Numerical modelling of POC dynamics in the southern Baltic under possible future conditions determined by nutrients, light and temperature*

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Abstract

This paper discusses predictions of particulate organic carbon (POC) concentrations in the southern Baltic Sea. The study is based on the one-dimensional Particulate Organic Carbon Model (1D POC), described in detail by Dzierzbicka-Głowacka et al. (2010a).

The POC concentration is determined as the sum of phytoplankton, zooplankton and dead organic matter (detritus) concentrations. Temporal changes in the phytoplankton biomass are caused by primary production, mortality, grazing by zooplankton and sinking. The zooplankton biomass is affected by ingestion, excretion, faecal production, mortality and carnivorous grazing. The changes in the

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pelagic detritus concentration are determined by the input of dead phytoplankton and zooplankton, the natural mortality of predators, faecal pellets, and sinks – sedimentation, zooplankton grazing and biochemical decomposition.

The model simulations were done for selected locations in the southern Baltic Sea (Gdańsk Deep, Bornholm Deep and Gotland Deep) under predicted conditions characterized by changes of temperature, nutrient concentrations and light availability. The results cover the daily, monthly, seasonal and annual POC concentration patterns in the upper water layer. If the assumed trends in light, nutrients and temperature in the southern Baltic correctly predict the conditions in 2050, our calculations indicate that we can expect a two- to three-fold increase in POC concentration in late spring and a shift towards postponed maximum POC concentration. It can also be anticipated that, as a result of the increase in POC, oxygenation of the water layer beneath the halocline will decrease, while the supply of food to organisms at higher trophic levels will increase.

1. Introduction

The high phytoplankton productivity in the Baltic (Hagström et al. 2001) makes it a key area on the European shelf as regards atmospheric CO_2 uptake (Thomas et al. 2003, 2005). Since particulate organic matter (POM) is a carrier of carbon to the sediments, it plays an important role in the biological pump mechanism (e.g. Pempkowiak et al. 1984, Chisholm 2000, Turnewitsch et al. 2007). The measure of particulate organic matter is particulate organic carbon (POC). POC concentrations depend on the equilibrium between the sources and sinks of organic substances. As the rate of organic substance supply increases, the concentration of organic matter in seawater also does so until a new equilibrium is reached. POM is defined as suspended organic matter that remains on 0.2–1.0 μm pore filters during the filtering of sea water (Turnewitsch et al. 2007). Nominally, therefore, POM consists of phyto- and zooplankton cells, detritus and bacteria (Chen & Wagnersky 1993, Hygum et al. 1997, Nagata 2000, Dzierzbicka-Głowacka et al. 2010a).

Processes supplying organic matter to seawater are especially intensive in coastal areas and land-locked seas. This is attributed to the elevated supply of terrestrial nutrients, which enhances primary productivity. As a result, POC concentrations in land-locked seas like the Baltic are 3–4 times higher than in the oceans (Pempkowiak et al. 1984, Grzybowski & Pempkowiak 2003, Kuliński & Pempkowiak 2008). Quantification of factors influencing POC concentrations in seawater based on actual measurements is tedious owing to the natural variability of POC (Dzierzbicka-Głowacka et al. 2010a). Therefore, experimental assessment of long-term organic matter changes in seawater is unrealistic, unless an extensive survey of several years' duration is carried out.

An obvious solution to the problem of assessing seasonal dynamics and changes in long-term organic matter concentrations is modelling. This enables the concentration dynamics due to specific factors of environmental regimes to be studied (Dzierzbicka-Głowacka et al. 2010a, Kuliński et al. 2011). Validation of results, based on the comparison of the modelled and the measured POC concentrations in the Gdańsk Deep, Baltic Sea, proved successful (Dzierzbicka-Głowacka et al. 2010a). The POC model used in this work is based on the 1D Coupled Ecosystem Model, forced by a 3D hydrodynamic model, developed by Dzierzbicka-Głowacka (2005), Dzierzbicka-Głowacka et al. (2006, 2010b) and further parameterized by Kuliński et al. (2011).

Another advantage of POC modelling is the possibility of assessing changes that may be brought about by future regime shifts. The most certain regime shift that is being experienced in today's world is due to the increasing concentration of atmospheric CO_2. Directly or indirectly, this shift will influence several factors important to organic matter levels in seawater: they include river run-off, river water nutrient concentrations, primary productivity, phytoplankton species composition and succession, seawater pH, and a number of others grouped under the general heading of climate change. The impact of future climate change on the physical conditions of the Baltic Sea and the dynamics of the deepwater inflows has been investigated in several studies (e.g. Meier 2006, Meier et al. 2006, BACC Author Team 2008). Biogeochemical models of this impact are also available (e.g. Omstedt et al. 2009). But the effect of global change on POC dynamics in the Baltic Sea has not yet been investigated, and the response of the marine ecosystem to the expected changes is unknown.

This paper assesses the annual dynamics of particulate organic matter concentrations in Baltic Proper seawater. Contemporary POC concentrations are modelled in the context of predicted increases in temperature and nutrient concentrations. Average values and increases of sea water nutrient concentrations, temperature and photosynthetically active radiation (PAR) recorded in the period 1965–1998 (Renk 2000) are used for evaluating realistic environmental conditions in the years to come. These factors have been selected as they are regarded as limiting for phytoplankton primary production, thus influencing POC concentrations directly and indirectly. Moreover, the rate of increase in these factors has already been quantified on the basis of actual observations (Renk 2000). The study concerns predictions for several areas of the southern Baltic Sea (Gdańsk Deep, Bornholm Deep and Gotland Deep).

2. Basic concept of the 1D POC model

The biological part of the 1D CEM – Coupled Ecosystem Model (Dzierzbicka-Głowacka 2005, 2006), converted to a 1D POC – Particulate Organic Carbon Model with an equation for dead organic matter (pelagic detritus), is presented in Dzierzbicka-Głowacka et al. (2010a) and Kuliński et al. (2011). The 1D POC model is an ecosystem model able to simulate the particulate organic carbon (POC) concentration as the sum of pelagic detritus and both phytoplankton and zooplankton biomass concentrations.

In this model phytoplankton was modelled with the aid of only one state variable. The phytoplankton concentration was taken to be a dynamically passive physical quantity, i.e. it was incapable of making autonomous movements. Cyanobacteria blooms were not incorporated separately at this stage of the model development, so nitrogen fixation was ignored. The fact that cyanobacteria activity is less intense in the open sea than in the near-shore zone (Voss et al. 2005) provided additional motivation for choosing three stations located away from the coastal zone.

Nutrients are represented by two components: total inorganic nitrogen ($NO_3{}^- + NO_2{}^- + NH_4{}^+$) and phosphate ($PO_4{}^{3-}$). The temporal changes in the phytoplankton biomass are caused by primary production, excretion, mortality, grazing by zooplankton and sinking. The zooplankton biomass is affected by ingestion, excretion, faecal production, mortality and carnivorous grazing. The changes in the pelagic detritus concentration are determined by the input of dead phytoplankton and zooplankton, the natural mortality of predators, faecal pellets, and sinks – sedimentation, zooplankton grazing and decomposition (Dzierzbicka-Głowacka et al. 2010a).

The zooplankton variable represents zooplankton of the first order. They ingest both phytoplankton and pelagic detritus – dead organic material in the model. The closure term of the model system is the carnivorous grazing of the zooplankton. The way the closure term is formulated sets up the behaviour of the model. The detritus pool is increased through the faecal production of zooplankton and the natural mortality of autotrophs and higher predators.

All physical components such as velocities, salinity and temperature were calculated in the 3D hydrodynamic model. The output from this model as an average value for the period 1960–2000 (ECOOP IP WP 10.1.1) at temporal and special vertical scales for three areas (Gdańsk Deep, Bornholm Deep, Gotland Deep) was linearly interpolated at every time and vertical step of the 1D POC model. The 3D model was forced using daily-averaged reanalysis and operational atmospheric data (ERA-40) obtained from the European Centre for Medium-range Weather Forecasts (ECMWF).

The 1D POC model is a one-dimensional biogeochemical model. It has a high vertical resolution with a vertical grid of 1 m, which is constant throughout the water column. This means that the model calculates the vertical profiles of all its variables and assumes that they are horizontally homogeneous in the sub-basins. In comparison with vertical changes, the dynamic characteristics remain almost unchanged in a horizontal plane. Hence, the magnitudes of the lateral import/export are lower, and the above assumption can be made. The horizontal velocity components (v, u) obtained in the ECOOP IP project WP 10.1.1 model for the Baltic Sea (ECOOP IP project WP 10.1.1) were averaged and used to calculate hydrodynamic variables such as w, K_z, S and T. In order to include horizontal variations in the southern Baltic (a larger area) it was divided into three sub-basins – 1 – Bornholm Deep (BD), 2 – Gdańsk Deep (GdD) and 3 – Gotland Deep (GtD) – each of which has 64 pixels; 1 pixel $= 9 \times 9$ km^2.

The main average circulation of the Baltic Sea is called the *Baltic haline conveyor belt* (BCB, Doos et al. 2004, Meier 2006). If we take BCB into account, the main flow though the sub-basins is assumed to be part of BCB, and other flows can be neglected. The horizontal transport of the variables $Nutr$, $Phyt$, $Zoop$ and $DetrP$ between sub-basins is treated as a typical advection process. For each time step the POC concentration is determined as the sum of phytoplankton, zooplankton and pelagic detritus concentrations. The model does not include the inflow of nutrient compounds from rivers or the atmosphere. Hence, the 1D POC model has zero boundary conditions (from the land and atmosphere).

2.1. Initial values

It was assumed that the initial conditions of the numerical simulations were the average winter values from the previous 4 decades and that the final states of one year would be the starting points of the next year. It was further assumed for GdD that since there were few phytoplankton values for January and December, a constant value of $\{Phyt\}_0 = 10$ mgC m^{-3} (Witek 1995) could be applied. Owing to the long simulation period (from January) preceding the spring bloom (April/May) the model is not sensitive to the initial phytoplankton concentration. The initial zooplankton biomass was calculated on the basis of data from Witek (1995) as $\{Zoop\}_0 = 1$ mgC m^{-3}. The initial nutrient values were taken from the Institute of Meteorology and Water Management (IMGW) database as the average values for January: total inorganic nitrogen – $Nutr_N = 6$ mmol m^{-3} and phosphate – $Nutr_P = 0.6$ mmol m^{-3}, the assumption being that these values were constant with depth. No data for the detritus content at the bottom were available, and the instantaneous sinking of detritus was a more arbitrary model assumption. The initial detritus content in the subsurface water layer was prescribed as 100 mgC m^{-2}. However, a constant value of 50 mgC m $^{-3}$ for pelagic detritus was assumed throughout the water column. For BD and GtD, all the initial values were assumed to be the same as for the GdD except for the nutrient concentrations, i.e. total inorganic nitrogen – $Nutr_N = 5$ mmol m^{-3} and phosphate – $Nutr_P = 0.5$ mmol m^{-3}.

2.2. Model validation

The model was validated for GdD (Dzierzbicka-Głowacka et al. 2010a) on the assumption that processes governing POC concentrations in other areas of the Baltic Proper are similar. Thus, the POC concentration and POC dynamics in GtD and BD differ from those in GD owing to differences in nutrient concentration and physical factors. The modelled values of the primary production for the 1965–1998 period and POC concentrations for 2010 were compared to the measured values (see Discussion).

3. Prediction of future changes

The most important factors, with an overriding influence on primary production, are PAR, nutrients and temperature. Fourier analysis of the archived data (34 years) reveals seasonal and annual variations in the sea surface temperature and nutrient concentrations in the past and shows the main trend of increasing temperature and nutrient during more than 40 years in the southern Baltic Sea, mainly in the Gdańsk Deep (GdD). The equation describing long-term variations of hydrological parameters, $S = S_o + A(x - 1960) + B\sin(\omega x + \varphi_1) + C\sin(2\omega x + \varphi_2)$, where A is the average annual increase of the parameter under investigation, was used by Renk (2000) to analyse the data set from the Sea Fisheries Institute (Gdynia). The tendency for the average temperature in the surface water to increase by 0.006°C yr^{-1}, and in the upper layer by 0.0117°C yr^{-1} was evident by the end of the 1965–1998 period (Renk 2000: Table 4). An increase of 1% of the average annual nutrient value with the exception of summer, when nutrient concentrations are close to zero (i.e. 0.0036 mmolP m^{-3} and 0.022 mmolN m^{-3}), was recorded in GdD (Renk 2000: Table 4). This will lead to a nutrient concentration in 2050 higher than in 1965–1998 by ~ 0.18 mmolP m^{-3} for phosphate and by ~ 1.1 mmolN m^{-3} for total inorganic nitrogen. For BD and GtD we assumed lower values: 0.0034 mmolP m^{-3} and 0.021 mmolN m^{-3}. The increase in nutrients includes the inflow of nutrient compounds from the river and atmosphere. This rise in nutrient concentrations in the southern Baltic Sea over a period of many years has enhanced the average annual primary production by about 2 to 3% (Renk 2000: eq. (39)) and average annual chlorophyll concentrations by about 2% (Renk 2000: eq. (40)). The average chlorophyll *a* concentrations in the southern Baltic Sea (average values for 1965–1998 – see Table 1, page 987) were used to calculate primary production (PRP) after Renk (2000: eq. (32), Table 8). The primary production values obtained in this way were subsequently compared with the simulated ones. The modelled average primary production values for 1965–1998 agree with the experimental data for PRP for the same period (see Discussion) The primary production was obtained using the equation ($PRP = f_{\max} f_{\min} F_I Phyt$) (see Dzierzbicka-Głowacka et al. 2010a: Appendix A). The average increase in daily solar energy in Gdynia was $0.02\% \cong 0.003$ MJ m^{-2} d^{-1} in the spring and summer, and the corresponding decrease during the winter was ca $0.005\% \cong 0.00053$ MJ m^{-2} d^{-1}. The calculations were made on the basis of experimental data provided by the Institute of Meteorology and Water Management in Gdynia.

In Dzierzbicka-Głowacka et al. (2010a) the photosynthetically available radiation (PAR) at the sea surface $I_o(I_o(t) = \varepsilon Q_g)$ was identified as $\varepsilon(\varepsilon = 0.465(1.195 - 0.195 T_{cl}))$, where T_{cl} is the cloud transmittance function (Czyszek et al. 1979) of the net flux of short-wave radiation Q_g. Here the irradiance $I_o(t)$ (kJ m^{-2} h^{-1}) is expressed as a function of the daily dose of solar radiation η_d transmitted through the sea surface using

$$I_o(t) = \frac{\eta_d}{\lambda}\left(1 + \cos\frac{2\pi t}{\lambda}\right) \tag{1}$$

(λ is the length of day, in hours), where the average value of η_d for the southern Baltic Sea (for 1965–1998 period) was derived using the least squares method (Renk & Ochocki 1998).

Based on this trend, seasonal variability of POC was numerically calculated for the next 50 years. This main trend was used as a scaling factor for the prediction of the future Baltic climate. In the first step of our study, the calculations were made on the assumption that:

1. the water upper layer temperature rises at a rate of 0.008°C per year,
2. the light intensity increases by 0.02% of the average value per year in the growing season, and decreases by 0.005% during the winter,
3. the flow field has the same level as the average value for 1960–2000 from the hydrodynamic model (the flow field was not changed, only daily average values were calculated),
4. nutrients increase by 1% of the average annual value.

3.1. Description of the method used

We assumed the long term variations of the parameters T, PAR and $Nutr$ to be:

$$S = So + Sa \times Yd\,(Year - 2000), \tag{2}$$

where:

S – parameter examined (temperature, PAR, nutrients),
So – simulated values for nutrients at every time step,
So – mean value of each day for the period 1965–1998 for PAR,
So – mean value of each day calculated in the 3D hydrodynamic model for the period 1960–2000 for temperature,
Sa – average annual rise (trend) of the parameter S,
Yd – time ($Yd = x/365$ as a fraction of the year).

4. Results

The starting-point of the numerical simulations was taken to be the end of 2000 with the daily average values of the hydrodynamic variables for 1960–2000. Based on the trend indicated above, daily, monthly, seasonal and annual variabilities of primary production, phytoplankton, zooplankton, pelagic detritus and particulate organic carbon (POC) in different areas of the southern Baltic Sea (Gdańsk Deep – GdD, Bornholm Deep – BD and Gotland Deep – GtD) in the upper layer (0–10 m) were calculated for the different nutrient concentrations, available light and water temperature scenarios. The effect on primary production of the decrease in radiation, which is exponential, is seen mainly in the upper layer.

As primary production is the basic food resource for zooplankton and serves both as a direct and an indirect source of detritus, special attention is given to the characteristics of primary production in the study period. The seasonal variability of gross primary production in the southern Baltic Sea in the course of a year for 1965–1998 (average) and the scenario for 2050 in the upper layer are presented in Figure 1.

The seasonal dynamics of primary production in the upper layer at the study sites in 1965–1998 is characterized by two peaks: a sharp one during the spring bloom (ca 12 mgC m^{-3} h^{-1} in April – GdD, ca 8 mgC m^{-3} h^{-1} in the second half of April – GtD and ca 9 mgC m^{-3} h^{-1} in late April and early May – BD) and another one at the end of summer, slightly higher than the first one in the upper layer (ca 9 and 9.5 mgC m^{-3} h^{-1} in GtD and BD respectively) (Figure 1).

The increase in primary production in the scenario for 2050 as compared to 1965–1998 can be attributed to changed nutrient, temperature and radiation conditions (Dzierzbicka-Głowacka 2005, Kuliński et al. 2011).

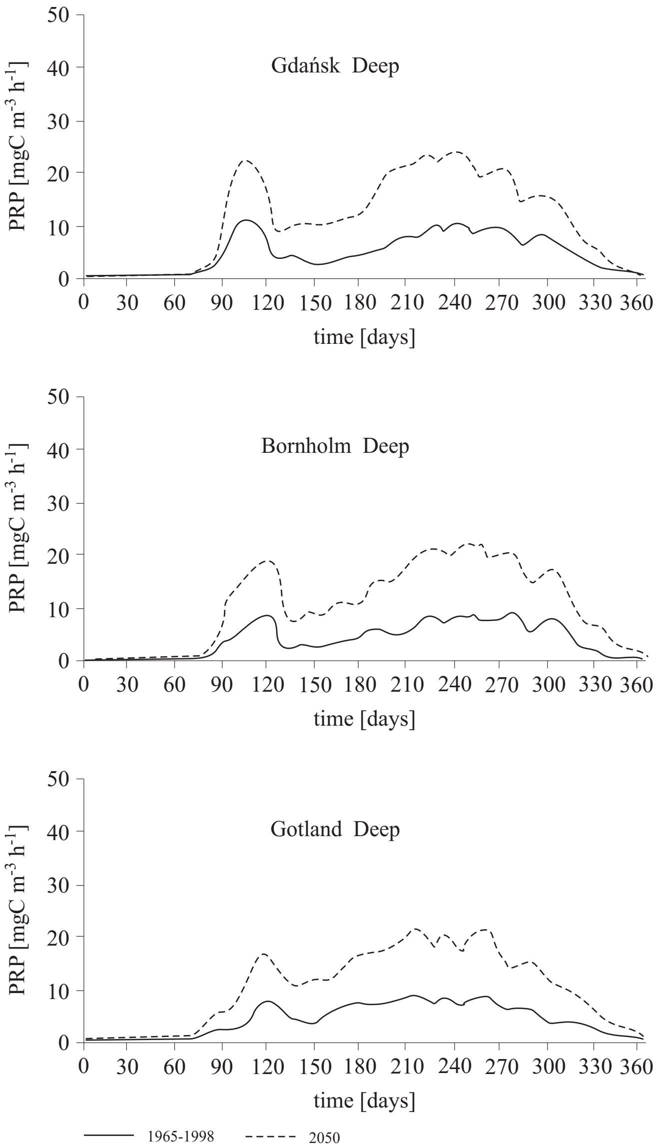

Figure 1. Simulated annual cycles for primary production (midday values) in the upper layer of the Gdańsk Deep, Bornholm Deep and Gotland Deep for 1965–1998 and 2050

Typical features of the seasonal dynamics of primary production are well reflected in the annual primary production cycles. In particular, a well developed spring bloom (April), and a somewhat less intensive but prolonged late summer/autumn bloom (August and September) are clearly distinguishable. The curve representing primary production integrated over the whole upper water layer exhibits a slightly less intensive spring peak in BD and GtD (Figure 1), obviously because of the limited primary production in the subsurface water layer.

Time series scenarios of the state variables *Phyt*, *Zoop*, *DetrP* and POC are presented in Figure 2 (Gdańsk Deep, upper layer), while simulated monthly and seasonal averages for phytoplankton, zooplankton, pelagic detritus and POC in the all three areas (GdD, BoD, GtD) for 1965–1998 and 2050 are presented in Figures 3 and 4.

In 1968–1998 (Figure 2), phytoplankton, zooplankton, detritus and POC increase and decrease in the upper layer of GdD; their first-spring concentration maxima are 200 mgC m^{-3} for phytoplankton biomass in April, 110 mgC m^{-3} for zooplankton biomass in June and 360 mgC m^{-3} for pelagic detritus at the end of May.

The POC concentration reaches a level of about 410 mgC m^{-3} in the upper layer from April to November. The POC concentrations in the 2050

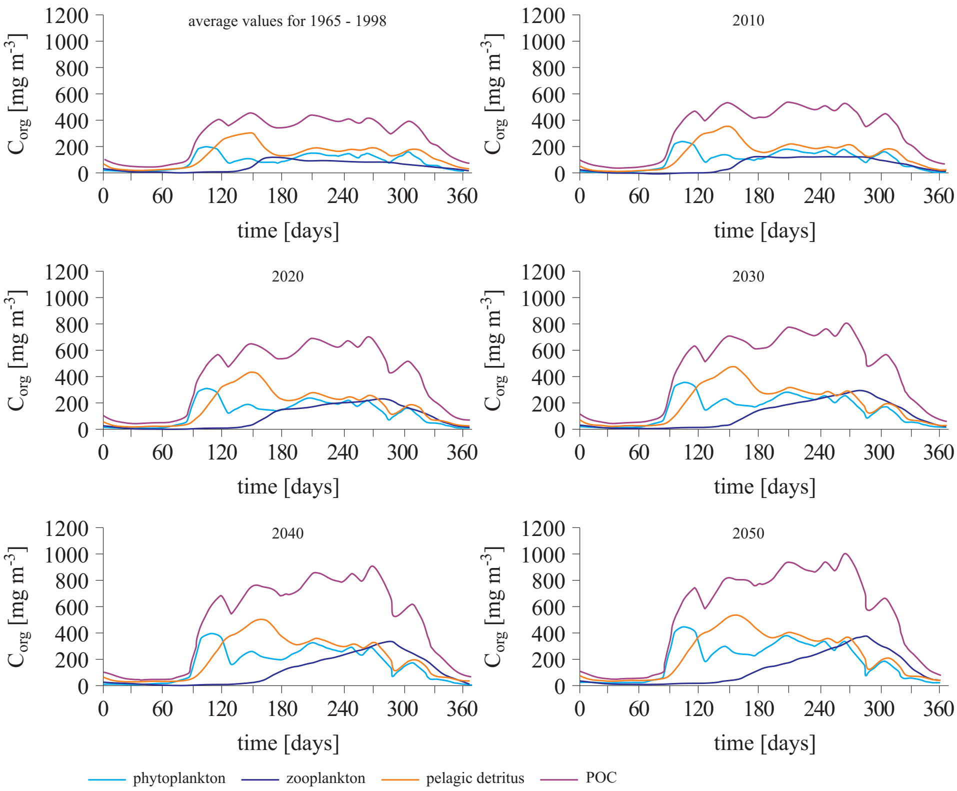

Figure 2. Simulated annual cycles for phytoplankton, zooplankton, pelagic detritus and POC in the upper layer of the Gdańsk Deep for 1965–1998, 2010, 2020, 2030, 2040 and 2050

scenario are twice those characteristic of the scenario for 2010 and are 2.5 times larger than in 1965–1998.

The annual cycles of POC and the contributions of phytoplankton (*Phyt*), zooplankton (*Zoop*) and detritus (*DetrP*) in the whole upper water layer (Figure 2) indicate large POC concentrations in early summer resulting from the *Phyt* bloom and the detritus due to *Phyt* mortality. *Zoop* contributes little, if anything, to the POC pool until late June. Between July and November, zooplankton is the smallest of the three POC components. The contribution of *Phyt* to POC is close to that of detritus. One feature of the *Phyt* cycle presented in Figure 2, as compared to the primary productivity (Figure 1), is the much lower biomass in the second half of the year. This is caused by the *Phyt* decrease due to mortality and *Zoop* grazing. The larger concentrations of POC calculated for successive decades are reflected by the increased primary production in 2010 as compared to the average in 1965–1998. This, of course, leads to larger *DetrP* and *Zoop* concentrations, both contributing to POC. The POC increase is even more pronounced. An interesting shift in the cycles can be noticed towards 2050: a large zooplankton peak develops in October, which leads to a rapid decrease in phytoplankton and detritus in October and November. *Zoop*, however, gains in importance as a component of POC, giving rise to an extended POC concentration peak between August and early October. As a consequence, a POC concentration between 900 and 1000 mg m^{-3} persists between April and October with just a three-week long break in July.

The cycles of POC itself and POC components are different in BD (Figure 3). For one thing POC levels are lower: primary production is lower because of the limited supply of nutrients (Renk 2000). Zooplankton thus never develops into a major component of POC, and both *Phyt* and *DetrP* concentrations decrease slowly in the autumn. This leads to a gradual decrease in POC concentration by 25% in September/October and by 20% in October/November. Yet another POC cycle characterizes the Gotland Deep. The primary productivity peak begins in April/May. There is no zooplankton that could modify *Phyt* and *DetrP*, so POC consists of *Phyt* and *DetrP*, the latter derived from phytoplankton. There is just one POC peak, occurring in June (1965–1998) and July (2050). Because of the slow growth of zooplankton in August and September (both 1965–1998 and 2050), phytoplankton and detritus levels fall slowly, leading to a gradual decrease in POC.

The varying patterns and levels of POC in the three deeps are best visualized in Figures 3 and 4, which show monthly and seasonal averages of POC. In GdD elevated POC concentrations from 400 mgC m^{-3} (2010) to 900 mgC m^{-3} (2050) in spring are evident. Moreover, the monthly averages

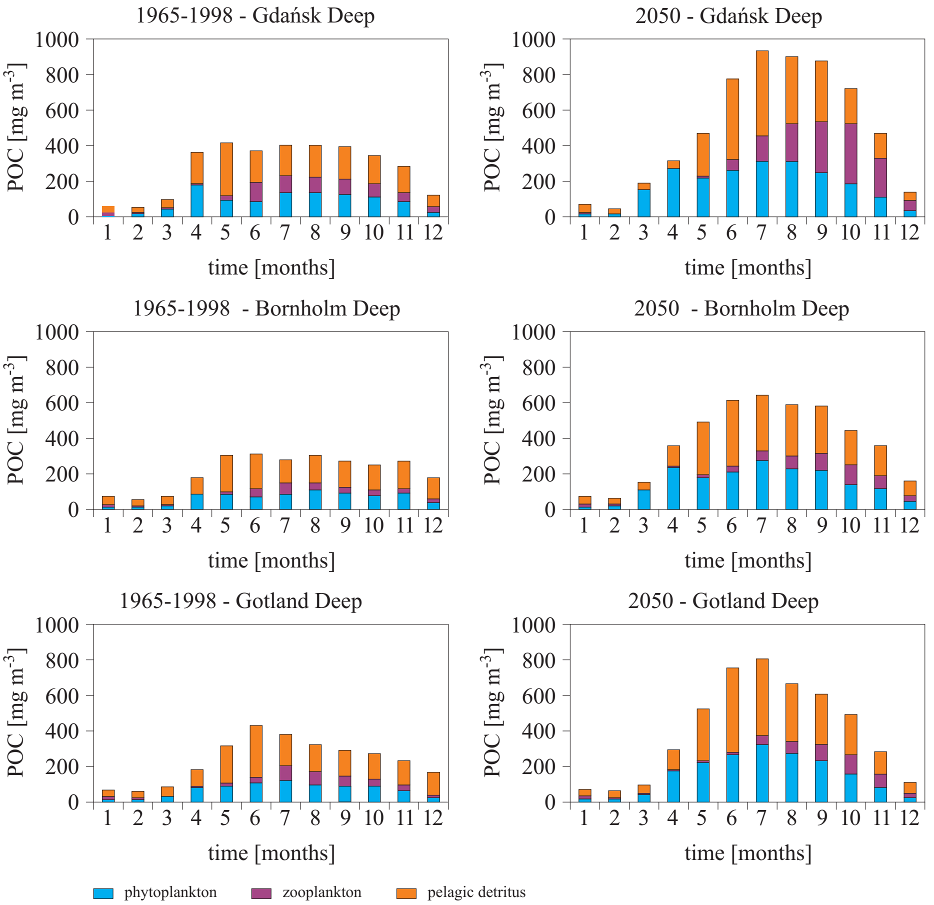

Figure 3. Simulated monthly averages for phytoplankton, zooplankton, pelagic detritus and POC in the upper layers of the Gdańsk Deep, Bornholm Deep and Gotland Deep for 1965–1998 and 2050

for August and September 2050 exceed those of April and May 2050, whereas in 1965–1998 the August and September averages are lower than those for April and May by some 25%. Another difference in the pattern – the greater contribution of the zooplankton biomass to POC in August and September – is also evident (Figure 2). Zooplankton growth leads to a third effect – a rapid decrease in POC concentrations: by 50% in November 2050 but by just 20% in November 1965–1998. This difference is caused by the rapid decline in both *Phyt* and *DetrP* due to zooplankton feeding on the other two POC components. Increased temperature and light will prolong the growing season in 2050.

The greatest increase in the seasonal averages of the investigated variables in the surface layer of GdD takes place in spring (April) for

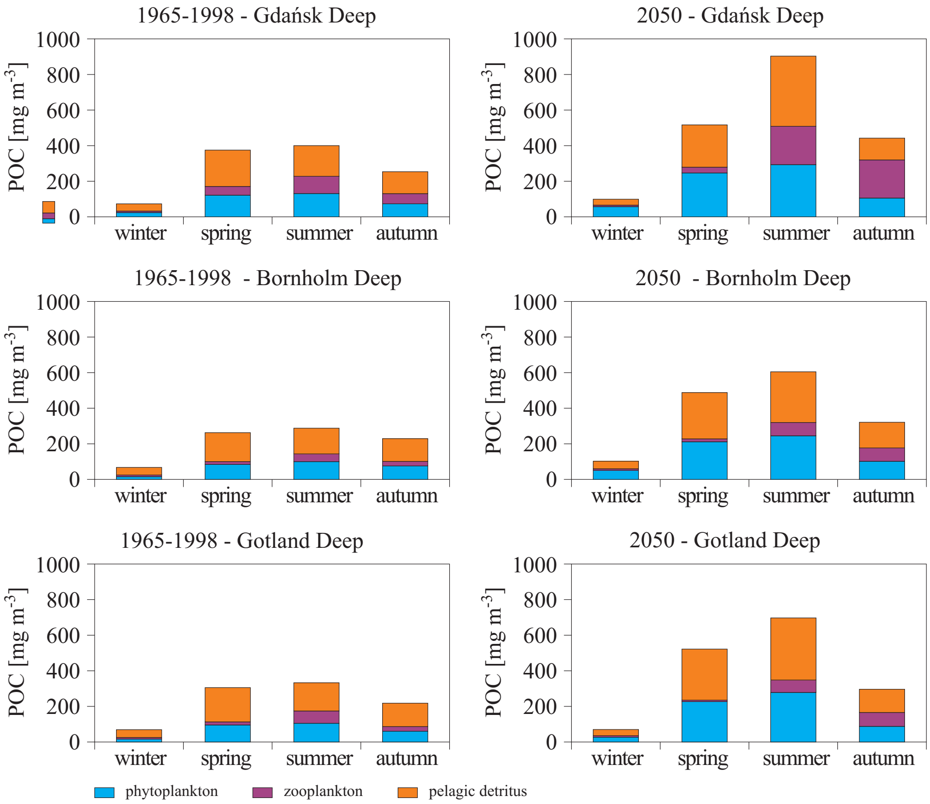

Figure 4. Simulated seasonal averages for phytoplankton, zooplankton, pelagic detritus and POC in the upper layers of the Gdańsk Deep, Bornholm Deep and Gotland Deep for 1965–1998 and 2050

phytoplankton (ca 141%), in autumn (October) for zooplankton (ca 360%), in spring (May) for pelagic detritus (145%) and in summer (September) for POC (ca 131%). However, the biggest increase in the seasonal averages of the pelagic variables in the upper layer of the three deeps takes place in spring and summer (phytoplankton), in autumn (zooplankton), and in summer (pelagic detritus, POC): a) GdD: phytoplankton (ca 145% and 138%), zooplankton (ca 267%), pelagic detritus (ca 101%) and POC (ca 123%); b) BD: phytoplankton (ca 152% and 143%), zooplankton (ca 192%), pelagic detritus (ca 104%) and POC (ca 111%); c) GtD: phytoplankton (ca 138% and 161%), zooplankton (ca 153%), pelagic detritus (ca 125%) and POC (ca 108%).

The percentage contributions of the POC components in the upper layer of the study sites for 1965–1998, 2010, 2020, 2030, 2040 and 2050 are presented in Figure 5. The increasing contribution of zooplankton in

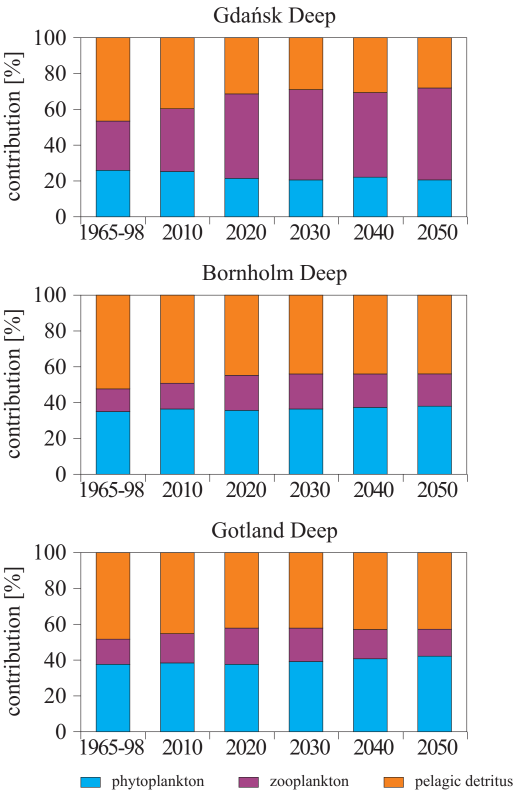

Figure 5. Percentage contributions of the POC components in the upper layer of the study sites for 1965–1998, 2010, 2020, 2030, 2040 and 2050

POC over decades is evident in the case of GdD, whereas the contribution is similar and constant in GtD and BD. This corroborates the overview of results presented earlier. The contribution of phytoplankton to POC increases by 10%, 5% and 2%, thus leading to respective decreases in pelagic detritus by 8%, 5% and 2% in GtD, BD and GdD. The contribution of zooplankton to POC increases by 5% in GdD only; it decreases by 2% in GtD and is constant over time in BD.

5. Discussion

The data presented in this paper are the results of numerical simulations based on one of many possible assumptions. The prediction of future changes was made on the basis of the changes that took place in the period from 1965 to 1998, mainly in the Gulf of Gdańsk. It is difficult to assess how realistic our assumptions are – this is the main reason why people examine different scenarios. So we examined several options based on historical data (1965–1998). Some of them were extrapolations, some were not. The temperature increase assumed in our study (0.008°C) is somewhat lower than that accepted by the BACC Author Team (2008). Those authors suggested a temperature increase of 2.9°C in the period from 1961–1990 to 2071–2100 as the most realistic for the Baltic Sea region. That finding was obtained by testing different scenarios with global and regional climate models. The other unknown is the future nutrient input to the Baltic Sea, since it is closely related to the direction in which the region's agriculture is going to take. However, most of the scenarios based on global and regional climate models point to an increase in precipitation over the Baltic Sea region of as much as 50% of present-day values by 2050 (BACC Author Team 2008). Since the Baltic's nutrient input enters the sea mostly from waterborne sources, it is to be expected that nutrient loads will increase together with precipitation and river runoff.

The modelled primary production (PRP) values for 1965–1998 and POC concentrations for 2010 agree very well with experimental data for PRP expressed as average values over the 1965–1998 period (Figure 6) and for POC from 2007 and 2008 (see Dzierzbicka-Głowacka et al. 2010a) and from 2009 and 2010 (data presented at the Baltic-C Third Scientific Study Workshop, Lund, Sweden, 8–10 November 2010, *POC/DOC for model validation* by Anna Maciejewska) (Figure 7). Model output describes the average state of the ecosystem and provides average values of the investigated variables. When comparing modelled with experimental results, one must bear in mind that the latter reflect only a temporary state of the ecosystem, i.e. the state at the time of sampling. Thus, the modelled

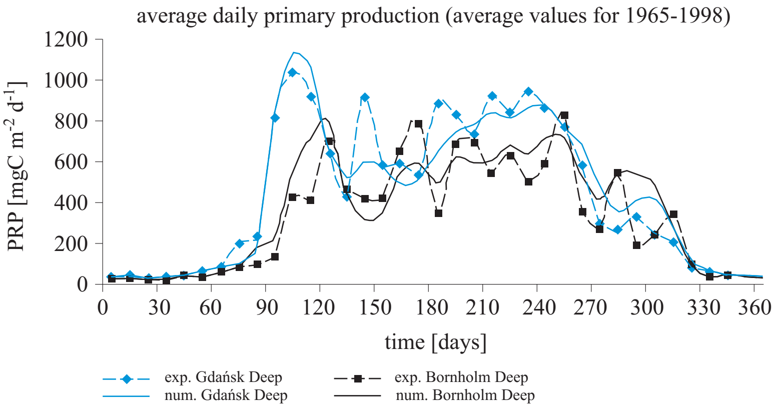

Figure 6. Average, daily primary production in the Gdańsk Deep (blue) and the Bornholm Deep (black); numerical simulation (solid line) and experimental results (dashed line)

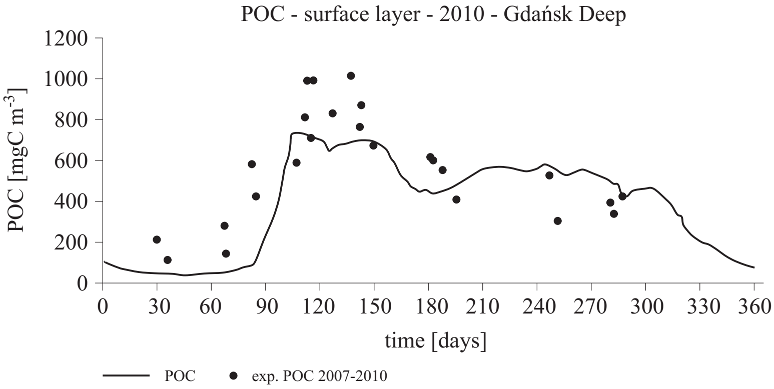

Figure 7. Modelled (line) and measured (dots) POC concentrations in the surface layer in the Gdańsk Deep

POC concentrations may differ from the measured values, especially during phytoplankton blooms, when biomass variability is the highest.

Ten-day average chlorophyll a concentrations Chl*a* (mg Chl*a* m^{-3}) for the three areas under consideration and primary production (mgC m^{-2} d^{-1}) for two of those areas (GdD, BD) for 1965–1998 were given by Renk (2000: Table 8). The monthly primary production (gC m^{-2} $month^{-1}$) in different areas of the southern Baltic Sea, as averaged for 1966–1995 for GdD and BD and for 1970–1971 and 1982–1996 for GtD, were also presented by Renk (2000: Table 11).

The simulations and measurements in the investigated areas were compared. The correlations between experimental and modelled data for primary production and chlorophyll *a* were quite good ($r > 0.62$ and $r > 0.59$ respectively) (unpublished results). The differences between measurements and modelled data depend on the time and place where the calculations were made, and also on the C/Chl*a* ratio for converting simulated carbon contents to chlorophyll *a*, which was assumed to be the variable obtained for the Gulf of Gdańsk (after Witek 1993). The Pearson product-moment correlation coefficients for the variables PRP and Chl*a* were higher in GdD than in BD because the parameterization of the primary production factors was done for the Gulf of Gdańsk.

The increase in $Phyt$, $Zoop$, $DetrP$ and POC concentrations resulting from the enhanced nutrient supply and favourable light and temperature conditions is also well visualized when the 2010 data are compared to the average of 1965–1998 (Figures 2–4). Therefore, it can be safely assumed that the calculated data are a sufficiently good reflection of the POC variations in the southern Baltic, caused by the increase of nutrients, PAR and temperature.

The higher POC will have opposing effects on the Baltic ecosystem. On the one hand this will imply a greater biomass at the bottom of the food pyramid (Raymont 1976) and a decrease in contaminant levels in particulate organic matter (Pohl et al. 1998, Pempkowiak et al. 2006). Both factors will have a favourable influence on the ecosystem, with important consequences for the Baltic fishery as the enhanced supply of zooplankton will enable

Table 1. Average chlorophyll *a* concentration in the upper layer in the southern Baltic Sea (average values from 1965 to 1998) (Renk 2000)

Period	Chlorophyll *a* [mg m^{-3}]		
	Gdańsk Deep	Bornholm Deep	Gotland Deep
1–10 January	0.56	0.60	
11–20 January	0.48	0.59	
21–31 January	0.40	0.60	
1–10 February	0.41	0.51	0.45
11–20 February	0.48	0.50	0.50
21–28 February	0.55	0.47	0.53
1–10 March	0.55	0.76	1.09
11–20 March	1.14	0.62	0.55
21–31 March	1.58	1.08	1.13
1–10 April	5.39	0.94	1.26
11–20 April	4.99	2.79	1.62
21–30 April	5.35	3.39	3.63
1–10 May	2.11	3.57	3.01
11–20 May	2.80	1.64	1.45
21–31 May	3.04	1.60	2.81
1–10 June	2.20	1.42	2.46
11–20 June	1.97	1.83	2.22
21–30 June	1.71	1.42	1.76
1–10 July	2.10	1.42	2.06
11–20 July	2.34	1.70	2.07
21–31 July	2.71	1.53	2.34
1–10 August	2.56	1.92	2.16
11–20 August	2.42	2.26	1.86
21–31 August	2.46	2.04	2.18
1–10 September	3.01	1.61	1.86
11–20 September	2.55	2.57	2.48
21–30 September	3.62	2.06	2.14
1–10 October	2.88	2.09	2.26
11–20 October	2.06	2.46	3.15
21–31 October	4.68	1.78	2.29
1–10 November	5.76	4.21	2.85
11–20 November	3.63	4.28	3.22
21–30 November	1.86	2.11	1.69
1–10 December	2.18	2.69	1.83
11–20 December	1.19	2.14	1.04

southern Baltic fish stocks to flourish. On the other hand the greater POC supply will increase the load of fresh organic matter sinking beneath the halocline; hence, more organic matter will reach the bottom sediments, with possible ecological consequences resulting from yet further oxygen depletion in the water below the halocline and in the bottom sediments, a scenario that must have an adverse effect on the ecosystem (Voipio 1981). Moreover, in view of the extent of anoxic zones in the Baltic in the 1990s (HELCOM 1996) resulting from the level of primary production in 1965–1998, and its increase in 2050 (Table 1), the inference must be that the situation will deteriorate considerably.

There are a very few other factors influencing POC concentrations that have not been considered in our simulations. They include organic matter originating from resuspended sediments, and organic matter discharged with river runoff (Pempkowiak & Kupryszewski 1980, Pocklington & Pempkowiak 1984, Pempkowiak 1985, Petterson et al. 1997). These are certain to have minor effects on POC concentrations in the 'open' Baltic, as far as loads of particulate organic matter are concerned. Another such factor not considered in the simulations is the increase in CO_2 concentrations in the atmosphere. This is sure to lead to both acidification of sea water and enhanced primary productivity (Caldeira & Wicket 2003, Tortell et al. 2006, Omsted et al. 2009). Nonetheless, the acidification expected to take place by 2050 may be insufficient to have any substantial effect on primary productivity (species and species succession).

Of course, actual levels of nutrients, light and temperature may differ from those assumed in our simulations. Even so, our results indicate clearly and quantitatively the types of changes in POC concentrations in Baltic sea water that can be expected in the forthcoming few decades.

6. Conclusions

According to the simulated data – the daily, monthly, seasonal and annual variability of POC for the assumed nutrient concentrations, available light, water temperature and wind speed scenarios – increases in the annual average POC concentration in the southern Baltic Sea are anticipated (see Figure 3 and Table 2): ca 110% for phytoplankton, ca 63% for pelagic detritus, ca 72.5% for POC (90% in GdD), and ca 50% and 75% for zooplankton in GtD and BD respectively, and a considerable increase of ca 130% in GdD. This situation is due to the occurrence of a large zooplankton biomass in the autumn (ca 380 mgC m^{-3} in the second half of October), resulting from the high phytoplankton biomass (ca 370 mgC m^{-3}) and pelagic detritus concentration (ca 380 mgC m^{-3}) throughout the summer.

Table 2. The simulated annual averages of the investigated variables in the upper layer from 1965 to 1998 and in 2050

Region	Variables	1965–1998	2050	Increase
Gdańsk Deep	phytoplankton	88 mgC m^{-3}	180 mgC m^{-3}	105%
	zooplankton	49 mgC m^{-3}	115 mgC m^{-3}	130%
	pelagic detritus	135 mgC m^{-3}	221 mgC m^{-3}	64%
	POC	272 mgC m^{-3}	516 mgC m^{-3}	90%
Bornholm Deep	phytoplankton	69 mgC m^{-3}	141 mgC m^{-3}	104%
	zooplankton	24 mgC m^{-3}	42 mgC m^{-3}	75%
	pelagic detritus	115 mgC m^{-3}	180 mgC m^{-3}	57%
	POC	210 mgC m^{-3}	364 mgC m^{-3}	73%
Gotland Deep	phytoplankton	70 mgC m^{-3}	155 mgC m^{-3}	121%
	zooplankton	30 mgC m^{-3}	45 mgC m^{-3}	50%
	pelagic detritus	123 mgC m^{-3}	203 mgC m^{-3}	65%
	POC	230 mgC m^{-3}	395 mgC m^{-3}	72%

The increased primary production and phytoplankton biomass will lead to a rise in zooplankton biomass and pelagic detritus concentrations, and larger numbers of zooplankton consumers, including fish. The results of the scenarios assumed in this work will have important consequences for the Baltic ecosystem. Excess particulate organic matter sinks to the bottom, where it is mineralized, causing loss of oxygen in the water layer below the halocline. Hence, increased primary production will contribute to more frequent and more intense oxygen depletion events in benthic waters and the production of larger amounts of hydrogen sulphide there.

References

BACC Author Team, 2008, *Assessment of climate change for the Baltic Sea basin*, Springer-Verlag, Berlin, 473 pp.

Caldeira K., Wicket M. E., 2003, *Anthropogenic carbon and ocean pH*, Nature, 425 (6956), 365–371.

Chen W., Wagnersky P. J., 1993, *High-temperature combustion analysis of dissolved organic carbon produced in phytoplankton cultures*, Mar. Chem., 41 (1–3), 167 –171.

Chisholm S. W., 2000, *Stirring times in the Southern Ocean*, Nature, 407 (6805), 685–686.

Czyszek W., Wensierski W., Dera J., 1979, *Solar radiation energy inflow and absorption in the Baltic water*, SiMO, 26, 105–140, (in Polish).

Doos K., Meier H. E. M., Doscher R., 2004, *The Baltic haline conveyor belt or the overturningcir culation and mixing in the Baltic*, Ambio, 33 (4–5), 258–262.

Dzierzbicka-Głowacka L., 2005, *Modelling the seasonal dynamics of marine plankton in southern Baltic Sea. Part 1. A Coupled Ecosystem Model*, Oceanologia, 47 (4), 591–619.

Dzierzbicka-Głowacka L., 2006, *Modelling the seasonal dynamics of marine plankton in southern Baltic Sea. Part 2. Numerical simulations*, Oceanologia, 48 (1), 41–71.

Dzierzbicka-Głowacka L., Bielecka L., Mudrak S., 2006, *Seasonal dynamics of Pseudocalanus minutus elongatus and Acartia spp. in the southern Baltic Sea (Gdańsk Deep) – numerical simulations*, Biogeosciences, 3, 635–650.

Dzierzbicka-Głowacka L., Kuliński K., Maciejewska A., Jakacki J., Pempkowiak J., 2010a, *Particulate Organic Carbon in the southern Baltic Sea: numerical simulations and experimental data*, Oceanologia, 52 (4), 621–648.

Dzierzbicka-Głowacka L., Żmijewska I. M., Mudrak S., Jakacki J., Lemieszek A., 2010b, *Population modelling of Acartia spp. in a water column ecosystem model for the South-Eastern Baltic Sea*, Biogeosciences, 7, 2247–2259.

Grzybowski W., Pempkowiak J., 2003, *Preliminary results on low molecular weight organic substances dissolved in the waters of the Gulf of Gdańsk*, Oceanologia, 45 (4), 693–704.

Hagström Å., Azam F., Kuparinen J., Zweifel U.-L., 2001, *Pelagic plankton growth and resource limitations in the Baltic Sea*, [in:] *A systems analysis of the Baltic Sea*, F. V. Wulff, L. A. Rahm & P. Larsson, Springer-Verlag, Berlin, 177–210.

HELCOM, 1996, *The third periodic assessment of the state of the marine environment of the Baltic Sea*, Baltic Sea Environ. Proc. No. 64B, Helsinki Commission, Helsinki, 252 pp.

Hygum B. H., Petersen J. W., Søndergaard M., 1997, *Dissolved organic carbon released by zooplankton grazing activity – a high quality substrate pool for bacteria*, J. Plankton Res., 19 (1), 97–111.

Kuliński K., Dzierzbicka-Glowacka L., Maciejewska A., Pempkowiak J., 2011, *Parameterisation of a zero-dimensional Pelagic Detritus Model, Gdańsk Deep, Baltic Sea*, Ochr. Środ., 13, 187–206.

Kuliński K., Pempkowiak J., 2008, *Dissolved organic carbon in the southern Baltic Sea: Quantification of factors affecting its distribution*, Estuar. Coast. Shelf Sci., 78 (1), 38–44.

Meier H. E. M., 2006, *Baltic Sea climate in the late twenty-first century: a dynamical downscaling approach using two global models and two emission scenarios*, Clim. Dyn., 27 (1), 39–68.

Meier H. E. M., Kjellström E., Graham L. P., 2006, *Estimating uncertainties of projected Baltic Sea salinity in the late 21st century*, Geophys. Res. Lett., 33, L15, 705, doi:10.1029/2006GL026488.

Nagata T., 2000, *Production mechanisms of dissolved organic matter*, [in:] *Microbial ecology of the oceans*, D. L. Kirchman (ed.), Wiley-Liss, Inc., New York, 121–152.

Omstedt A., Gustafsson E., Wesslander K., 2009, *Modelling the uptake and release of carbon dioxide in the Baltic Sea surface water*, Cont. Shelf Res., 29 (7), 870–885.

Pempkowiak J., 1985, *The input of biochemically labile and resistant organic matter to the Baltic Sea from the Vistula River*, SCOPE/UNEP, 58, 345–350.

Pempkowiak J., Kupryszewski G., 1980, *The input of organic matter to the Baltic from the Vistula River*, Oceanologia, 12, 79–98.

Pempkowiak J., Walkusz-Miotk J., Bełdowski J., Walkusz W., 2006, *Heavy metals in zooplankton from the Southern Baltic*, Chemosphere, 62 (10), 1697–1708.

Pempkowiak J., Widrowski M., Kuliński W., 1984, *Dissolved organic carbon and particulate carbon in the Southern Baltic in September*, Proc. XIV Conf. Baltic Oceanograph., IMGW. Gdynia, 699–713.

Petterson C. A., Allard B., Boren H., 1997, *River discharge of humic substances and humic-bound metals to the Gulf of Bothnia*, Estuar. Coast. Shelf Sci., 44 (5), 533–541.

Pocklington R., Pempkowiak J., 1984, *Contribution of humic substances by the Vistula River to the Baltic Sea*, [in:] *Transport of carbon and minerals in major world rivers*, E. T. Degens, S. Kempe & H. Soliman (eds.), SCOPE/UNEP, 55 (2), Hamburg, 365–370.

Pohl C., Hennings U., Peterson I., Siegel H., *Trace metal budget, transport, modification and sink in the transition area between the Oder and Peene rivers and the Southern Pomeranian Bight*, Mar. Pollut. Bull., 36 (8), 598–616.

Raymont J., 1976, *Plankton and productivity in the oceans*, Pergamon, Oxford, 660 pp.

Renk H., 2000, *Primary production in the southern Baltic*, Stud. Mater. Sea Fish. Inst., Gdynia, 35 (A), 78 pp.

Renk H., Ochocki S., 1998, *Photosynthetic rate and light curves of phytoplankton in the southern Baltic*, Oceanologia, 40 (4), 331–344.

Thomas H., Bozec Y., de Baar H. J. W., Elkalay K., Frankignoulle M., Schiettecatte L.-S., Kattner G., Borges A. V., 2005, *The carbon budget of the North Sea*, Biogeosciences, 2 (1), 87–96.

Thomas H., Pempkowiak J., Wulff F., Nagel K., 2003, *Autotrophy, nitrogen accumulation and nitrogen limitation in the Baltic Sea: A paradox or a buffer for eutrophication?*, Geophys. Res. Lett., 30 (21), 2130.

Tortell P. D., Martin C. L., Corkum M. E., 2006, *Inorganic carbon uptake and intracellular assimilation by subarctic Pacific phytoplankton assemblages*, Limnol. Oceanogr., 51 (5), 2102–2110.

Turnewitsch R., Springer B. M., Kiriakoulakis K., Vilas J. C., Aristegui J., Wolff G., Peine F., Werk S., Graf G., Waniek J. J., 2007, *Determination of particulate organic carbon (POC) in seawater: the relative methodological importance of artificial gains and losses in two glass-fiber-based techniques*, Mar. Chem., 105 (3–4), 208–228.

Voipio A., 1981, *The Baltic Sea*, Elsevier Sci. Publ., Amsterdam, 123–143.

Voss M., Emeis K.-C., Hille S., Neumann T., Dippner J. W., 2005, *The nitrogen cycle of the Baltic Sea from an isotopic perspective*, Global Biogeochem. Cyc., 19, GB3001, doi:10.1029/2004GB002338.

Witek Z., 1995, *Biological production and its utilization within a marine ecosystem in the western Gdańsk basin*, Stud. Mater. Sea Fish. Inst., Gdynia.