Papers

Primary production in the eastern and southern Baltic Sea

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Abstract

The results of long-term measurements of the photosynthetic primary production in the Baltic Sea have been collected (over 800 daily values from the 1968–1991). During this period substantial eutrophication of the sea was found to have taken place, leading to an annual increase in production of between 5.2 and 10 g C m^{-2} in consecutive years, depending on the area. Taking this process into account, a map of annual production in 1991 was prepared. This shows the production in the sea to be spatially highly diverse, a fact which can probably be explained by the influence of the dynamics of nutrient-carrying water masses.

1. Introduction

The photosynthetic primary production rate (PP) is one of the basic biological parameters used in describing marine regions. PP measurements in the Baltic Sea have been carried out using the intercalibrated method for monitoring purposes (BSEP, 1983). Polish research in this area has continued, with varying intensity, since 1965 (Rochoń, 1966, 1968). The majority of the Baltic states monitor biological parameters in their economic zones, and as this work includes the measurement of PP, the research material is very extensive. A large number of papers on Baltic Sea primary production has been published, as have maps of the annual production (Renk, 1994). Normally the state of a selected region would be singled out for scrutiny, but in cases where the total primary production of the entire Baltic Sea was estimated, its magnitude for large areas would be approximated on the basis of a small number of observations. The intention of the authors of the present study was to compile all the available data obtained by different methods (variants of the radio-isotopic method – the incubator method, in situ profile, surface sampling – or the oxygen method) and, having elaborated algorithms for comparing these results, to prepare an exact map of the annual Baltic Sea primary production.

The question arises whether such an enterprise makes sense in view of the fact that satellite data from a new generation of sensors (such as the SeaWiFS) will be soon available and that the images will show the spatial distribution of sea colour over immense areas. Several years' observations at least are required for collecting enough satellite material to obtain average distributions in areas of different productivity and to evaluate long-term trends. However, it is not possible to study these long-term changes in comparison to previous states without refererence to the materials collected by traditional methods.

This article presents the preliminary results, obtained while preparing the primary production map, based on data collected in the research institutes employing the authors of this study. Some of this data has never been taken into consideration in any estimates of the annual primary production in the Baltic Sea.

2. Materials

This article is based on the results of studies carried out in the years 1968–1991. The C^{14} method was used in all PP measurements (Strickland, 1960; Nielsen and Bresta, 1984). In the majority of cases, incubation was carried out using the *in situ* method. Water samples were taken at selected depths with the use of a bathometer. After the samples had been treated with the isotope, the incubation was performed by hanging the bottles containing the samples at the depths at which they had been taken. The incubation time differed from voyage to voyage: 4, 6 hours, or half a day, *i.e.* from sunrise to midday or from midday to sunset. Geiger and scintillation counters were used to measure sample activity. Production was usually measured together with the solar energy dose reaching the sea surface; thus it was possible to calculate the daily primary production by using the 'light factor' method.

The results obtained with the 'surface sampling' method constituted a part of the data used (*ca* 100). Water samples were taken only from the surface layer of the sea, and the incubation was carried out on board in natural light, ensuring the same temperature as that in the surface layer of the sea by keeping the samples being incubated in a tank filled with water from next to the ship. This method allows measurements to be performed without the need to stop the vessel at the measurement sites for the incubation period.

Measurements of primary production were carried out in various scientific establishments. The data obtained by the Sea Fisheries Institute in Gdynia (SFI) were collected during the monitoring of the Baltic Sea (since 1981), during cruises organised by the SFI and in co-operation with other institutes. Half-day incubations were used until 1982; since 1983, a 4-hour incubation around midday has been standard practice. Initially, the standard depths were 0.5, 10, 15, 20 m; later, 3 and 5 m, and sometimes 7.5, 25 and 30 m were added. The results of these measurements have been published in many papers: Renk, 1973 (data from 1970–1971); Torbicki, 1975 (1972–1974); Renk *et al.*, 1985 (1982–1983); Renk *et al.*, 1987 (1984–1985); Renk, 1990. The data obtained by the SFI makes up about two-thirds of the entire material.

In 1979–1980 the monitoring was done by a team of scientists from the Institute of Oceanology PAN (IO PAS) (Dera *et al.*, 1980, 1981). This team also carried out the *in situ* PP measurements during the international voyage of r/v 'Professor Albrecht Penck' in 1973 (Dera *et al.*, 1974), and during the PEX ′86 Experiment (ICES Rep., 1989). Several research voyages to the Baltic Sea were jointly organised by Polish and Russian scientists, when the PP measurements were carried out by workers from the SFI, IO PAS and the P.P. Shirshov Institute of Oceanology in Moscow (IO RAS). These included the voyages of r/v 'Profesor Siedlecki' in July 1980 (Koblentz-Mishke *et al.*, 1985), r/v 'Akademik Kurchatov' in May and June 1984 (Koblentz-Mishke and Belayeva, 1987), and r/v 'Professor Shtokman' from January to March 1990. The scientists from IO PAN employed a 4-hour exposure time at depths of 0, 1, 2, 3, 5, 7, 10, 15, 20, 30 m. More intensive sampling in the upper layer allowed the observation of photoinhibition effects.

The results of measurements carried out using surface sampling by the scientists from IO RAN during the voyages of r/v 'Akademik Kurchatov' in September 1973 and in June and July 1978 extended the data set

(Koblentz-Mishke and Konovalov, 1981). A half-day incubation time was applied during these trips, and the daily production was estimated by doubling the value obtained. Surface sampling with a 4-hour incubation time was employed for the additional measurements during these voyages of r/v 'Akademik Kurchatov' in 1984 and r/v 'Professor Shtokman' in 1990.

The production measured during the incubation time was used to determine the daily production by using the above-mentioned light factor method. This assumes that the photosynthetic primary production is proportional to the solar energy dose, so that the daily production is derived from the formula

$$\frac{P_{\text{day}}}{P_{\text{exp}}} = \frac{\eta_{\text{day}}}{\eta_{\text{exp}}}, \tag{1}$$

where

P_{day} – daily primary production,
P_{exp} – primary production during the incubation time,
η_{day} – daily PAR radiant energy dose at the sea surface,
η_{exp} – dose of radiant energy in the PAR range at the sea surface during the incubation time.

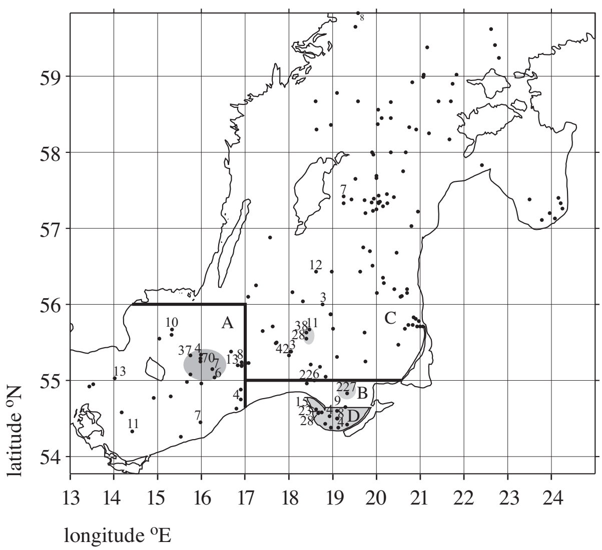

Fig. 1. Location of measurement stations. The numbers refer to the number of measurements performed at a given station (there are no numbers where only 1 or 2 measurements were made). The hatched areas represent 'model areas' for obtaining the annual PP distribution. The letters denote the regions into which the sea area was divided, and the bold lines mark their borders

The material obtained provided 727 values of the daily primary production, calculated on the basis of the data obtained from *in situ* profiles and 99 PP measurements using the surface sampling method. The latter were usually additional measurements performed in between the standard monitoring stations, and their value consists in rendering the data network denser. The spatial distribution of these data is very uneven (Fig. 1). Since a large proportion of measurements was made at the monitoring stations, the data set includes a number of sites at which several tens of measurements were made (even more than two hundred at the Gdańsk Deep, station P1). Other stations are fairly evenly spread, but only a few, sometimes just one or two measurements were carried out at each of them during the entire research period.

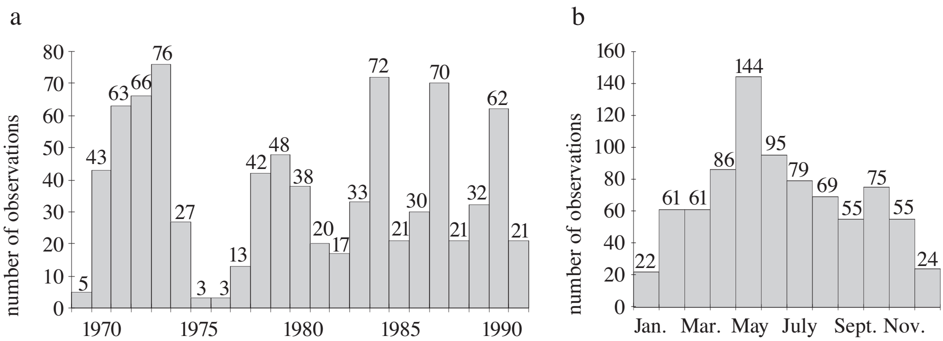

Fig. 2. Time distributions of the data used in the study: number of measurements in consecutive years (a), seasonal distribution (b)

The quantity of data varied from year to year, but there were no long interruptions in the measurement series except during 1975–1976 (Fig. 2a). The seasonal distribution of the data shows a shortage of winter measurements (Fig. 2b).

3. Calculations

The data set includes only a few stations (or groups of adjacent stations) with a sufficient number of measurements to obtain the annual primary production function and average annual production values. However, there are far too few such stations to prepare annual production maps based on data from them only. Although it would be possible to prepare a number of maps for particular periods of the year (months or seasons) and use them to calculate the annual production, the data set is unfortunately insufficient even for this method. Too few measurements were made in the various seasons, especially during the winter.

It was therefore decided to estimate the annual production on the basis of each individual production measurement. If the annual primary production function is assumed known at a certain site, then the annual production there can be calculated from a single measurement.

Stations (or groups of adjacent stations) where the data set was sufficient to determine the annual function were designated, hereafter referred to as 'model areas' (the hatched areas in Fig. 1). The area surrounding each station was allotted to it and the same relative annual PP function was assumed to hold for the model area and its surroundings. Since in the last twenty years eutrophication of the sea has visibly increased, the annual primary production increments were determined for each individual region separately by linear regression. On that basis all measured daily PP values were converted into the figures which would have occurred in 1991. After eliminating the influence of eutrophication, the annual primary production function and its annual value in every model area was determined. Next, the annual production was estimated from each daily production measured, and the map could be drawn. The details of the calculations are given below.

Determining the production in the water column on the basis of surface layer production

Some of the data was obtained by the surface sampling method, which means that only the PP value in the surface layer is known. The relationship

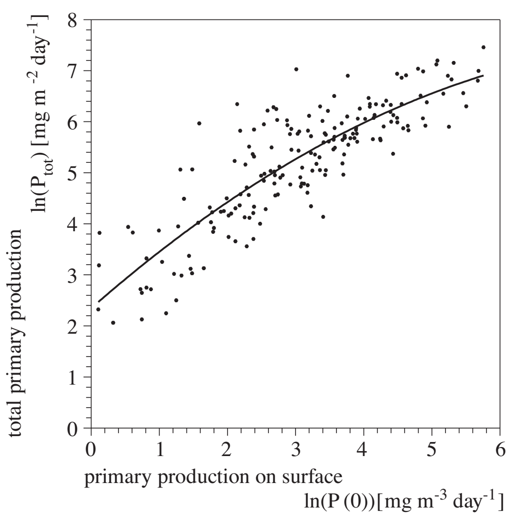

Fig. 3. Interdependence between production in a column of water 0–30 m, P_{tot} and production in the surface layer, $P(0)$. Solid line – approximation by using eq. (3)

between the surface layer production $P(0)$ and that in the water column from the surface to a depth of 30 m was examined, so that this data could be used in further calculations. The result is shown in Fig. 3.

The curve approximating this relationship is given by the following equation:

$$P_{\text{tot}} = \exp[(2.348 + 1.169 \ln P(0) - 0.0656 \ln^2 P(0))]. \tag{2}$$

The systematic error of this approximation $\langle \varepsilon \rangle_g$, calculated by using logarithmic statistics, *i.e.*

$$\langle \varepsilon \rangle_g = 10^{\langle \log(P_{\text{tot},c}/P_{\text{tot},m}) \rangle} - 1, \tag{3}$$

is equal to –11%.
The statistical variability range is

$$\begin{aligned} \varepsilon_{\min} &= 10^{\langle \log(P_{\text{tot},c}/P_{\text{tot},m}) \rangle - \sigma_{\log}} - 1 = -59\%, \\ \varepsilon_{\max} &= 10^{\langle \log(P_{\text{tot},c}/P_{\text{tot},m}) \rangle + \sigma_{\log}} - 1 = +90\%, \end{aligned} \tag{4}$$

where
$\sigma_{\log}$ – standard deviation of $\log(P_{\text{tot},c}/P_{\text{tot},m})$.

Eq. (2) was determined on the basis of 195 measurements and was used to convert the data obtained by surface sampling into production values in a column of water.

Division into regions

The annual production function could be determined for a few sites only: station P1 in the Gdańsk Deep (227 measurements), station P40 and its vicinity at the southern edge of the Gotland Deep (77 measurements), as well as station P5 in the Bornholm Deep and a number of sites a short distance away from this (127 measurements). Each of these sites (model areas) was assigned its surrounding area, the annual PP function of which was assumed to be identical with the corresponding model area (area borders are indicated by bold lines (Fig. 1), and each area is marked with a letter). Unfortunately, there are too few stations with sufficient measurements to determine the annual PP function for the entire sea region north of lat. 56°N. For this reason it was necessary to extend area (C) northwards. The Gulf of Gdańsk was treated as a separate area, and its annual function was established on the basis of all the measurements made there (96 measurements).

Eutrophication

The year-by-year increase in PP, related to the progressive eutrophication of the sea, was reported much earlier (Nakonieczny *et al.*, 1989; Renk, 1991; Renk *et al.*, 1992). The material collected for this study confirms this. But since the rate of eutrophication can vary at different times of the year, this period was divided into three parts in accordance with the analysis of the seasonal daily production graph. Production remains low in November or December (the time spans could vary for different regions). The spring phytoplankton bloom can occur at any time from mid-March onwards, resulting in a sharp peak in the daily production as a function of time. However, the spring phytoplankton bloom can commence at different times depending on the weather conditions in a given year, and its duration and intensity can vary considerably from one year to the next. A diagram of daily PP versus day in the year shows a great spread of measured values in this season. Later, in the summer and autumn, the production is maintained at a fairly high level, whereby the values are greater if measurements were made during a bloom period.

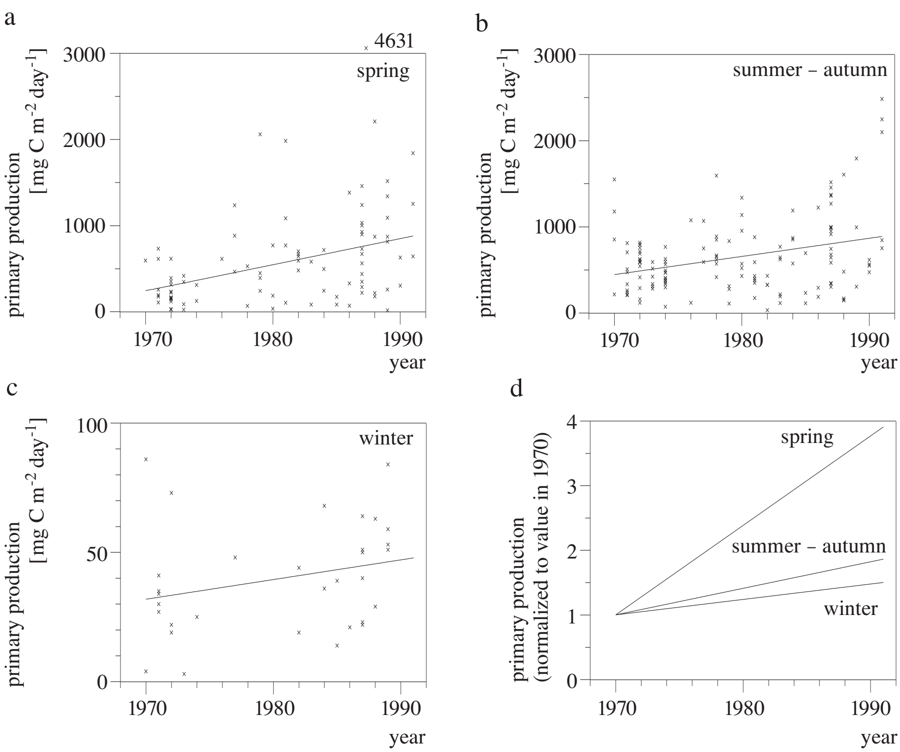

Fig. 4. Illustration of the long-term changes in primary production in area (B) (mainly the Gdańsk Deep): measured daily production in particular seasons as a function of time and a linear regression line (a–c), regression lines in (a–c) normalised to the average production in 1970 (d)

Figs. 4a, 4b and 4c show the daily production measured in region (B) (mainly in the Gdańsk Deep) as a function of the time interval from 1968 to 1991, separately for each of the three seasons. Linear regression lines were determined for each season, which showed that there was a long-term tendency for production to increase. Fig. 4d shows the regression lines after normalisation to their 1970 values. It can be seen that the greatest relative increase in production took place in the spring months, indicating that the spring blooms were becoming ever more intense in relation to the average annual production.

Similar calculations were repeated for the other three regions. The results of the linear approximations of production growth are given in Tab. 1.

Table 1. The parameters of the linear regression function $y = ax + b$, approximating the long-term variation in daily primary production for the regions and seasons outlined. Daily production values are expressed in mg C m^{-2} day^{-1}; the x axis represents years starting from 1970; n – quantity of data

Region	Parameters	Season		
		spring	summer–autumn	winter
A	n	104	113	37
	a	22.3	11.1	7.1
	b	137.5	358.5	28.4
B	n	90	136	32
	a	33.7	18.9	0.76
	b	243.6	461.4	31.9
C	n	125	118	54
	a	22.7	18.3	5.43
	b	164.7	337.8	19.7
D	n	30	43	25
	a	26.8	29.9	4.34
	b	521.8	617.5	22.5

The calculated annual production increments were used to convert each daily production measured into the value anticipated for 1991.

The occurrence of eutrophication was the reason for bringing the research period to a close in 1991. While more recent data is available, there are not enough to confirm or negate the premise that the PP growth trend is being maintained at the same level. According to economic publications, the economic changes in post-communist countries have brought about an abrupt and considerable decrease in the use of artificial fertilisers, and this is probably why the flow of nutrients from the land to the sea has fallen. Extrapolation of earlier data therefore gives no indication of whether eutrophication of the sea is continuing at the same level.

Annual production in the model areas

The average annual functions of daily primary production were determined for the four model areas (for data reduced to 1991 values), $P_{\mathrm{day},w}$. The distribution of all the $P_{\mathrm{day},w}$ figures is presented in the two histograms in Fig. 5: on the linear scale (a), on the logarithmic scale (b). It may be seen that the distribution on the logarithmic scale is more similar to the normal distribution; so in working out annual functions, monthly averages, calculated according to logarithmic statistics, were used.

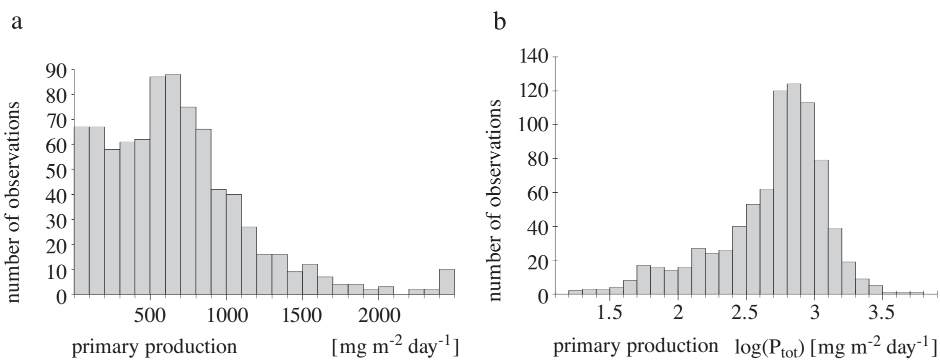

Fig. 5. Histograms of daily primary production: on a linear scale (a), on a logarithmic scale (b)

$$\bar{x} = \exp\left[\sum_{i=1}^{n} \frac{\ln(x_i)}{n}\right]. \tag{5}$$

The average annual functions $P_{\mathrm{day},w}$ for all four model areas are presented in Fig. 6. Measured values and the standard deviations of monthly means are indicated in the diagrams.

The annual primary production $P_{\mathrm{year},w}$ and the seasonal distribution of the primary production $f_p(t)$, were derived from the annual PP function for each model area (t denotes time, *i.e.* the day number in the course of the year).

$$f_p(t) = \frac{P_{\mathrm{day},w}(t)}{P_{\mathrm{year},w}}. \tag{6}$$

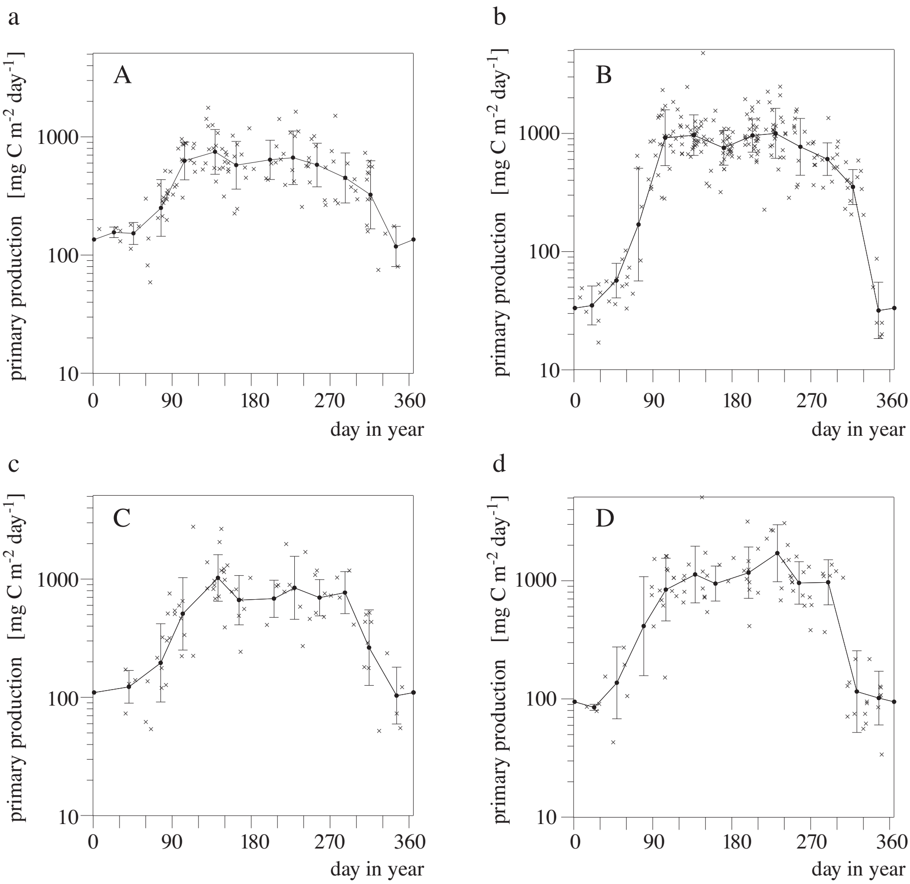

Fig. 6. Average annual primary production in four selected sea regions (marked with capital letters); daily primary production is marked (after converting it into values for 1991), monthly averages are joined with lines and standard deviations are marked (a–d)

Converting daily production into annual values and preparing a map

The assumption that the seasonal PP distribution is uniform in the entire region surrounding the model area implies that it is possible to calculate the annual production $P_{\text{year},x}$ on the basis of each daily production $P_{\text{day},x}(t)$ measured in that area

$$P_{\text{year},x} = \frac{P_{\text{day},x}(t)}{f_p(t)}. \tag{7}$$

The annual production values obtained in this way were used to prepare a map of this parameter (Fig. 7). This was done using the 'kriging' method from the 'Surfer' programme.

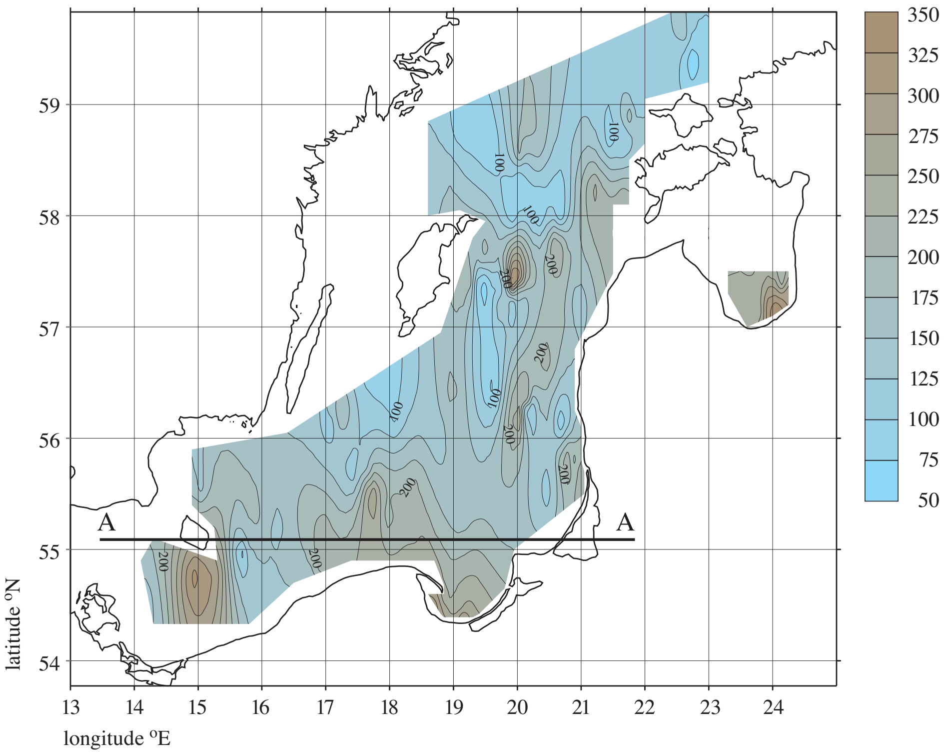

Fig. 7. Map of the Baltic Sea annual primary production in 1991 (expressed in g C m^{-2} $year^{-1}$). The straight line A–A marks the intersection of Fig. 9

4. Discussion

The fact that measuring primary production is a time-consuming and laborious undertaking means that there are fewer such measurements than of other oceanographic parameters. The production measurements are fraught with methodological errors, which have been discussed in many papers (*e.g.* Koblentz-Mishke and Vedernikov, 1977). The measurement depends on such factors as the period of exposure, the time of day at which the measurement is carried out, and even the capacity of the bottles containing the incubated samples (Fogg and Calvario-Martinez, 1989; Harris *et al.*, 1989). The conversion of the measured production into daily values using the light factor method is also an approximation. For analytical purposes a sufficient quantity of such data is required, so that the dispersion resulting from measurement errors can be eliminated with the use of statistical methods. For this reason an algorithm was used, enabling all measurements to be taken into consideration to the same extent. This necessitated certain approximations.

The annual PP pattern obtained on the basis of monthly averages does not reflect correctly the changes in PP in the course of a single year. It is the result of the averaging of the data from many years, in which the spring phytoplankton blooms and the subsequent drops in daily production occurred at different times, which almost caused the production peak related to the spring phytoplankton bloom to disappear from the diagrams obtained. The same holds true for subsequent phytoplankton bloom, though to a lesser extent.

The greatest approximation that might be a source of a systematic error in the results was that a given function $f_p(t)$ also holds true at stations situated far from the site where it was determined. In particular, this diminishes the credibility of the results obtained for the region lying north of lat. 56°N. However, even if the absolute annual production for the region shown on the map is distorted with a systematic error, the relative distribution of this production in areas located at a similar latitude should be correct. Therefore, this part of the map should be treated as a source of data concerning the relative productivity distributions. The PP value estimated for the Polish economic zone should be correct.

The results were compared with the literature data (Renk, 1983, 1990; Lorenz *et al.*, 1991), which give the annual PP in the selected areas in consecutive years and averaged over periods of several years. Since the map presents the PP values for 1991, for comparative purposes it was necessary to convert these into the values for the respective years. Therefore the annual production increments for each region were calculated on the basis of the data from Tab. 1. The increments for each season were averaged using the production value as a weight factor. The increments obtained for subsequent regions of the map are (A) – 5.2, (B) – 8.4, (C) – 6.8, (D) – 10.0 [g C m^{-2} $year^{-1}$].

Fig. 8 shows the result of this comparison. The systematic error (according to formula (3)) is equal to –3.7%, and the logarithmic standard deviation (according to formulae (4)) varies from –29% to 18.5%. In view of the fact that the literature data includes years characterised by exceptionally low and exceptionally high productivity, the result confirms that the algorithm employed was correct.

The spatial distribution of the annual production is in general agreement with existing findings (Kaiser *et al.*, 1981; Renk, 1994). The Gulf of Gdańsk and the Gulf of Riga are high-production areas. The eastern part of the

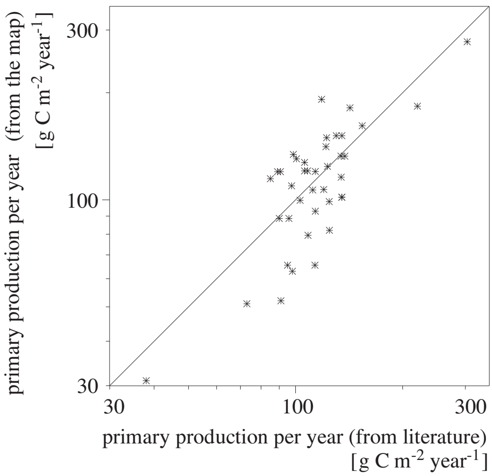

Fig. 8. Comparison of the annual primary production of Fig. 7 with the literature data

Baltic Proper is more productive than its western part. However, the new map presents a more complex spatial structure of productivity than the existing maps. The map shows relatively small areas of high productivity. One of them is located south of Bornholm. The number of measurements performed in this region was rather small and the result obtained, exceeding 300 g C m^{-2} $year^{-1}$, is not sufficiently well documented. However, later measurements, which were not included in this map, also indicate high productivity in this region. Regular monitoring of PP in this region would be useful. Another PP maximum confirmed by a large number of data occurs in the Słupsk Furrow area. Another two maxima are located in the Gotland Deep, north of lat. 56°N; hence the reservation concerning absolute values applies to them too.

These PP maxima occur at the edges of deep-sea areas, where upwelling could occur. The map was compared with the results of studies in marine dynamics. According to Kielmann (1981), who developed a simplified distribution pattern of surface currents for the Baltic Sea on the basis of measurements and model examinations, there is a cyclonic configuration of surface currents in the central Baltic. The higher PP in the eastern Baltic can be explained by the existence of a current carrying north the waters of large rivers flowing into the sea from the south and east. Within the general cyclonic circulation of waters, smaller mesoscale vortices are formed. Their location and duration depend on the anemobaric and internal forces resulting from the inhomogenous water density. This vortex structure was presented in the study by Mikhaylov (1992). In his study on the mathematical modelling of the water flow in the Baltic Sea, Jankowski

(1988) confirms the existence of a extensive and variable structure of flows. The results of the modelling of the vertical current velocity in the Baltic Sea are given in other papers by Jankowski (1996, in preparation). The latter can be of great importance as regards the overall picture of Baltic primary production, since these currents may carry nutrients from the bottom up to the euphotic zone. Fig. 9 presents a vertical section of the Baltic Sea along the lat. 55°05′ N (Fig. 7 – line A–A) with the isolines of the vertical current velocity in June (the isolines of the upward currents are hatched). As can be seen, upward currents can stretch from the bottom zone to the surface layer, so the transport of nutrients to the euphotic zone is possible. Upwelling areas can be found in the intersection in the vicinity of long. 17°E and between long. 18° and 19°E. Fig. 7 shows a high annual production in these regions.

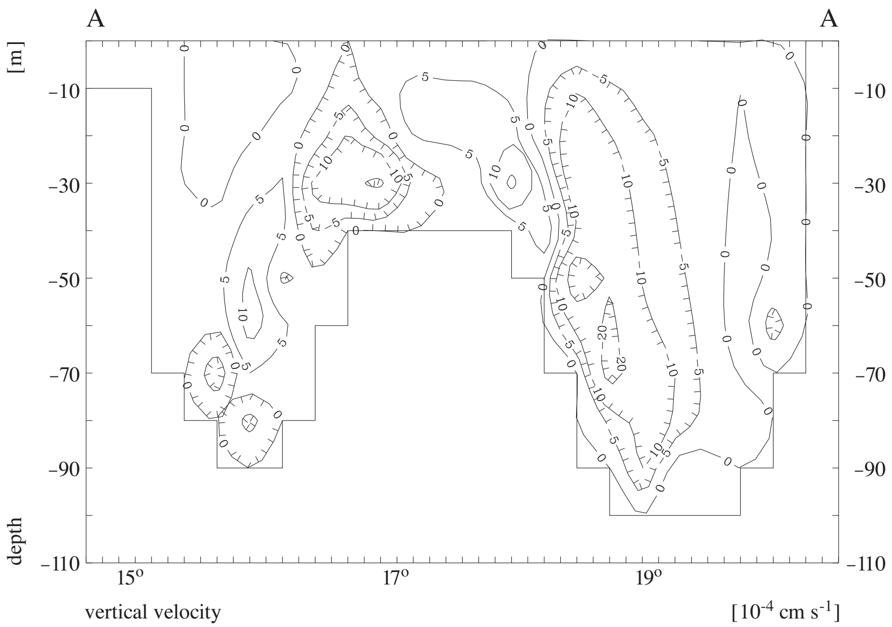

Fig. 9. Current velocity vertical distributions for the intersection A–A of Fig. 7 (along lat. 55°05′ N) obtained by model calculations for conditions typical in June. Upward currents are marked with hatched lines (from Jankowski, in preparation – published by permission of the author)

Fig. 10 shows the spatial distribution of vertical currents in June, modelled by using the average (most probable) wind fields and water density for that month. Areas of upward currents (represented by dark patches) appear south-west and south of Bornholm, in the Słupsk Furrow, the Gdańsk Deep and north of it, and also east of northern Gotland. In these areas of

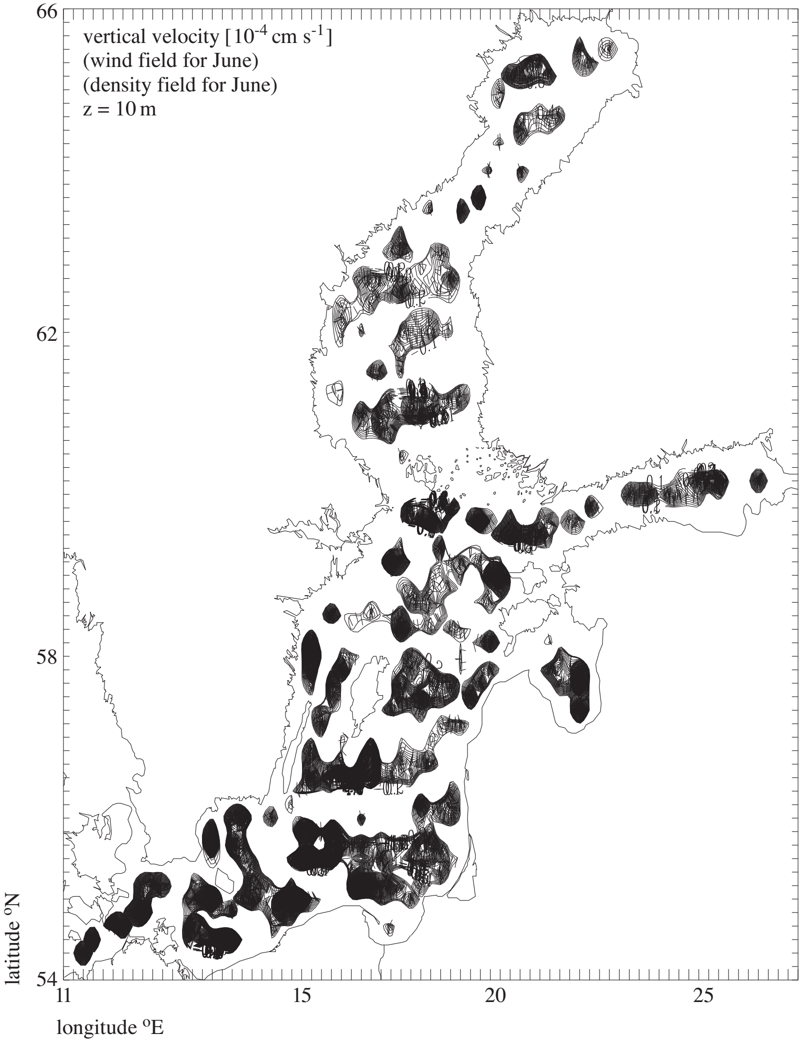

Fig. 10. The spatial distribution of upward currents in the Baltic Sea in June (dark patches) (from Jankowski, in preparation – published by permission of the author)

upward currents, primary production is high. The only exception is the area south of Gotland. Though the current map shows upwelling in that area, the annual production is extremely low. PP measurements carried out after 1991 confirm the above distribution. Figs. 9 and 10 are only an example illustrating that the dynamics of water masses can influence productivity in the sea. To compare the vertical current fields and the productivity distribution, it would be necessary to make appropriate calculations for the same time intervals.

5. Conclusions

The map shows the annual primary production distribution calculated for 1991. The production in previous years can be estimated on the basis of this map, by using the annual production increment coefficient for the sea regions described in this paper. The map does not cover the entire Baltic Sea, and that part of it north of lat. 56°N should be treated as an approximation only. Data from other research centres are necessary to complete the map.

The spatial distribution of the annual primary production was found to be more complex in comparison to previous maps. The fact that the distribution is similar to the sea current field suggests that the latter exerts a strong influence on primary production by transporting nutrients.

Acknowledgements

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