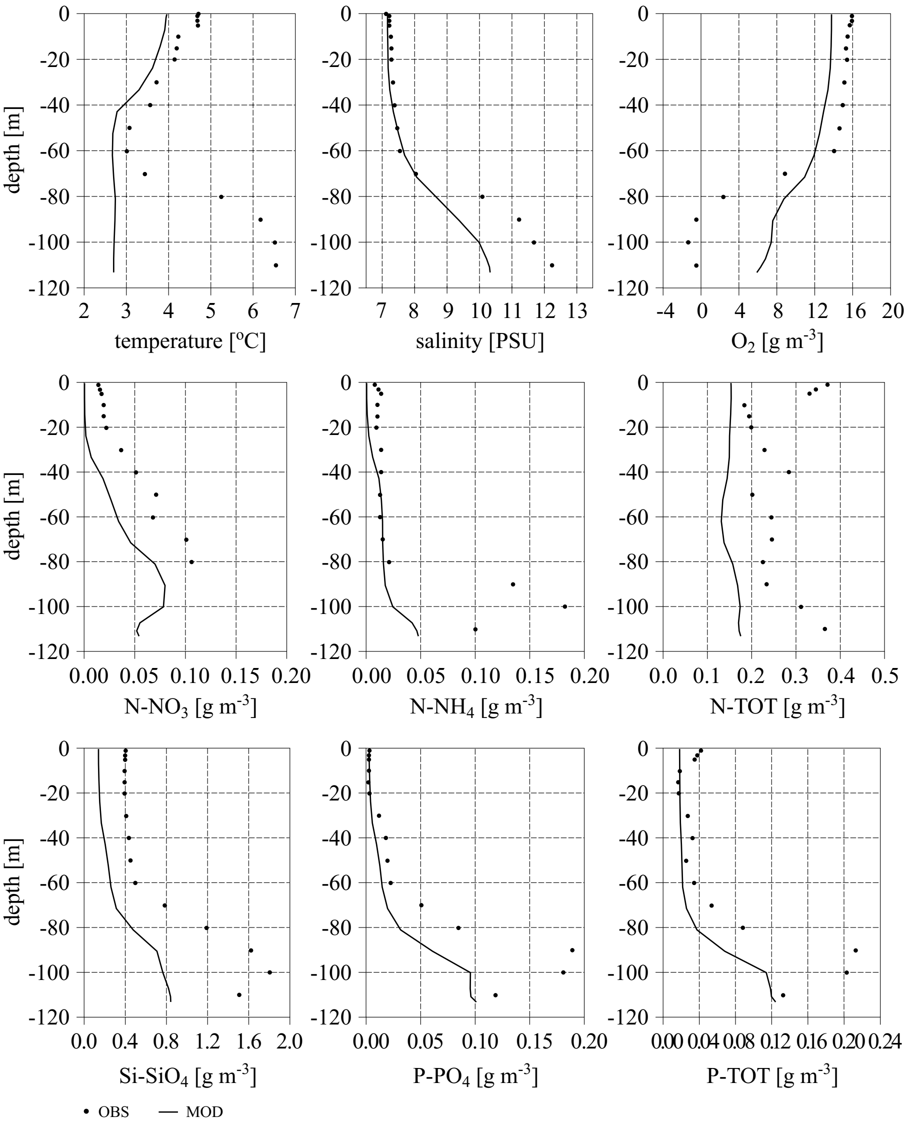

Fig. 3. Comparison of the model (MOD) with measurements (OBS) at station P1 (Gdańsk Deep) on 16.04.2000

excellent agreement with the model's predictions. Unlike April, however, the model calculations for September indicated a distinct drop in primary production in the upwelling area. This was confirmed by the measurements of potential primary production and phytoplankton biomass.

In September, as in April, the vertical distributions of the modelled parameters conformed more closely with the open-sea measurements in the Gdańsk Deep (Fig. 5) than in the Hel upwelling area. Most measurements

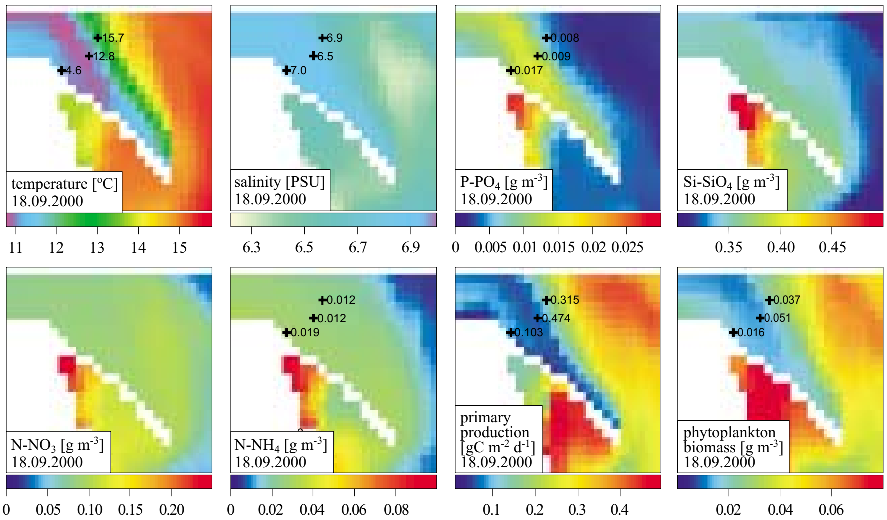

Fig. 4. Modelled spatial distributions and point data of physical, chemical and biological parameters for the surface layer in the Hel upwelling area on 18.09.2000

and the model simulations in the surface layer above the thermocline indicated very low concentrations of nutrients – evidence of their consumption. On the other hand, nitrate and phosphate concentrations were higher between the thermocline and halocline (40–70 m).

The results of the ProDeMo model simulation for the Gdańsk Deep generally conformed with the measurements carried out in April and September. However, significant discrepancies were found between the model validation and the measurements in the Hel upwelling area, especially in April.

4. The results of the model simulations

Nutrients upwelled to the sea surface can affect primary production on entering the euphotic zone. The thickness of this zone in the Baltic Sea depends mainly on the water transparency, which is subject to considerable fluctuations (from a few to 20 m). To estimate the inflow of nutrients, a more suitable depth for analysing the vertical fluxes of those substances should have been chosen. It would have been better to perform the calculations for a mixed-layer depth, as primary production is concentrated entirely in that layer, except in early spring when the thermocline may lie in shallower waters. Since nutrients are readily mixed, they are available for primary production even when the euphotic zone is thinner. Unfortunately, the thickness of the mixed layer is not constant either; this depends, among other things, on the season of the year and the wind velocity. In the face of these difficulties, the preliminary analysis of nutrient fluxes was carried

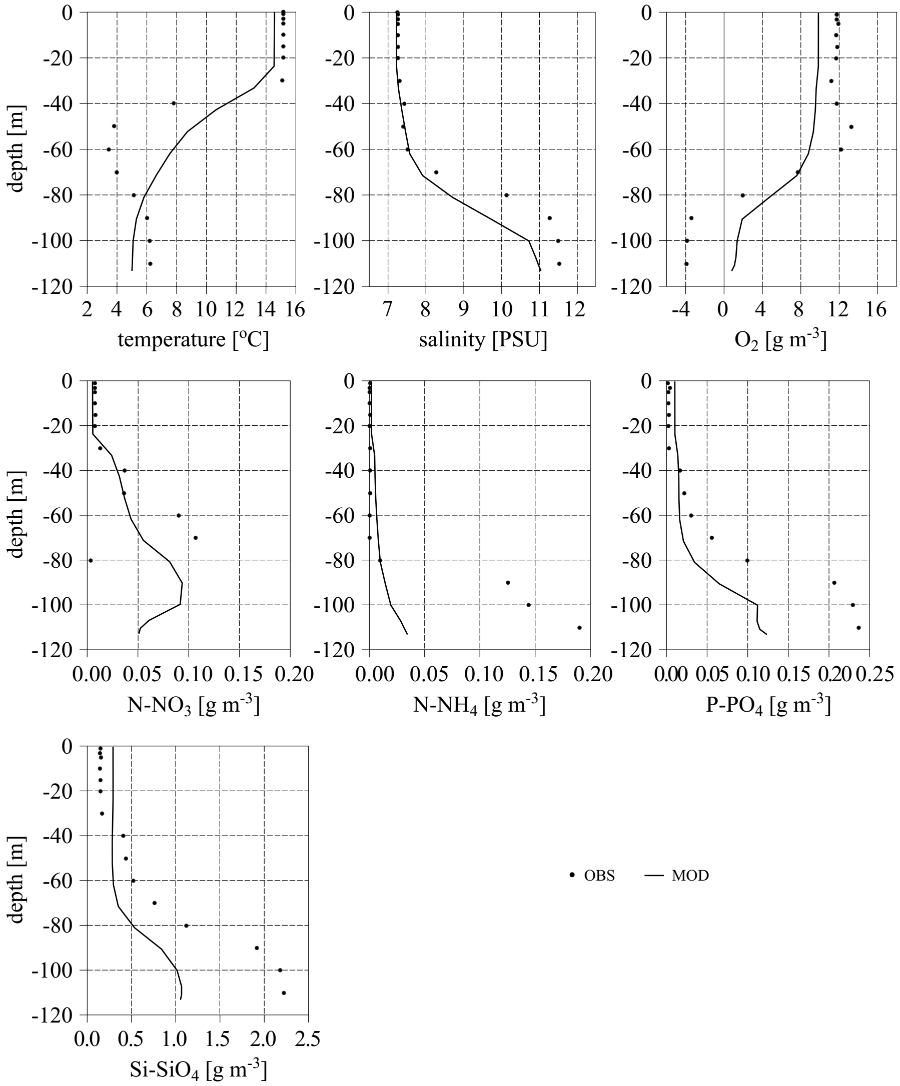

Fig. 5. Comparison of the model (MOD) with measurements (OBS) at station P1 (Gdańsk Deep) on 28.09.2000

out at 10 and 20 m depth. Since the results obtained were very similar, the depth of 20 m was assumed characteristic of the mixed layer.

The model simulations for the year 2000 enabled calculation of the mean water vertical flows at 20 m depth (Fig. 6) in the Hel upwelling region. This (Fig. 1) was determined on the basis of an analysis of vertical velocities (Kowalewski & Ostrowski 2005, this volume). Although upwelling alternated with downwelling, the periods dominated by one of these events were readily distinguishable. Strong downwelling was dominant in winter,

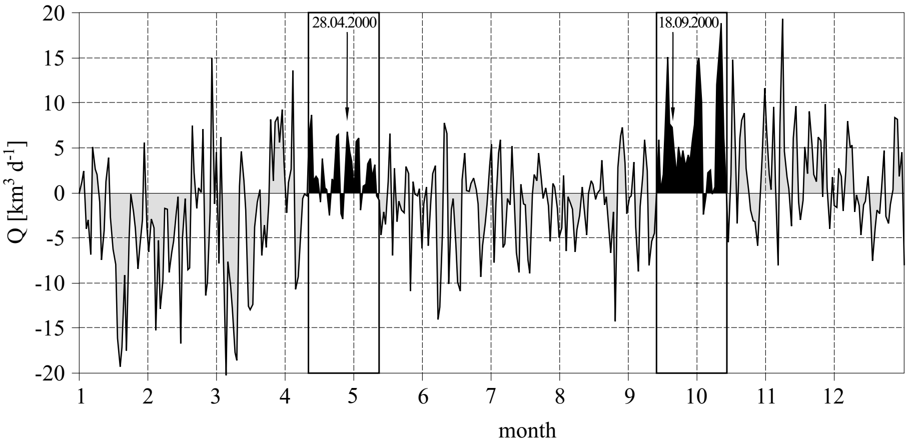

Fig. 6. Daily mean vertical flows (upwelling – positive values) calculated from the model at 20 m depth in the Hel upwelling area in 2000; periods of upwelling dominance (rectangles) and cruise dates (arrows)

upwelling in spring and autumn. In summer, however, the situation changed considerably, when downwelling prevailed slightly. Fig. 6 illustrates two 30-day periods when upwelling was almost permanent, and gives the dates of the respective cruises. In the first period (11.04.2000–10.05.2000) vertical fluxes were weak and downwelling dominated for four days. In late summer – early autumn (13.09.2000–12.10.2000) upwelling was much stronger, and downwelling was noted on only one day.

The nutrient loads carried by vertical currents at 20 m depth in the upwelling area are presented in Fig. 7. The figure also illustrates the loads carried by the Vistula, which is the chief source of nutrient salts in the Gulf of Gdańsk. In the first upwelling period analysed (spring), the nitrogenous load rising to the surface was much smaller than that carried by the Vistula. In autumn, on the other hand, upwelling induced an inflow of nitrates and ammonia to the surface layer that exceeded many times the load carried by the Vistula (Table 1). This was also reflected in the monthly loads carried up to the surface by vertical flows (Table 2), which were larger than the loads entering with the Vistula between September and November. The situation with phosphate phosphorus was very much the same, except that even in spring the upwelling load was larger than that of the Vistula.

The calculations made for two periods of upwelling dominance showed that the phosphate loads raised by the vertical current were much bigger than those carried by the Vistula (Table 1). The upwelling-induced inflow of mineral nitrogen compounds to the surface layer was smaller in spring but larger than that of the Vistula in autumn. However, it should be noted

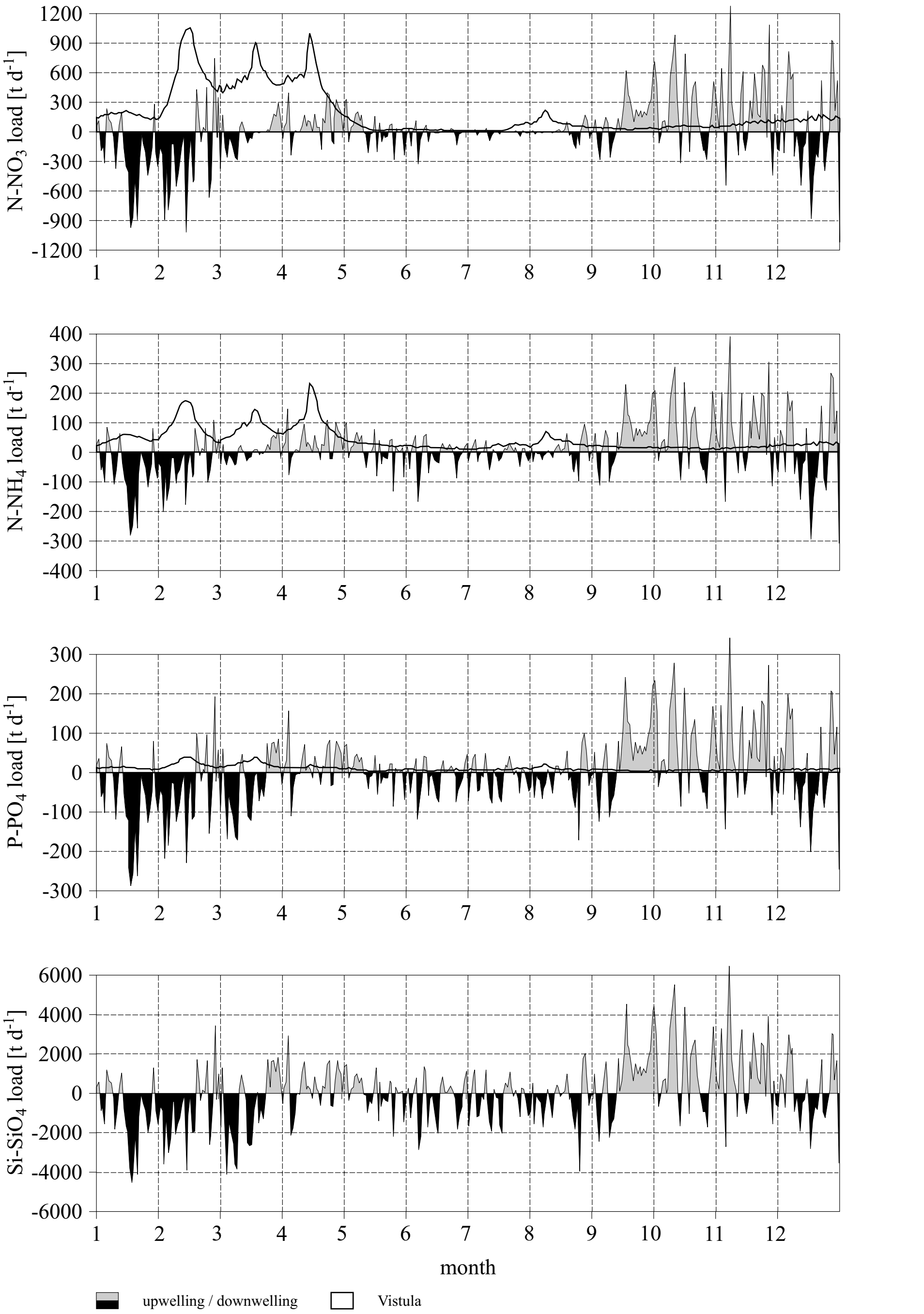

Fig. 7. Modelled daily loads of nitrate nitrogen, ammonium nitrogen, phosphate phosphorus and siliceous silicon carried by vertical flows at 20 m depth in the Hel upwelling area in comparison with the Vistula loads

Table 1. The modelled vertical water flow (Q_w) at 20 m depth, the loads of nutrients induced by those flows in the Hel upwelling area (HUA) and the Vistula river outflows (Q) and nutrient loads in two periods of upwelling dominance

Period	Q_w [km^3] HUA	Q [km^3] Vistula	N-NO$_3$ [10^6 kg] HUA	Vistula	N-NH$_4$ [10^6 kg] HUA	Vistula	P-PO$_4$ [10^6 kg] HUA	Vistula	Si-SiO$_4$ [10^6 kg] HUA
11.04–10.05	72.2	6.8	3.7	11.4	1.2	2.7	0.84	0.33	17.0
13.09–12.10	183.9	1.9	8.7	1.1	3.0	0.4	2.91	0.13	56.5

Table 2. The modelled vertical water flow (Q_w) at 20 m depth, the loads of nutrients induced by those flows in the Hel upwelling area (HUA) and the Vistula river outflows (Q) and nutrient loads in 2000

Month	Q_w [km^3] HUA	Q [km^3] Vistula	N-NO$_3$ [10^6 kg] HUA	Vistula	N-NH$_4$ [10^6 kg] HUA	Vistula	P-PO$_4$ [10^6 kg] HUA	Vistula	Si-SiO$_4$ [10^6 kg] HUA
January	−138.0	2.5	−7.3	5.3	−2.24	1.32	−2.19	0.33	−34.9
February	−110.5	5.9	−6.8	17.6	−1.41	2.84	−1.61	0.65	−27.5
March	−104.6	6.7	−0.4	17.3	0.00	2.45	−0.94	0.67	−22.8
April	36.6	7.8	2.5	15.6	0.85	3.16	0.46	0.36	8.6
May	−3.4	3.3	0.6	1.7	0.17	0.80	0.10	0.18	0.4
June	−66.7	2.1	−0.6	0.6	−0.44	0.42	−0.48	0.16	−13.4
July	−40.0	2.1	−0.2	0.9	−0.18	0.55	−0.36	0.24	−9.3
August	−37.8	3.6	−0.1	3.0	−0.15	1.05	−0.40	0.31	−10.4
September	84.0	2.0	4.2	1.1	1.52	0.48	1.42	0.18	26.4
October	126.7	1.7	6.5	1.6	2.16	0.38	1.92	0.13	38.5
November	88.7	1.8	6.9	2.5	2.25	0.45	1.86	0.17	32.6
December	5.1	2.0	0.3	4.0	−0.23	0.78	0.06	0.24	1.3
Total	−159.7	41.6	5.5	71.1	2.30	14.68	−0.17	3.61	−10.5

that the Vistula flows in the spring of 2000 were significantly greater than the many years' mean: in March by 86%, in April by 50%, and close to the mean in May.

The overall flow of water in the Hel upwelling region in 2000 showed that downwelling was dominant; this is the typical situation (Kowalewski & Ostrowski 2005, this volume). Nevertheless, the annual flow of nitrogen compounds was positive (Table 2), i.e. more nitrates and ammonia were upwelled to the surface layer than were removed by downwelling. This can be explained by the fact that nitrogen compounds were depleted during the summer dominance of downwelling, and even strong downwelling could not induce large flows.

Figs 8 and 9 illustrate the averaged spatial distributions of mean nutrient concentrations at 1, 10 and 20 m depth, and their vertical fluxes during the spring upwelling. The spatial distributions of the vertical fluxes were very similar for the individual nutrients. There was a zone along the Hel

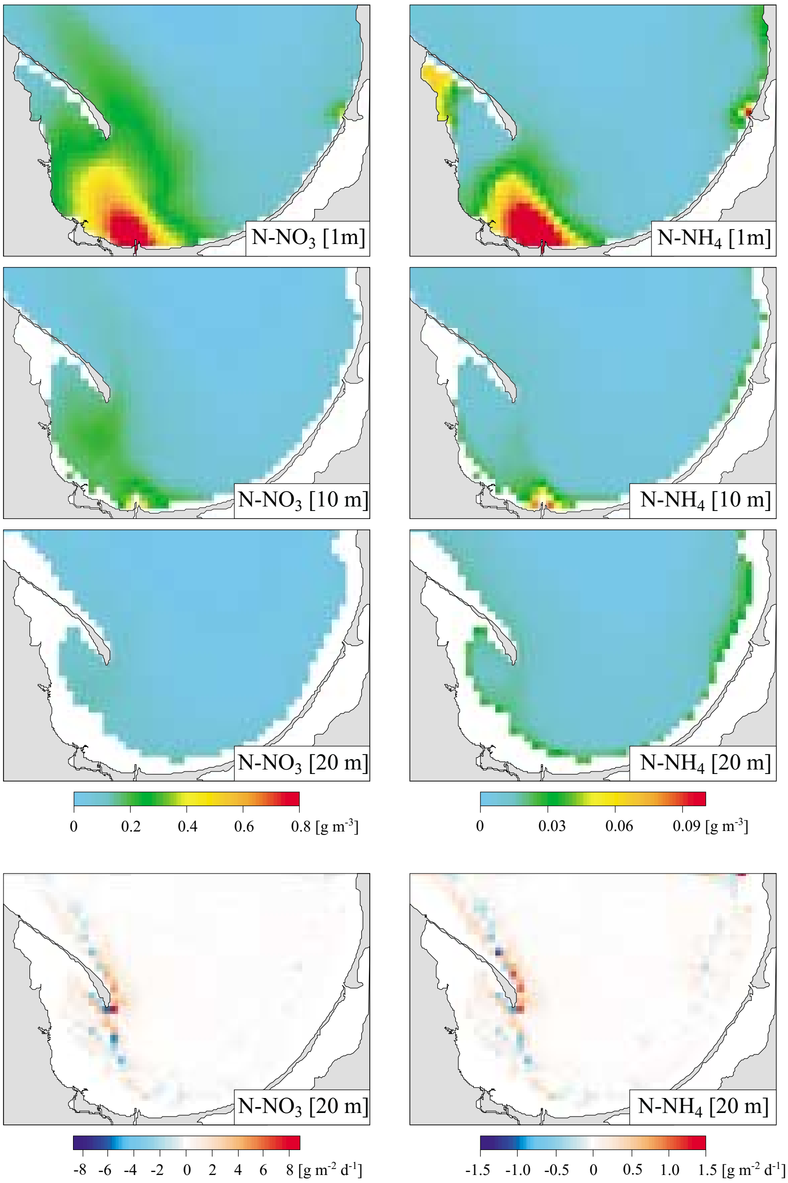

Fig. 8. Mean concentrations of nitrate and ammonium nitrogen at 1, 10 and 20 m depth and their vertical fluxes at 20 m depth, calculated for the period between 11.04.2000 and 10.05.2000

Peninsula where nutrient salts were raised, alongside which there were very much smaller downwelling zones. That the Vistula is the main source of nitrogen compounds in the Gulf of Gdańsk is strongly manifested in the surface water layer (0–10 m) of the latter (Fig. 8). The influence of the Hel

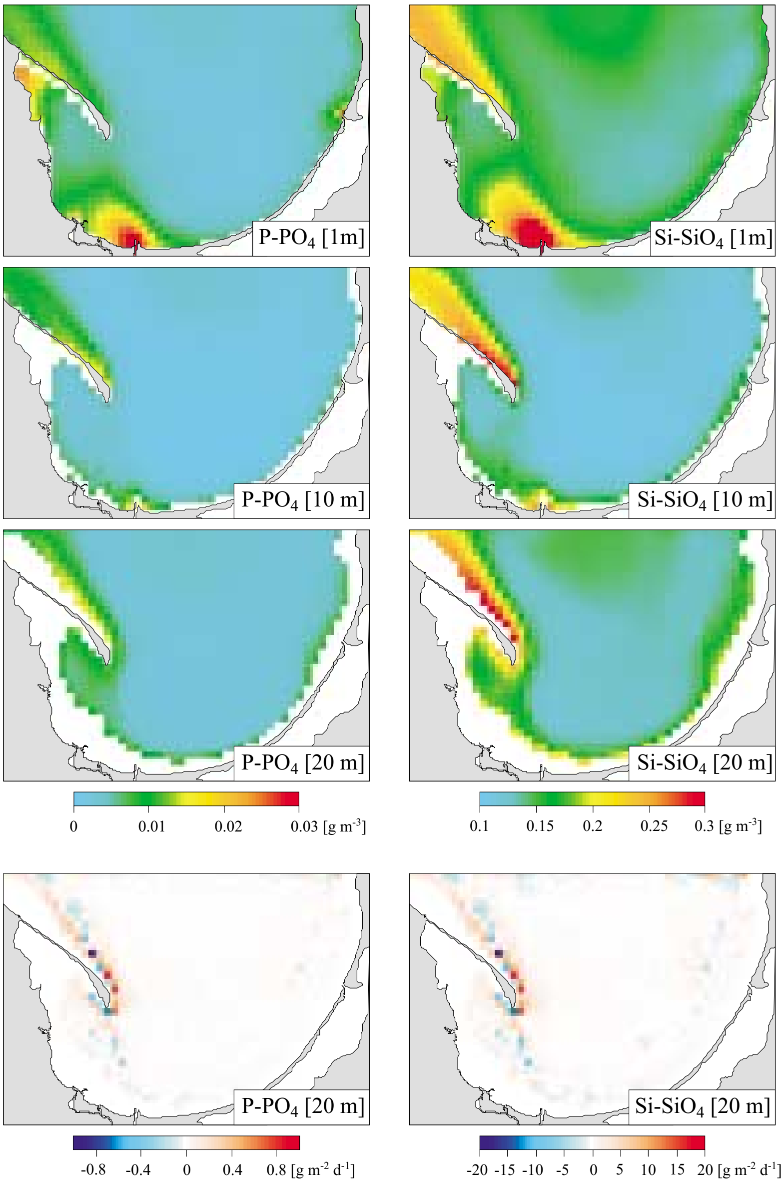

Fig. 9. Mean concentrations of phosphate phosphorus and siliceous silicon at 1, 10 and 20 m depth and their vertical fluxes at 20 m depth, calculated for the period between 11.04.2000 and 10.05.2000

upwelling made itself felt in a rise of waters containing lower concentrations of nitrogen compounds, which was especially clear at 10 m. In contrast, the ammonia concentration at 10 and 20 m in the upwelled waters was slightly higher than in the surrounding waters. This effect was more pronounced in the case of phosphates and silicates (Fig. 9), since the influence of upwelling, the only source apart from the Vistula, was also apparent at the surface.

The mean vertical velocity at 20 m in the spring upwelling (Fig. 10) shows that upwelling was strongest to the north of the Hel Peninsula. As a result of upwelling, the decrease in surface water temperature was shifted north-westwards, and the biological effects, i.e. the increase in phytoplankton production and biomass was observed further away (Fig. 10). The spatial distribution of primary production showed high values near the Vistula mouth and in the Hel upwelling region, the values in the latter region being even higher than in the former. A third area with higher levels of primary production lay along the Vistula Spit, near the straits by Baltiysk that join the Vistula Lagoon with the Baltic. The intensive primary production in that region is due to the nutrient-rich waters flowing out of the Vistula Lagoon. There was a similar spatial distribution pattern of the mean phytoplankton biomass. This was significantly higher in the

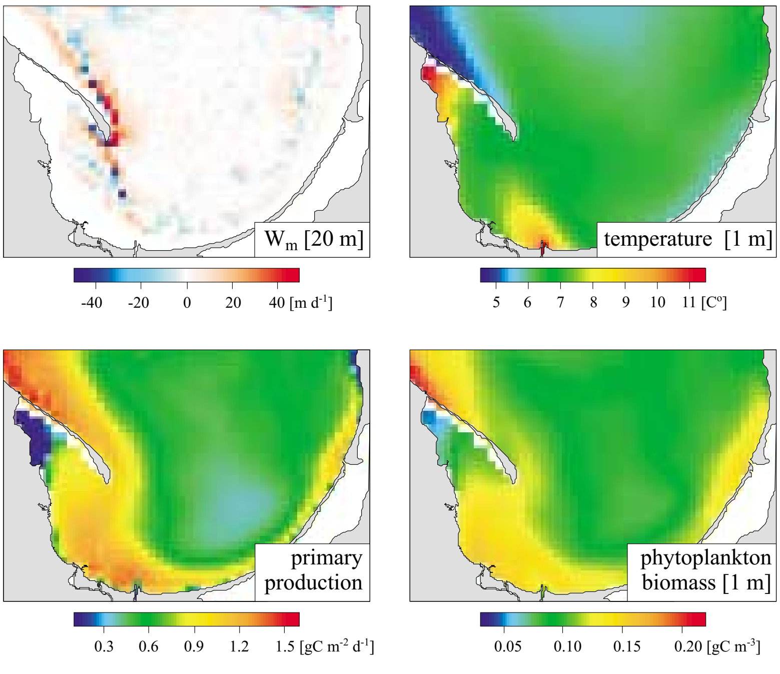

Fig. 10. Mean vertical velocity W_m at 20 m depth, surface water temperature, phytoplankton primary production and biomass between 11.04.2000 and 10.05.2000

Hel upwelling region, at the Vistula mouth and in the Baltiysk Straits (Fig. 10). The highest biomass concentrations (c. 0.2 g m^{-3}) were also noted at the base of the Hel Peninsula.

The spatial distribution of the vertical fluxes of nitrate and ammonia nitrogen in the Gulf of Gdańsk, averaged over the period between 13.09.2000

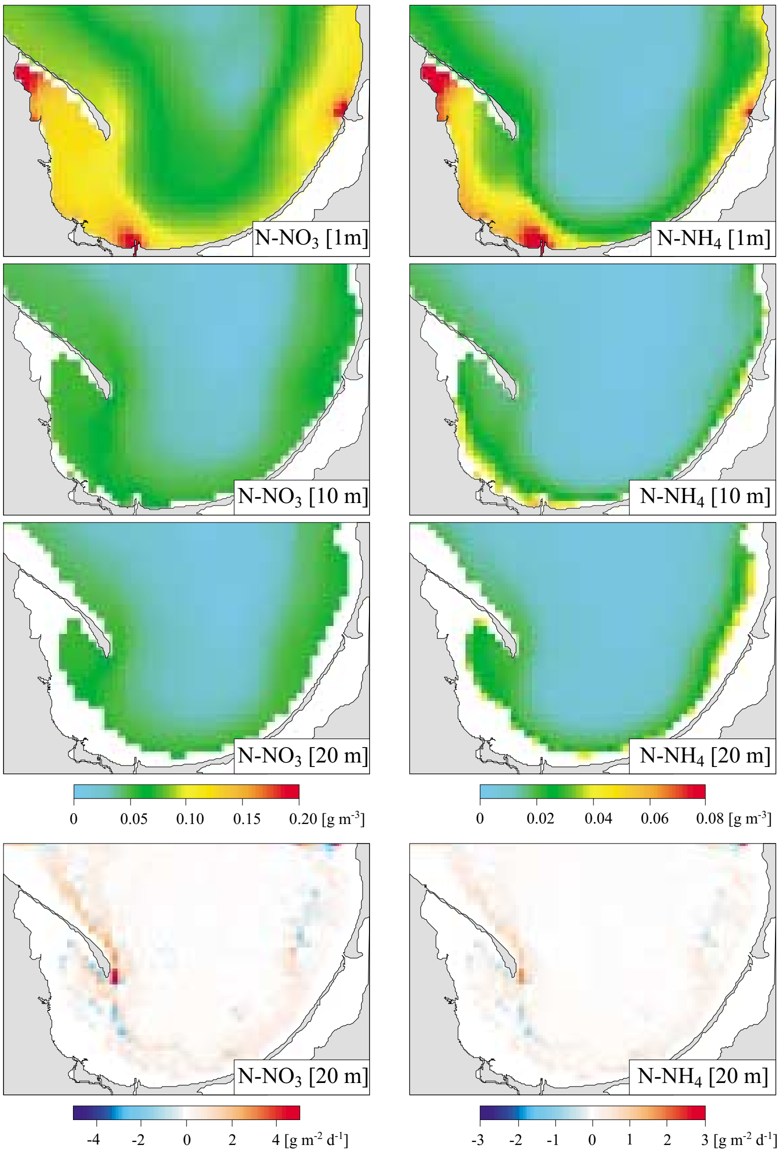

Fig. 11. Mean concentrations of nitrate and ammonium nitrogen calculated at different depths and their mean vertical fluxes at 20 m depth, calculated for the period between 13.09.2000 and 12.10.2000

and 12.10.2000 (Fig. 11), resembled those in the spring upwelling (Fig. 8). However, the nitrate fluxes were about half as large as in spring, which was the effect of lower concentrations but not of a weaker upwelling. In autumn, the distributions of mean nitrogen levels were more even than in

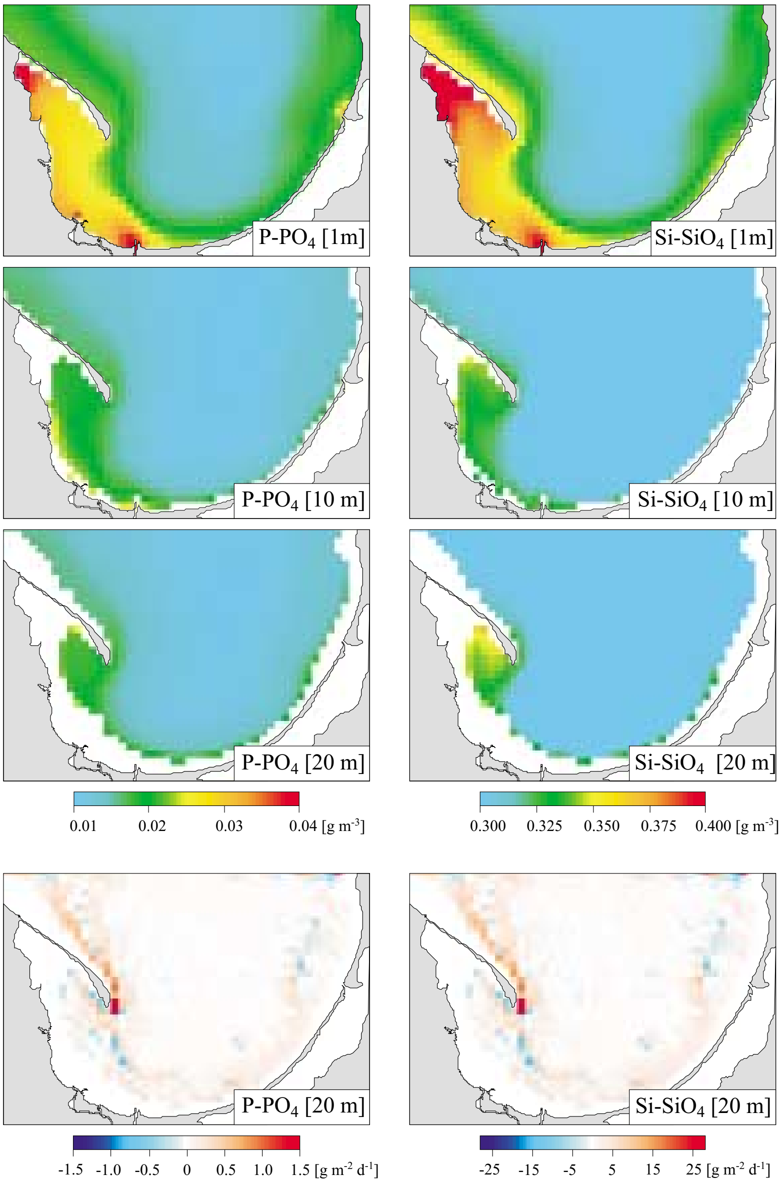

Fig. 12. Mean concentrations of phosphate phosphorus and siliceous silicon calculated at different depths and their mean vertical fluxes at 20 m depth, calculated for the period between 13.09.2000 and 12.10.2000

spring, when concentrations off the Vistula mouth were very high. The concentrations in the coastal zone of the Gulf of Gdańsk (at 10–20 m depth) were somewhat higher than in the central part of the gulf. The Hel upwelling affected surface nitrate concentrations only slightly. The pattern for phosphates and silicates was similar (Fig. 12). Concentrations in the Hel Peninsula region increased mainly in the surface layer; such a slight increase as a result of summer and autumn upwelling could be explained by the very similar nutrient concentrations from surface to halocline. Only an exceptionally powerful upwelling, capable of raising saline waters from beneath the halocline, could bring about a significant increase in surface nutrient concentrations. The Hel upwelling had a stronger influence on temperature, which fell by c. 4°C in that region (Fig. 13). The upwelling in the Vistula Lagoon also resulted in lower temperatures near the Vistula mouth. The occurrence of two upwellings was confirmed by the positive mean vertical velocities in both regions. The upshot of the low water temperature and the unchanged nutrient concentrations was a reduction in phytoplankton primary production and biomass. The effects of the Hel upwelling were more distinct because, on the one hand, the upwelling was stronger and resulted in a greater fall in temperature, and on the

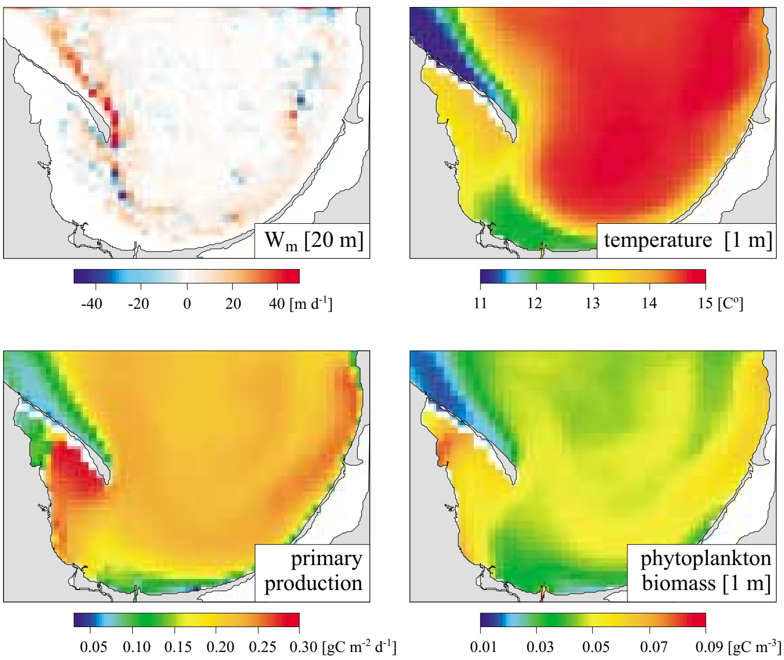

Fig. 13. Mean vertical velocity W_m at 20 m depth, surface water temperature, phytoplankton primary production and biomass between 13.09.2000 and 12.10.2000

other, the large nutrient loads carried by the Vistula to a certain extent compensated for the unfavourable thermal conditions. Therefore, upwelling reduced phytoplankton production in late summer. In contrast, an increase in primary production was noted in spring.

5. Discussion

The validation of the model results based on measurements revealed a greater consistency of the simulation results in the open sea (the Gdańsk Deep) than in the upwelling region. This was in large measure due to numerical errors, since the numerical grid spacing (c. 1 NM) was relatively long compared to the width of the upwelling zone (usually a few km). These errors smoothed out the steep gradients in the upwelling area. Such errors could have been reduced by using a smaller numerical grid size.

The biggest differences between the model results and simultaneous observations were found for April. Only the temperature and salinity distributions were generally similar. The model points to elevated nutrient concentrations in the Hel upwelling area, except for nitrates, where the measurements indicate the opposite. The model simulation gives increased values of phytoplankton primary production and biomass, whereas the measurements show a decrease in those values. This discrepancy can be explained partly by the fact that the area of higher productivity had shifted westwards, away from the measurement site. The choice of measurement points based on temperature distribution turned out not to be the best for validating the biological parameters. There is a temporal and spatial shift between the thermal and biological effects of upwelling. Therefore, the most significant influence of upwelling on phytoplankton primary production or biomass is observed after a few days, and not at the upwelling centre but on its borders (Nômmann 1991). The shift is greater in the case of zooplankton, and an increase in zooplankton biomass concentration (Kostrichkina & Yurkovskis 1986) was indeed observed 2–3 weeks after the upwelling event.

In the two selected periods of upwelling dominance in the Hel Peninsula region, i.e. in spring (11.04.2000–10.05.2000) and early autumn (13.09.2000 –12.10.2000), the nutrient loads raised by upwelling were compared to those carried at the same time by the Vistula to the Gulf of Gdańsk. Mineral nitrogen loads raised by upwelling were lower in spring and higher in autumn compared to those in the Vistula. On the other hand, the phosphate loads brought to the surface layer by the Hel upwelling were higher in both periods. This means that a prolonged upwelling in the Hel region and the Vistula are comparable sources of nutrient salts. The model calculations confirmed the increase in nutrient concentrations observed in the Baltic Sea under the influence of coastal upwelling (Haapala 1994, Burska & Szymelfenig, in press). The increase in surface nutrient concentrations as a result of upwelling was stronger in spring than in late summer, and was due specifically to the vertical distributions of nutrient concentrations. The vertical gradients were steeper in spring since the depletion of nutrients due to biological production began in the relatively thin and warm surface water layer (above the thermocline). In the much thicker layer delimited by the halocline (down to c. 60–70 m) nutrient concentrations were similar. The greatest increases in nutrient levels as a result of upwelling applied to silicate and phosphate. The concentrations of upwelled nitrogen compounds were even lower than those at the surface, which was due to an inflow of fresh Vistula water reaching the north shores of the Hel Peninsula as a thin surface layer. Such 'tongues' of fresh waters contain higher levels of nutrients and organic matter. In such a case, upwelled waters lead to a drop in productivity (Semovski et al. 1999, Krężel et al. 2005, this volume).

Previous measurements in the Baltic Sea had pointed to either a decrease (Uitto et al. 1997, Zalewski et al., in press) or an increase (Kahru et al. 1984, Nômmann 1991) in primary production as a result of an upwelling event. The conflicting results of satellite observations of chlorophyll *a* distribution were also noted. According to Siegel et al. (1999), both satellite images and the results of ecological model simulations point to the intensification of upwelling-induced blooms, which followed the first spring blooms. On the other hand, Semovski et al. (1999) and Krężel et al. (2005, this volume) found that chlorophyll *a* concentrations decreased in the Hel Peninsula region during the spring upwelling. In summer, during the cyanobacteria bloom, remote sensing indicated a decrease in productivity in the upwelling area (Siegel et al. 1999). However, in early autumn, Krężel et al. (2005, this volume) reported higher concentrations of chlorophyll *a*.

The model simulations showed that upwelling enhanced primary production in spring but reduced it in early autumn. Phytoplankton growth in spring was significantly higher as a result of the elevated phosphate concentrations made available by upwelling (phosphorus is a factor limiting phytoplankton growth). The area of enhanced production shifted northwestwards from the area of elevated concentrations as a result of a time-lag between the occurrence of favourable conditions and increased production, and of the simultaneous influence of current-induced transport.

Under the influence of the autumn upwelling, primary production dropped with the falling water temperature and for lack of a marked rise in nutrient concentrations. However, it should be borne in mind that the diatom group in the ProDeMo model includes only eurythermal species, which occur in spring. Autumn diatom blooms are formed by other species, typical of much warmer waters, and it is these that were abundant during the September upwelling (Gromisz & Szymelfenig, in press). In consequence, the autumn diatom bloom was not taken into account by the ProDeMo simulation; this may have been responsible for the decrease in primary production.

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