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An evaluation of the 1985 – 2008 time series

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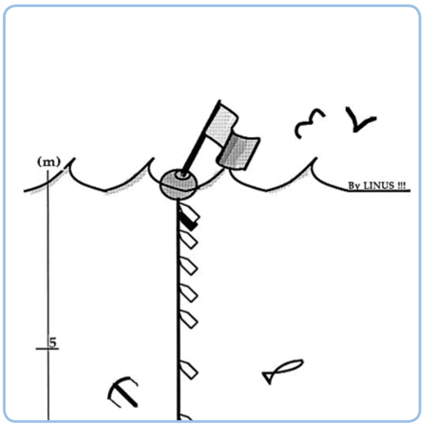

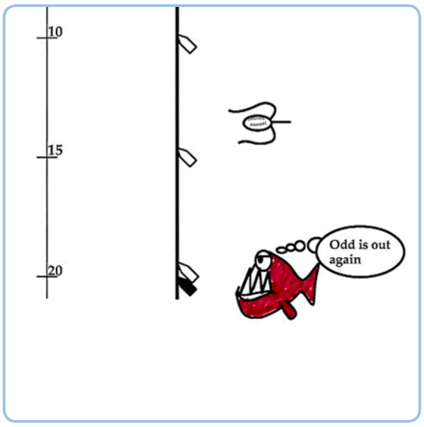

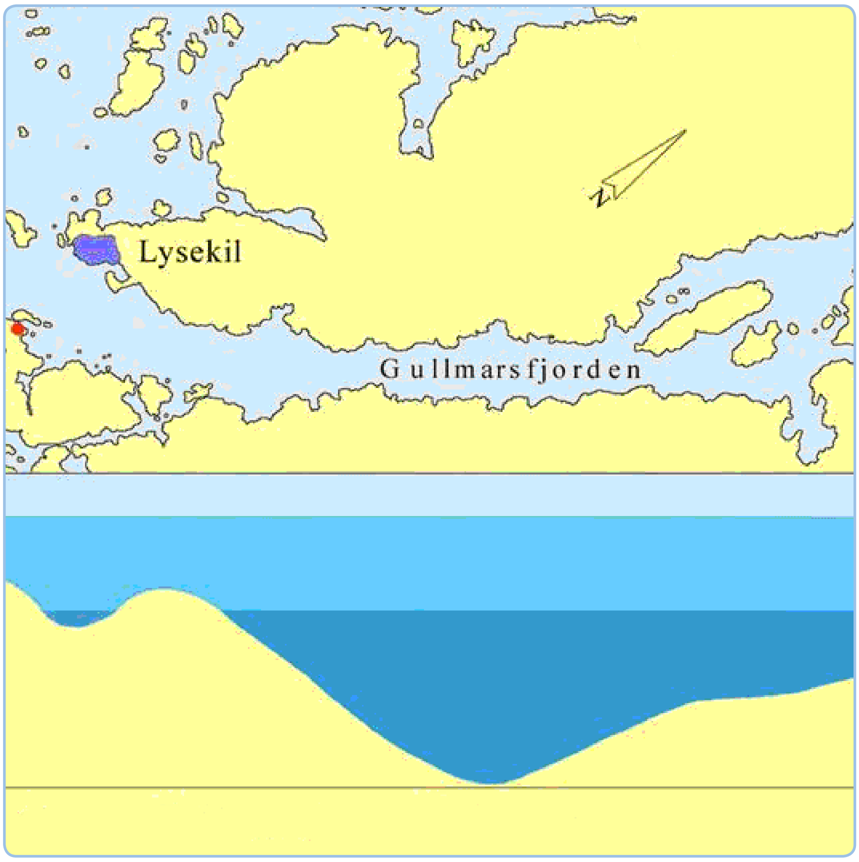

Primary phytoplankton productivity in the Gullmar Fjord, Sweden

An evaluation of the 1985–2008 time series

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Preface

Marine research has been carried out in the Gullmar Fjord, situated on the Swedish Skagerrak coast, and adjacent waters for far more than 100 years (figure 1). Primary phytoplankton productivity has since 1985 been measured in the mouth area of the Gullmar Fjord, as a part of the Swedish marine monitoring program.

A first comprehensive evaluation of this primary production time series was carried out in 1994. It was found that the primary production was comparatively large and elevated during the summer months, although biomass (chlorophyll) and nutrient concentrations were at low levels (Lindahl, 1995). The elevated summer production and a lack of a summer minimum in the sedimentation of organic particulate material indicated that there was a substantial nutrient input during summer. Further, an increasing trend of 4 ± 1.9% in the annual primary production was found.

A second evaluation was carried out in 1996 (Lindahl et.al., 1998; Belgrano et.al., 1999). Time series of monthly means of the North Atlantic Oscillation (NAO), wind, temperature, salinity, nutrients, precipitation, run-off, chlorophyll and primary production were compared using correlations on both original and detrended series. The results suggested the presence of an indirect link between NAO, the supply of nutrients to Kattegat, wind and the primary production in the Gullmar Fjord and revealed the importance of considering climatic and environmental forces among the factors that may be responsible for the observed development and fluctuations.

An application of artificial neural networks (ANN) to the Gullmar Fjord primary production time-series data was carried out and resulted in a good fit between observed and predicted values (Belgrano et al., 2001). The application of ANN was a novel and useful tool for primary production modeling compared to multiple regression methods, especially when the numbers of environmental and climatic co-variables are large.

After the millennium shift it slowly became obvious that the calculated annual production was decreasing and the annual mean production during the period 2000 to 2005 was clearly lower compared to the previous 5-year period (Lindahl, 2007). A simple trend analysis of the development of the time-series from 1985 to 2005 was made by calculating 5-year running means and it was found that a polynomial function of second order gave the best fit of the overall trend ($r^2 = 0.78$). It was found that the primary production in the Gullmar Fjord peaked during the 5-year period 1992 – 1996.

The aim of the present evaluation was to describe the observed fluctuations in the annual primary production during the period 1985 – 2008. Further, based on correlation analysis, present a likely explanation to the processes and mechanisms underlying this pattern.

The author assume sole responsibility for the contents of this report, which therefore cannot be cited as representing the views of the Swedish Environmental Protection Agency.

Swedish Environmental Protection Agency, November 2009

Anders Johnson
Director, Environmental Assessment Department

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Summary

Primary phytoplankton productivity has since 1985 been measured in the mouth area of the Gullmar Fjord, as a part of the Swedish marine monitoring program. Results from earlier evaluations of this primary production time series suggested the presence of an indirect link between NAO, supply of nutrients, wind, and the phytoplankton primary production and revealed the importance of climatic and environmental forces among the factors responsible for the observed development and fluctuations.

An analysis of five-year running means of the primary production time-series from 1985 to 2008 revealed that the primary production in the Gullmar Fjord increased and peaked during the five-year period 1992 – 1996, followed again by a decrease in production. The increase in production, as calculated from the first annual running mean and compared with the maximal mean, was 20 % and the decrease of the last annual mean was 25 %. The total result was that the mean annual primary production was 3.8 % lower when the difference between the first and the last 5-year running means compared to the over-all mean production for the whole period of time.

The present evaluation concludes that there is a direct link between primary production and nitrate concentrations in the mouth area of the Gullmar Fjord. Further, there is no influence from local runoff on the long term development of the primary production. Any long-term co-variation in primary production of the Gullmar Fjord and the adjacent Kattegat and Belt Sea areas is not evident,.

The overall results suggested that the primary production in the mouth area of the Gullmar Fjord during 1985 – 2008 has been controlled by the coupling of large climatic decadal patterns such as the NAO and the subsequent changes in the nutrient regime at a regional scale including the Skagerrak. It may further be concluded that the anomaly of an exceptional flux of nitrate-rich ocean water onto the NW European shelf most likely extended its distribution also to the Swedish west coast and the mouth area of the Gullmar Fjord, which in turn triggered the 19 % rise in annual primary production during the mid 1990s.

Material and methods

The Gullmar Fjord

The Gullmar Fjord, situated on the Swedish Skagerrak coast about 100 km north of Gothenburg (Fig. 1), is a typical fjord with a maximum depth of 120 m and a sill of 42 m depth at the inlet (Fig. 2). The main axis runs SSW – NNE and the total length is about 30 km and 50 km^2 surface area (Fig. 2). The total volume is 2.05 km^3, of which about 30 % is below the sill level (Svansson, 1984). The fjord has a drainage area of 1321 km^2 and one main stream, the Örekil River, enters in the inner end. The tide is only about 20 cm.

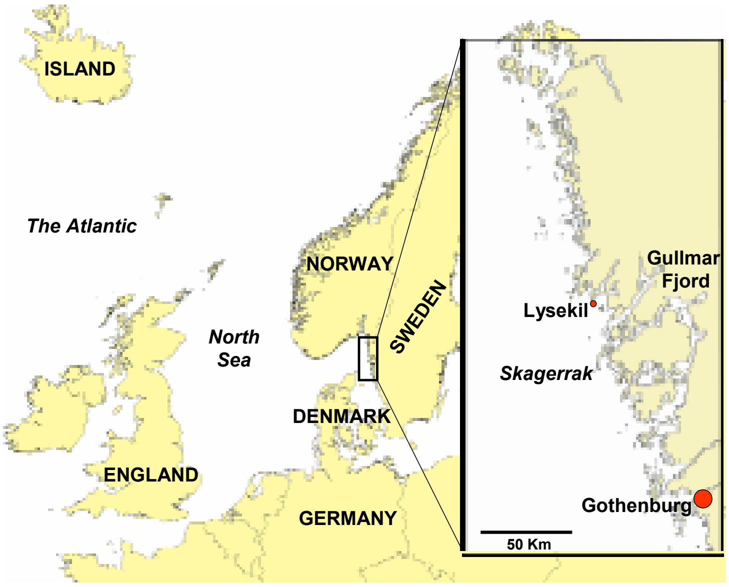

Figure 1: NW Europe and the Swedish Skagerrak coast.

Low-saline water from the Baltic mixed with Kattegat water is generally flowing northwards as a surface current along the west coast of Sweden, the so-called Baltic Current. Saline water from the North Sea – Skagerrak area is transported by the Jutland Current towards the Swedish coast. The surface water in the mouth area of the Gullmar Fjord is made up by a mixture of local runoff, Baltic and Jutland Currents water and extends generally down to about 15 m depth but varies considerably in thickness (Fig. 2). The salinity of the surface water may thus also vary a lot, from 15 to 30 PSU or even more. The water exchange above sill depth is a more or less continuous process and a mean residence time of the top layer above the halocline has been calculated to 12 days (Rydberg, 1977).

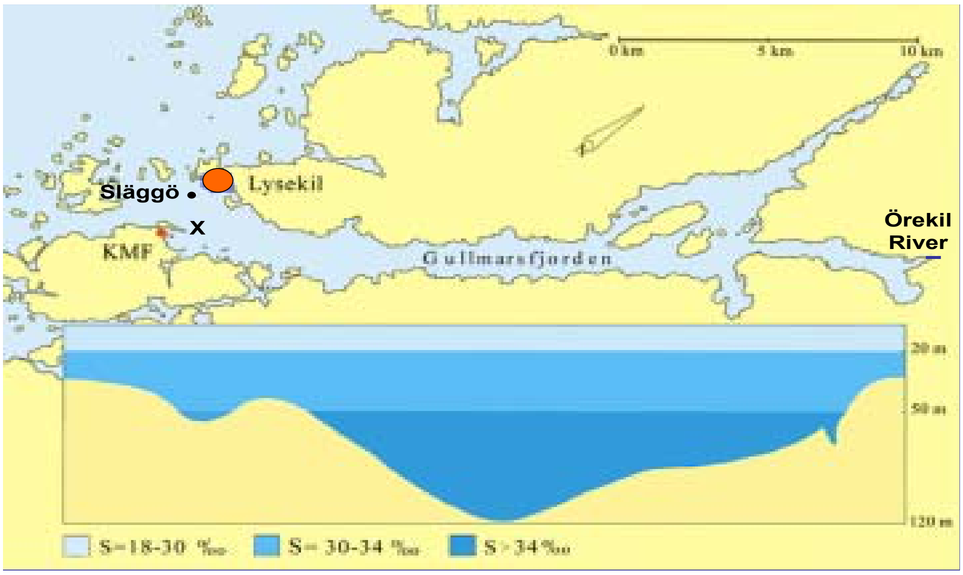

Figure 2: The Gullmar Fjord, its bottom profile and different water bodies. "x" marks the site of primary production measurements and the black dot indicates the monitoring station Släggö. KMF is the Kristineberg Marine Station.

In the Gullmar Fjord there are no major sources of water pollution either from sewage or from industrial origin. In fact, the fjord is a marine reserve since the 1980s. The environmental conditions at the fjord mouth may consequently be considered to represent the pelagic system of the outer archipelago relatively well. However, the fjord is not protected from the large-scale pollution of the seas in northern Europe, due to the transport of nutrients and pollutants coming through advection from Swedish sources, the Baltic and the North Sea. Consequently, the Gullmar Fjord experiences the same general fate concerning eutrophication and pollution as most coastal waters in NW Europe (Anon., 2008), despite the absence of local sources.

Temperature, salinity, nutrients, secchi depth, chlorophyll a and PAR

In this study data from two different areas have been used; i) 6 stations in the open Skagerrak used as a mean of offshore conditions and ii) the stations Släggö situated in the mouth area of the Gullmar Fjord and Stretudden nearby (Fig. 3). For the open Skagerrak area, the main part of the data used in this work comes from the Swedish National Monitoring Programme carried out by Swedish Meteorological and Hydrological Institute (SMHI).

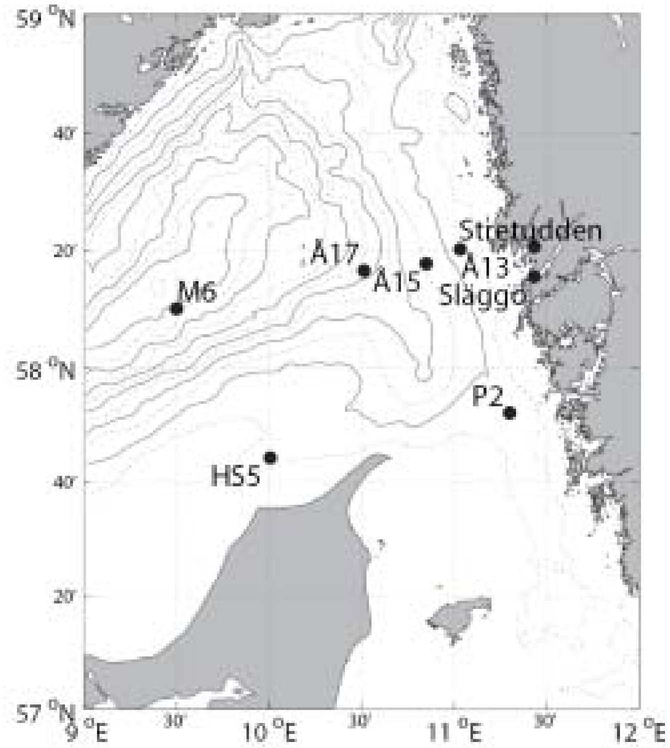

Figure 3: Skagerrak and coastal stations from which data has been used in the analyses

From 1985 to 1993, measurements were done approximately 4 to 6 times a year but since 1993 monthly measurements have been carried out. From the first years also measurements from other countries have been included, although for this part of the time series there were occasionally uneven distributions over a year, with more measurements carried out during winter than during summer. Data from the coastal zone comes mainly from the Bohuslän Water Conservation Association (BVVF) which has performed monthly monitoring at some stations since mid 1980s and from a larger number since 1990 (www.bvvf.se). From 1985 to 1996 one or two visits per month with hydrographical measurements were made at the station Släggö, situated at the mouth area of the Gullmar Fjord. However, during the period 1997 till 1999, no hydrographical measurements at all were carried out in this area and data from the nearest coastal station Stretudden was used to fill the gap. Since 2000, Släggö has been a high frequent monitoring station within the Swedish National Monitoring Programme and has since then been visited twice a month.

Sampling and analysis of water samples have been carried out by accredited laboratories and done according to the HELCOM/COMBINE recommendations at all stations. The sampling depths were every 5 meters from the surface down to 20 meters and thereafter every 10 meters down to 50 meters. Temperature measurements were done using a reversing thermometer and/or a CTD. Water samples for analysis of salinity, nutrients and chlorophyll were taken by Hydro Bios water samplers. Secchi depth measurements were done by deploying a 20 cm disc without using a under water viewer.

Parameters studied were temperature, salinity, phosphate, total-phosphorus, inorganic nitrogen (DIN= $NO_2 + NO_3 + NH_4$), total-nitrogen and silicate together with chlorophyll a. Monthly mean values, as well as annual means, of all parameters have been calculated for the surface layer 0-10 meters and for a deeper layer 20-50 meters.

In order to calculate a light factor (se below) for each day when a measurement was carried out, irradiation was measured. From 1985 to 1995 this was done by a pyranometer mounted at the top of the Kristineberg laboratory building approximately one km from the site of primary production measurements. The irradiation was integrated over 5 minute intervals and the light factor was calculated by dividing the total irradiation during the day by the irradiation during the incubation. From 1996 the pyranometer was exchanged for an instrument measuring the photosynthetic available radiation (PAR), also during 5 minute intervals. From early 2002 to April 2007 there was unfortunately no measurements done of PAR and during this period the light factor was estimated by calculating a mean value of the preceding years for the actual month.

The North Atlantic Oscillation (NAO) winter (December through March) index data were provided by the Climate Analysis Section, NCAR, Boulder, USA (Hurrell, 1995; http://www.cgd.ucar.edu/cas/jhurrell/indices.html). The NAO index is based on the difference of normalized sea level pressure (SLP) between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland since 1864.

Primary production

Primary production was measured using the ^{14}C-technique *in situ* at 10 depths (0, 1, 2, 3, 4, 6, 8, 10, 15 and 20 m) between 1985 and 2000, where after measurements at 20 m were excluded due to that measured production at this depth always was 0 or very close to 0. The water samples were collected with a Ruttner water bottle. Incubations were carried out in 125 ml glass bottles during 4 h at around noon and dark bottles were used at 0 and 20 or 15 m depths following the recommendations of the Baltic Marine Biologists (BMB, 1976). One certified ampoule (Carbon 14 Centralen, DHI Water & Environment, Hørsholm, Denmark) containing 10 µCi (370 kBq) ^{14}C was added to each incubation bottle.

Within 20 minutes after the incubation one subsample of 10 ml was taken from each bottle and was acidified and bubbled (no filtration). The radioactivity was measured by the liquid scintillation technique and the ^{14}C uptake was calculated, including a correction for respiration loss, extraneous ^{14}C fixation and isotope discrimination by multiplying by a factor of 1.1 (BMB, 1976). The dark value for each depth was calculated by linear interpolation and subtracted from the corresponding light bottle value.

The 4 h results were transformed into daily production by the light factor method (BMB, 1976). The production per m^2 sea surface area was calculated by integration over depth using the trapezoid formula. Monthly means of the daily production as well as the monthly and annual total production was calculated through linear integration over time. Measuring frequency was low during winter and also now and then during the rest of the year. Some few given values had therefore to be used in order to avoid unrealistic results when integrating the production over time. These values were found by comparing the measuring results from other similar periods of time.

It should clearly be pointed out that there has been no fundamental change in the measuring protocol used or of the calculations during the 24 years. The ^{14}C-technique involves some apparent uncertainties as to what is actually measured and how the measured ^{14}C-uptake should be converted into daily production (Williams, 1993). However, the method used of the present time-series seemed still to be a reasonable compromise (Maestrini et al., 1993) and the results can be used for studying and analyzing relative changes and trends of the primary production over time.

Statistical analysis

The time series of primary production covering the 24 years from 1985 to 2008 was analyzed to detect regime shift that may be related to a reorganization of the ecosystem and in particular the changes over time in primary production. For the detection of regime shift in the mean of the PP time series the monthly mean values from 1985 to 2008 was used and applied the Regime Shift Index (RSI) method proposed by Rodionov (2004, 2006), where the significance of the (RSI) is measured as a confidence level of the difference between the mean values of the neighbouring regimes based on the Student's two-tailed t-test with unequal variance and equivalent sample size. The RSI method has been used for detecting changes at the ecosystem level in both climatic and biological time series including fisheries (Rodionov and Overland, 2005).

Correlation coefficients between the variables were tested using the Pearson’s correlation coefficient.

Results

NAO and hydrography

The North Atlantic Oscillation (NAO) index is based on the difference of normalized sea level pressure between Lisbon in Portugal and Stykkisholmur on Iceland (Fig. 4). This climatic oscillation has a strong influence on the regime of the westerly winds across the North Atlantic resulting in changes in winter temperatures on both sides of the Atlantic (Kerr 1997). The NAO plays an important role in circulation and convection in the North Atlantic and may be responsible for the changes in intensity of the subpolar gyre and the flow of the North Atlantic Current (Dickson, 1997).

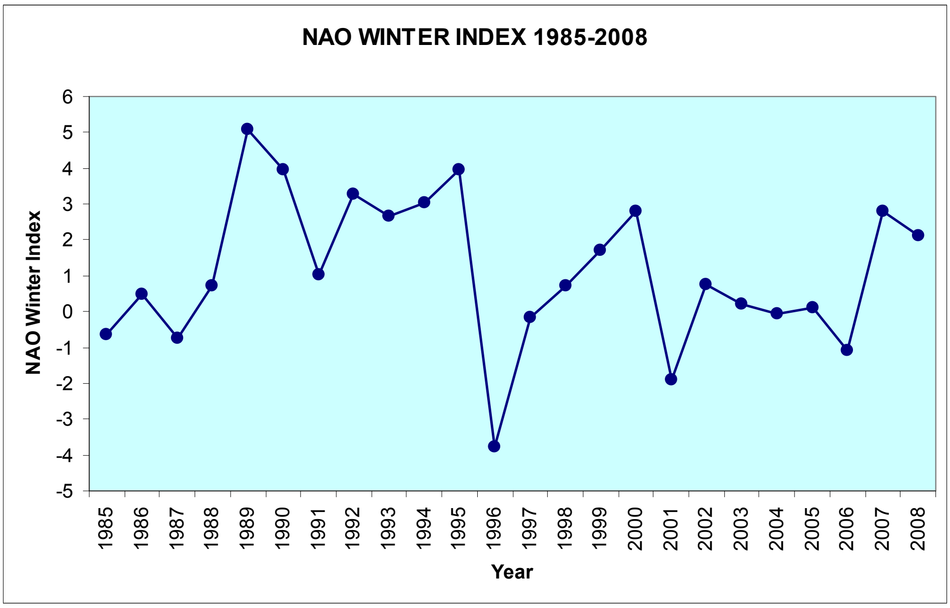

Figure 4: NAO Winter (December through March) index based on the difference of normalized sea level pressure (SLP) between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland (1985-2008). (http://www.cgd.ucar.edu/cas/jhurrell/indices.html).

5-year running means of the NAO climate index was calculated (Fig. 5). The period of strong positive NAO during 1980's and 1990's became obvious in this graph.

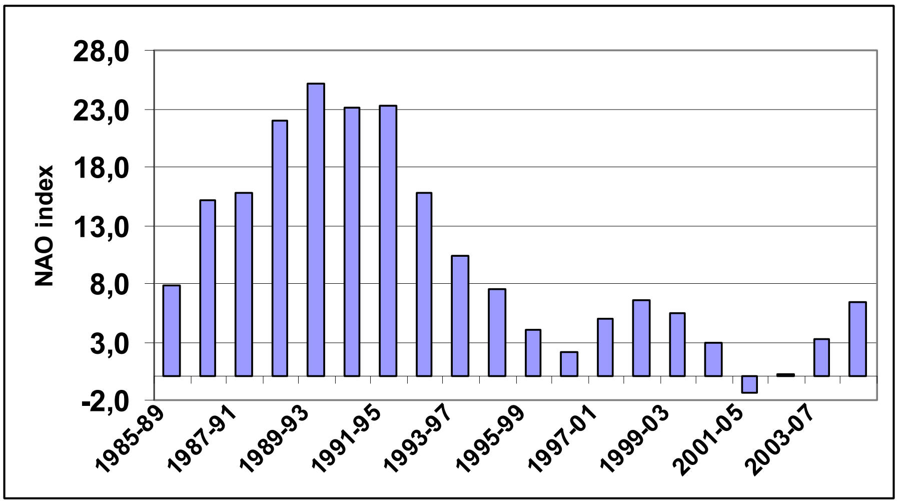

Figure 5: 5-year running means of NAO winter index.

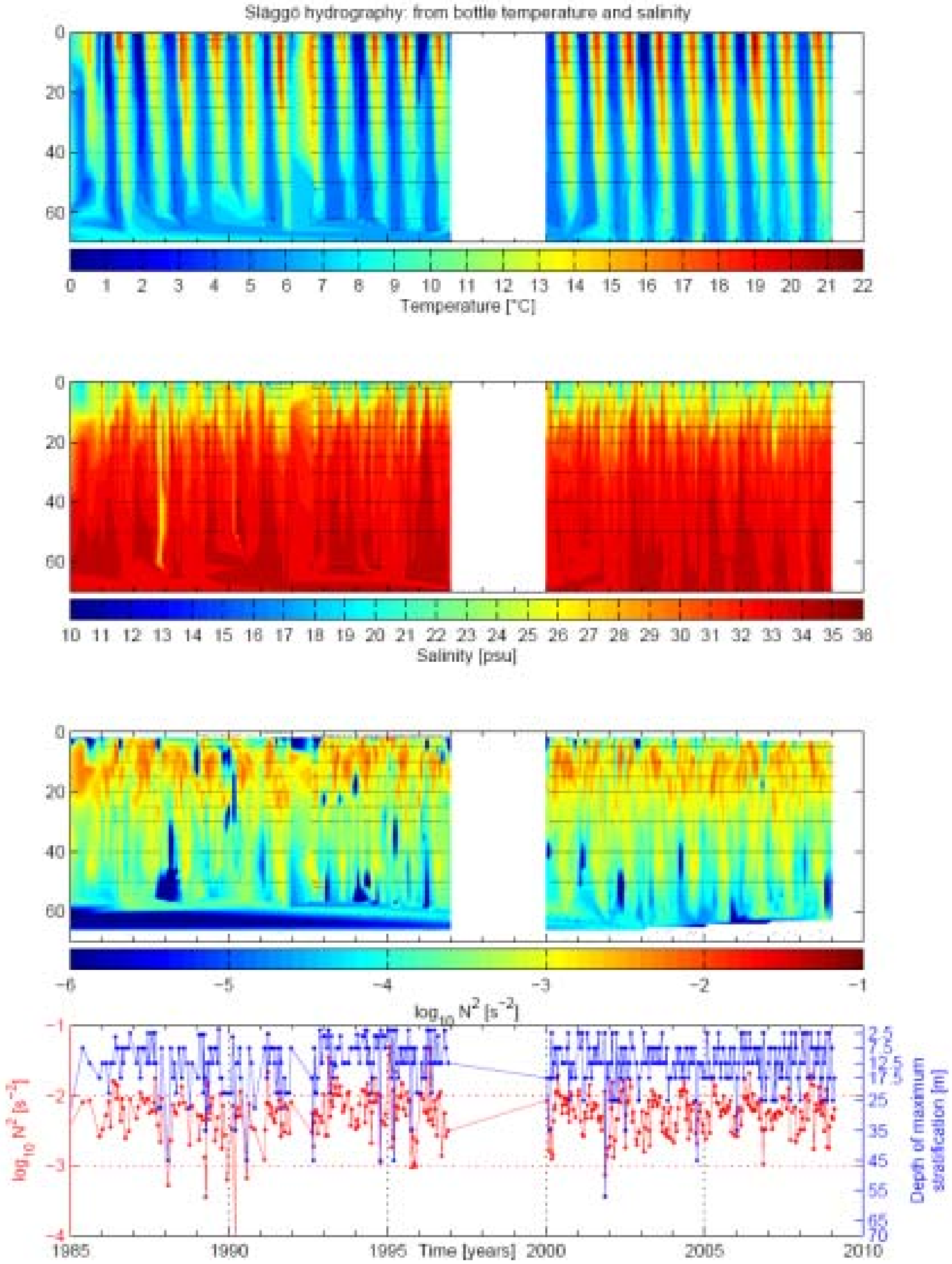

Figure 6: At the top temperature, then salinity, after that the Brunt-Vaisalla frequency and at the bottom the strength of stratification (red) and depth of pycnocline (blue) at Släggö from 1985 to 2008.

In the open Skagerrak there has been a significant increase in temperature over the period of interest, both in the surface layer as well as in the deeper layers, but no changes in salinity (Andersson et al., 2008a). At Släggö, in the mouth area of the Gullmar Fjord, no significant change was detected over the period as a whole, but from 1993 to 2008 there was an increase in temperature both in surface- and in deep water (Fig 6). There was, however, no significant change neither in the strength of the stratification or in the depth of the pycnocline (Fig. 6).

For the open Skagerrak area, there has been a significant decrease in total nitrogen and total phosphorus as well as in phosphate over the whole period in both the surface layer and in the deeper water (Andersson et. al., 2008b), (Figs. 7 – 10, table 5). Phosphate concentrations in the surface water during the first five years shows a higher annual mean than the rest of the period. For DIN, there were during the first years some high peaks, while the rest of the period shows rather stable values. In the deep water phosphate shows a more ore less continuous decrease over the period as a whole. Also DIN shows a slightly down going trend, but the variation between years was large and the trend was not significant.

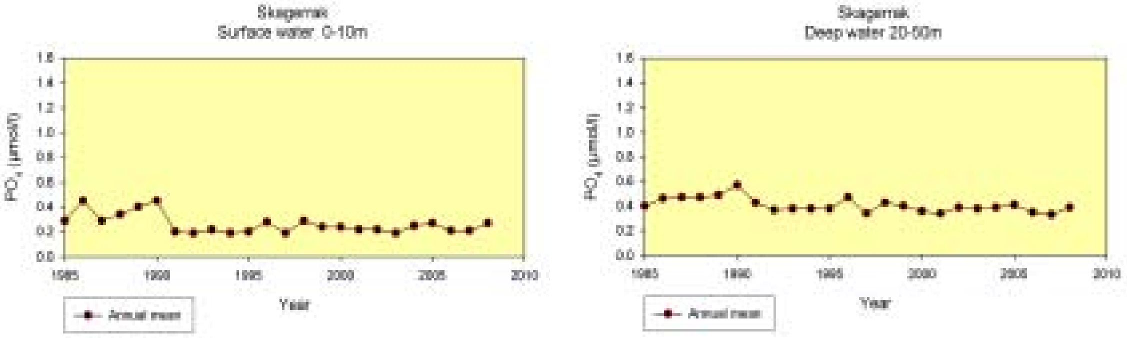

Figure 7: PO_4 concentration in Skagerrak surface and deep waters 1985 – 2008.

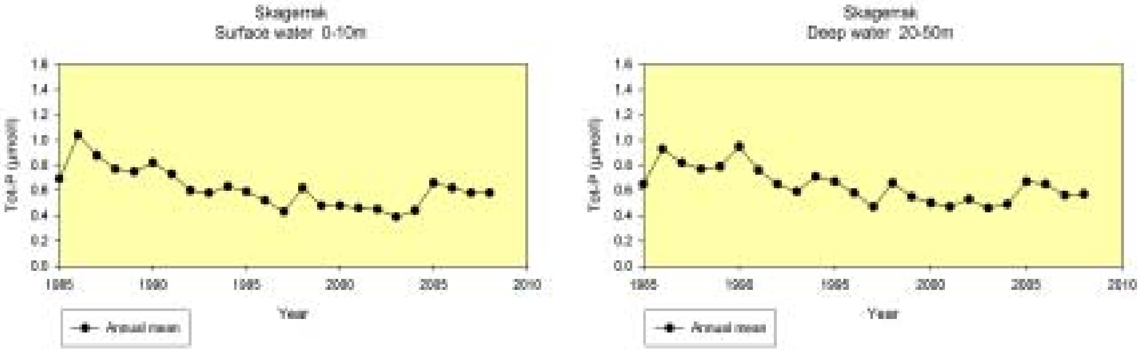

Figure 8: Tot-P concentration in Skagerrak surface and deep waters 1985 – 2008.

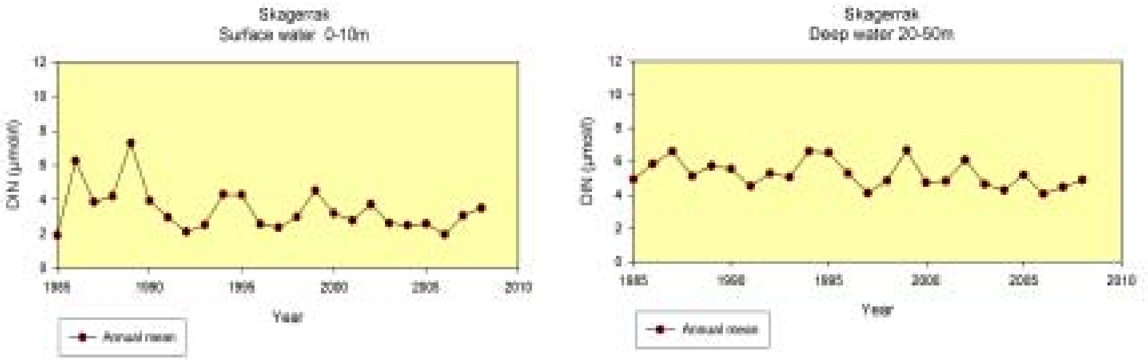

Figure 9: DIN concentration in Skagerrak surface and deep waters 1985 – 2008.

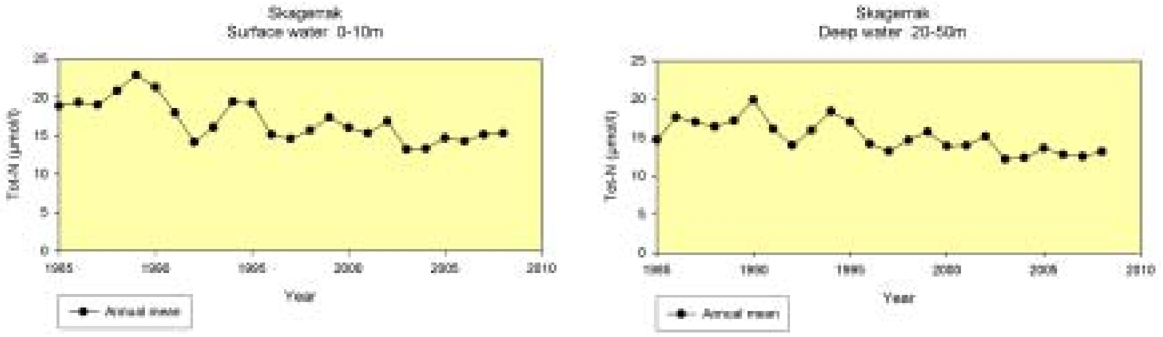

Figure 10: Tot-N concentration in Skagerrak surface and deep waters 1985 – 2008.

At Släggö there was also a significant decrease in total nitrogen but no significant changes in inorganic nitrogen, phosphate or total phosphorus (Figs. 11 – 14, table 6). In the deep water at Släggö there has been a decrease in both total phosphorus and total nitrogen as well as in DIN, but no changes in phosphate. Phosphate concentrations in the surface water at Släggö shows no trends at all over time, while it is obvious that the DIN concentrations increased up till 1995 were after there has been a more ore less continuous decrease, with the exception of a period of a few years (1996 and 1997) with very low concentrations. The deep water at Släggö shows the same pattern as the surface water.

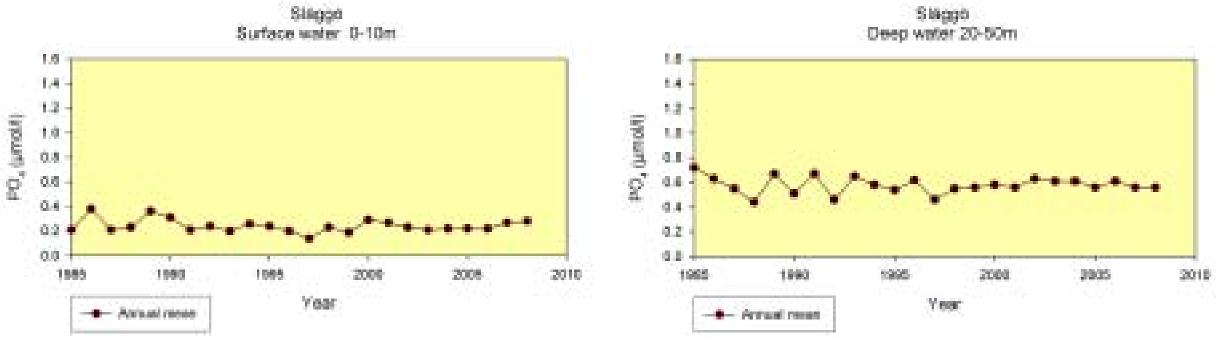

Figure 11: PO_4 concentration in Släggö surface and deep waters 1985 – 2008.

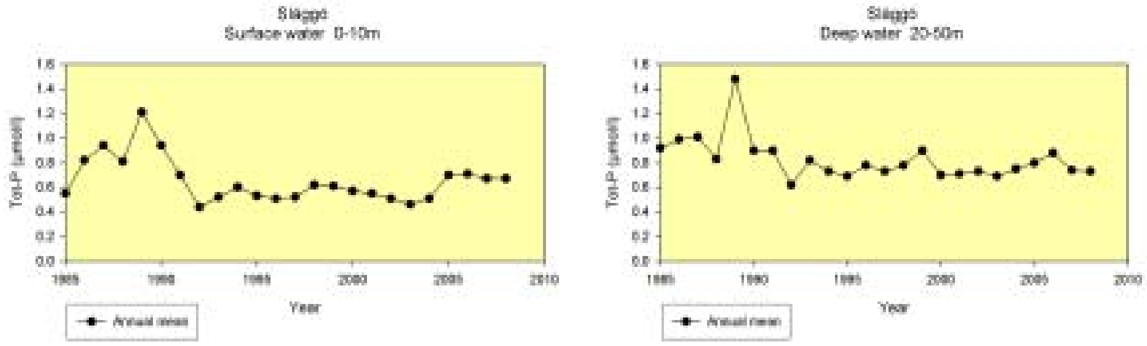

Figure 12: Tot-P concentration in Släggö surface and deep waters 1985 – 2008.

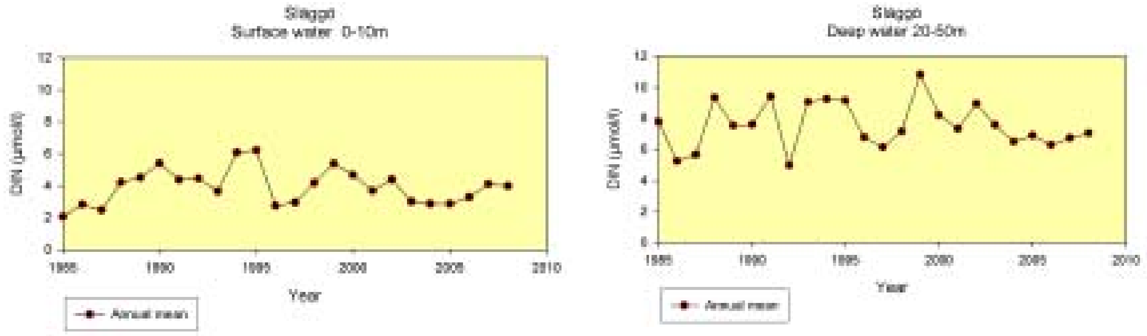

Figure 13: DIN concentration in Släggö surface and deep waters 1985 – 2008.

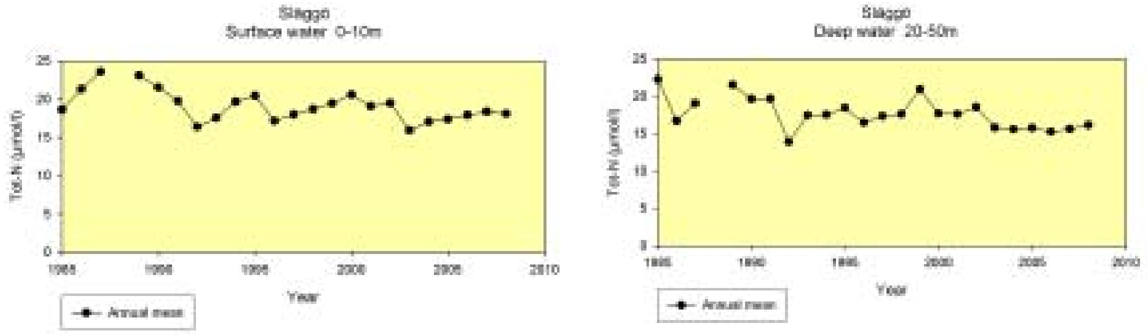

Figure 14: Tot-N concentration in Släggö surface and deep waters 1985 – 2008.

Primary production

Measuring frequency

The 24 year long time-series of primary production 1985 – 2008 is made up of altogether 482 measurements, or 20 per year as a mean. However, the number of measurements per year has been slightly changing over time (Fig. 15). The measuring frequency during winter (December – mid February) was during most years low with one or two measurements (Table 1). From the end of February until the spring bloom had terminated in March or early April, measuring frequency was generally once per week or per 10 days. During the period May to October about one measurement every second week was carried out, but occasionally there was also periods with both lower and higher measuring frequency.

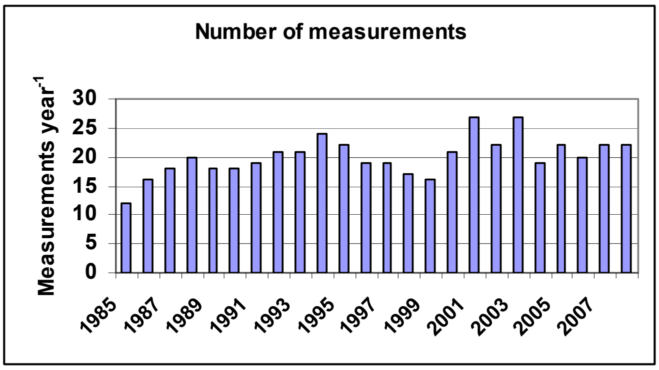

Figure 15: The number of measurements per year 1985 – 2008.

Table 1: The annual distribution and monthly means of measurements.

	J	F	M	A	M	J	J	A	S	O	N	D
Total number of measurements	6	36	84	46	57	48	39	52	53	39	18	5
Mean of number of measurements each month	0.3	1.5	3.5	1.9	2.4	2.0	1.6	2.2	2.2	1.6	0.8	0.2

Measured production

Figure 16 displays the measured primary production over depth of each measurement. It is obvious that bulk of the production occurred from surface and down to 10 m depth. Not so clear on figure 16, but obvious from the raw data set was that maximum production generally occurred at 1 or 2 to 4 m depth, probably as a result of photo inhibition at the surface. The production occurred shallower during the period 1985 – 1989 compared to 1990 – 1998. A shallower period was again from 1999 to 2001 and 2007. The secchi depth was as a mean 5 m during 1985 – 1990 and 6 m during 2000 – 2008. However, no significant co-variation between secchi depth and the depth distribution of the primary production was found.

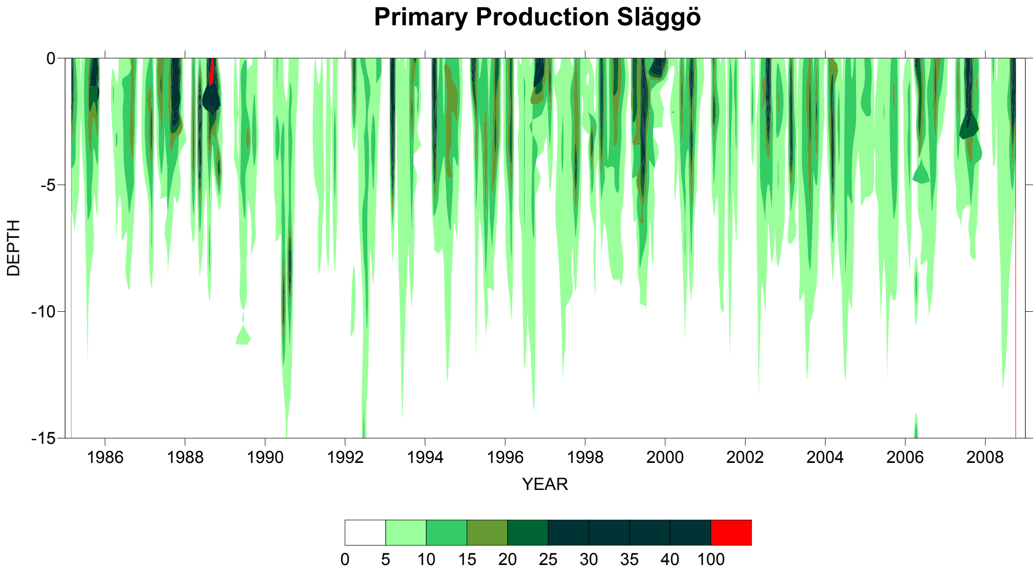

Figure 16: Measured primary production (mgC l^{-1} h^{-1}) over depth from 1985 to 2008.

Figure 17 displays the hourly mean value of measured primary production integrated over depth for all measurements. The bulk of the values were below 100 mgC l^{-1} h^{-1}, but there were also a considerable number between 100 and 200 mgC l^{-1} h^{-1}. Some few peaks over 200 in productivity were found and the highest of all, 450 mgC l-1 h^{-1}, was measured 1 October 1987 during a heavy bloom of the dinoflagellate *Ceratium* spp.

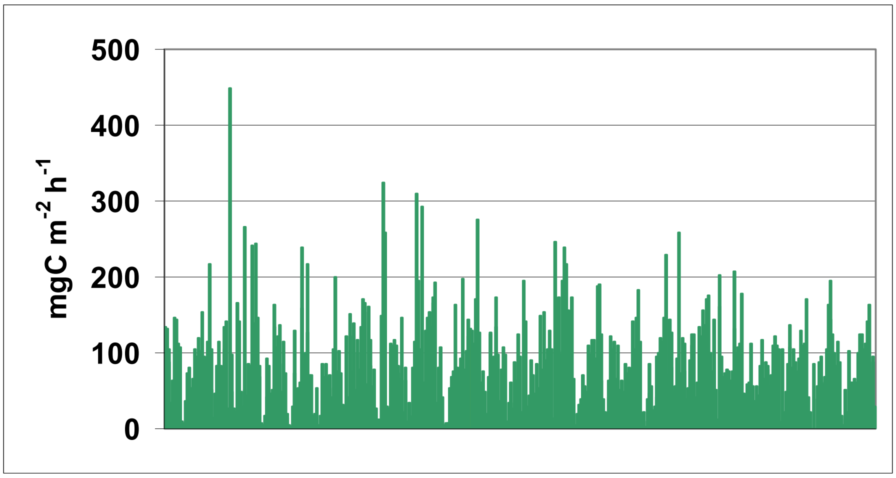

Figure 17: Measured hourly primary production (mgC m^{-2} h^{-1}) of all measurements 1985 – 2008, integrated over depth.

Calculated daily production

The measured primary production per hour been multiplied with the light factor of the actual day of measurement in order to calculate the daily production expressed in mgC m^{-2} day^{-1} is presented in figure 6. Here the bulk of the measurements were up to 1 000 mgC m^{-2} day^{-1}, but quite a number were in the range 1 000 to 2 000 mgC m^{-2} day^{-1}. Altogether 22 daily productions were over 2 000 mgC m^{-2} day^{-1} of which only 4 reached over 3 000 mgC m^{-2} day^{-1}. The seasonality and inter-annual variability were large as obvious in figure 18 and no trend over time was detected in the data set of the daily production.

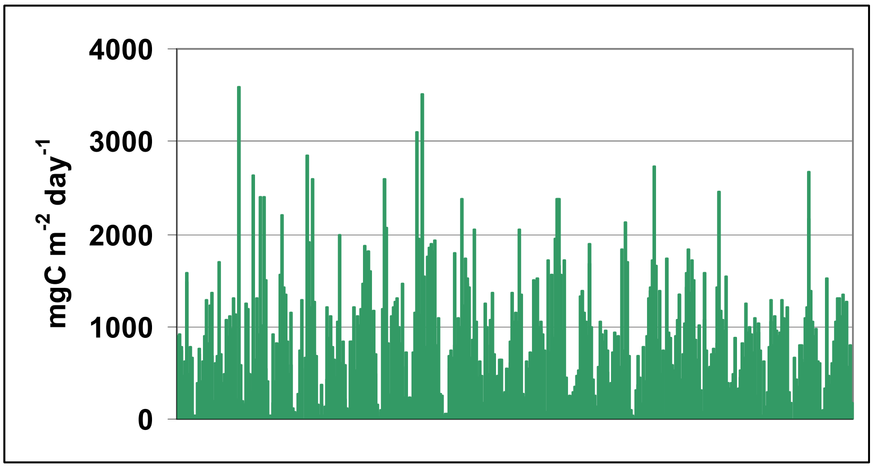

Figure 18: Calculated daily primary production (mgC m^{-2} day^{-1}) of all measurements 1985 – 2008, integrated over depth.

Monthly means

Monthly means of the daily production through linear integration over time was calculated or estimated for all of the 288 months of the 24 years of measurements (Table 2). Estimations were made for most, but not all, of the winter months January and December due to no measurements (see also table 1).

Table 2: Calculated or estimated daily mean production (mgC m^{-2} day^{-1}) for each month during the period 1985 – 2008, as well as a monthly mean of the daily production (mgC m^{-2} day^{-1}).

	J	F	M	A	M	J	J	A	S	O	N	D
1985	50	582	773	698	469	588	1429	1218	695	702	112	50
1986	50	47	438	602	578	843	968	1093	902	420	54	50
1987	50	756	364	472	1039	935	1131	1206	1107	1039	357	105
1988	50	151	682	395	1420	929	838	1317	1356	520	460	55
1989	34	34	336	637	1435	1308	975	530	1039	372	97	58
1990	30	39	416	895	1228	1459	1119	1954	701	292	37	30
1991	30	213	137	745	973	778	611	1312	627	499	150	33
1992	66	481	816	775	1001	1665	1776	1005	1044	608	174	20
1993	52	249	1427	257	1100	1266	923	885	647	633	61	23
1994	50	168	1600	852	1584	1045	1793	1782	1205	648	88	75
1995	49	61	607	1248	867	1471	1185	1441	1526	920	121	46
1996	49	285	1072	594	491	1403	895	944	1311	467	130	50
1997	267	411	249	403	696	1220	828	753	1638	1190	357	50
1998	151	401	585	496	1098	1023	979	1016	998	797	196	100
1999	66	341	1271	1006	1605	2285	1603	1371	447	344	76	50
2000	30	50	270	328	912	1160	1103	1295	1233	319	116	50
2001	50	172	645	575	765	784	630	1531	1175	298	61	49
2002	50	104	488	272	682	1379	2020	1126	843	670	162	50
2003	50	623	821	524	814	1019	1391	1405	1126	748	153	50
2004	65	418	868	443	690	909	1276	956	1100	249	180	50
2005	50	265	513	384	629	936	898	819	723	717	40	50
2006	50	390	141	682	982	1016	880	1144	893	779	149	50
2007	50	84	474	545	698	936	1760	1335	883	669	178	37
2008	50	68	531	494	834	1193	1192	962	928	443	74	50
mean	62	266	647	597	941	1148	1175	1183	1006	598	149	51

Figure 19 displays the monthly means of daily primary production from table 2, where the seasonal cycle became more pronounced compared to the plots in figure 5 and 6. The peak values were also more evened out.

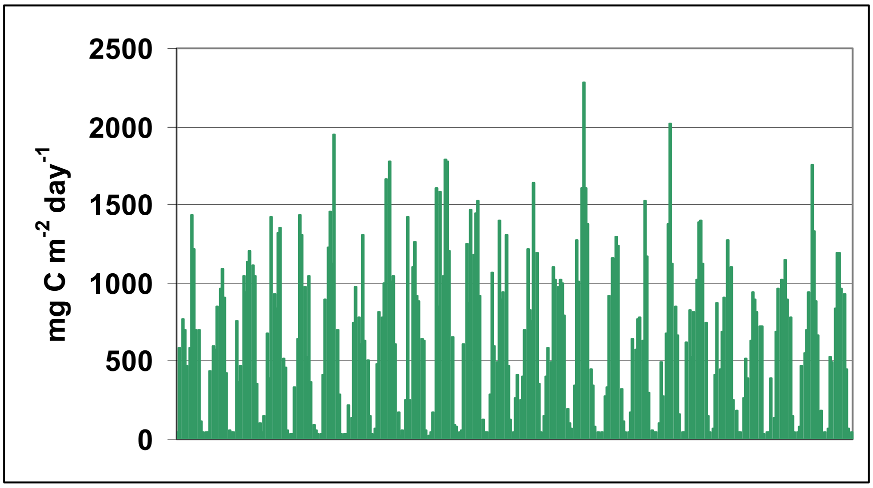

Figure 19: Monthly mean of daily primary production 1985 – 2008.

Table 3: The calculated monthly mean production (gC m^{-2} month^{-1}) of the period 1985 – 2008 and the contribution in % of each month to the annual production.

	J	F	M	A	M	J	J	A	S	O	N	D
Prod. gC	2	8	19	18	28	34	35	35	30	18	4	2
% of annual	1	3	8	8	12	14	15	15	13	8	2	1

In figure 20 the relative monthly production is presented in % of the annual mean production (Table 3). The relative contribution from the winter months December and January was very only 1 %. Spring bloom, which may start in February, but most often occurred in March made up 3 and 8 % respectively. The relative contribution from April was also as a mean around 8 %. The bulk of the annual production occurred from May until September and the contribution varied between 12 and 15 %. In October the production was about 8 % of the annual and in November it had dropped to 2 %.

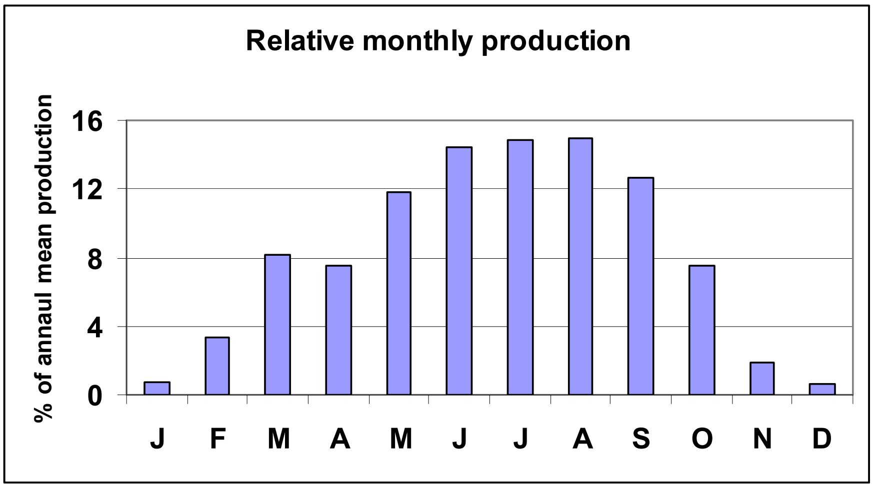

Fig 20: Relative monthly production expressed in % of annual mean production.

In figure 21 is 12-month running means presented. Here it became evident that there was a long term trend in primary production when the seasonal variability was evened out. A polynomial function of second order was applied ($r^2 = 0.214$), but the inter-annual variability was still too large in order to achieve an acceptable fit of a trend-line.

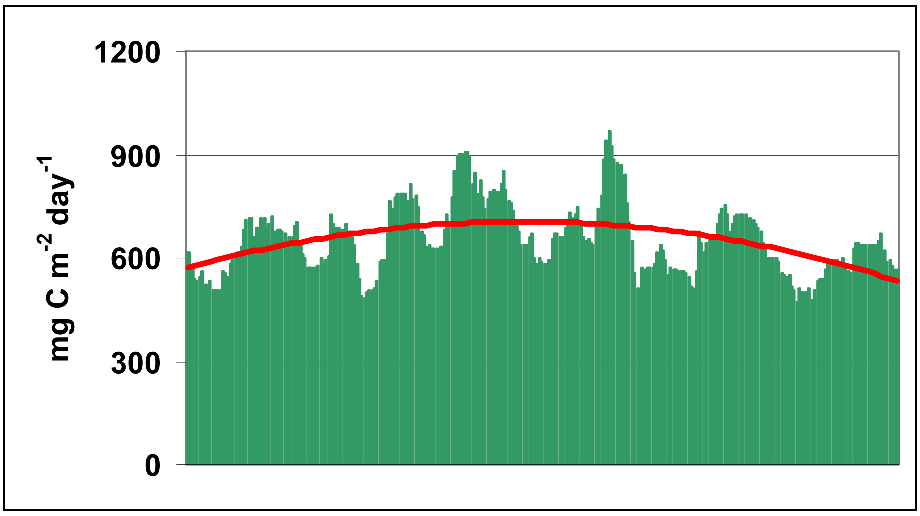

Figure 21: 12-month running means of monthly mean of the daily primary production 1985 – 2008. Red line is trend-line ($r^2 = 0.214$).

Annual production

During the period 1985 to 1999 the mean annual production increased during from around 230 gC m^{-2} year^{-1} 1985-86 to almost 250 gC m^{-2} year^{-1} at the end of the 1990's (Figure 22). The 10-year means of 1985 – 1994 was 240 gC m^{-2} year^{-1} and of 1991 – 2000 257 gC m^{-2} year^{-1} respectively. The lowest and highest annual value during the whole period was 182 gC m^{-2} year^{-1} (1986 and 1991) and 339 gC m^{-2} year^{-1} (1994) respectively.

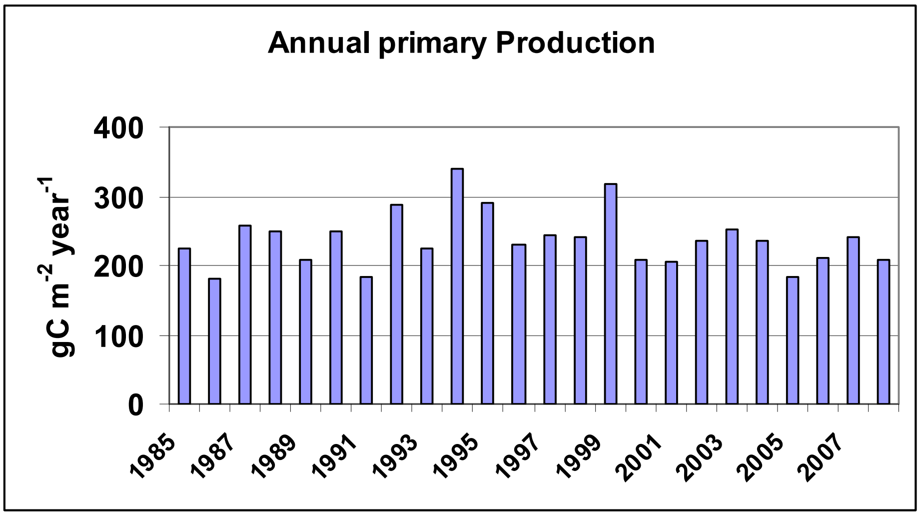

Figure 22: The annual primary production in the Gullmar Fjord 1985 – 2008.

The calculated annual production from 2000 to 2008 was significantly lower compared to the previous period. The mean annual production was then 220 gC m^{-2} year^{-1}, which was at the same level of production as the first five years of the time-series. The lowest and highest value during this period was 184 gC m^{-2} year^{-1} (2005) and 253 gC m^{-2} year^{-1} (2003) respectively. Thus, including the production from after the millennium shift in the time series, it became obvious that the trend of increasing annual primary production from 1985 to the end of the 1990's was broken.

In order to study the long-term trend five-year running means of the complete time-series from 1985 to 2008 were calculated (Figure 23). A polynomial function of second order gave the best fit ($r^2 = 0.74$) to a trend-line and revealed that the primary production in the Gullmar Fjord peaked during the five-year period 1992 – 1996. The increase in production as calculated from the first annual running mean to the maximal was 20 % or roughly 4 gC m^{-2} year^{-1} during 10 years and the decrease to the last annual mean was 25 %, or also 4 gC m^{-2} year^{-1} but during 14 years.

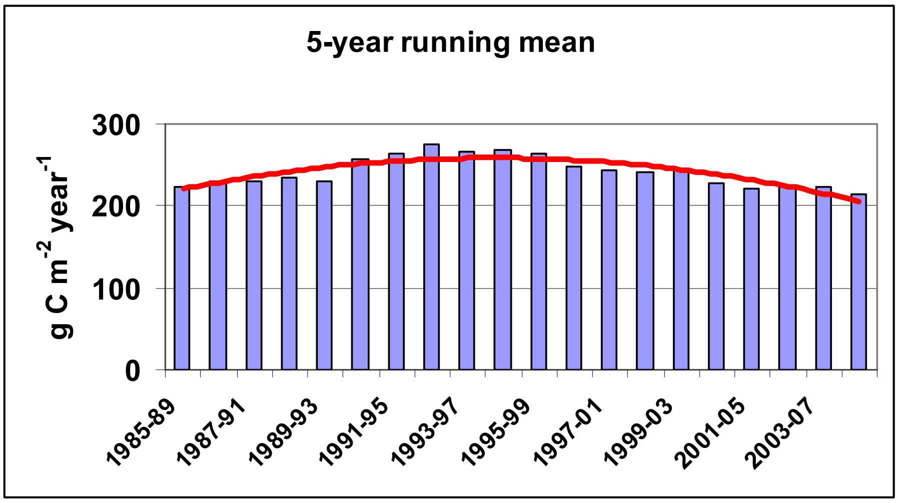

Figure 23: Five-year running means of annual primary production and its trend line (r^2 = 0.74)

The good fit of the trend-line, as demonstrated by the high r^2-value, must be regarded as quite remarkable when it is taken into account that the dataset represents a rate measurement (phytoplankton ^{14}C-uptake) carried out *in situ* during 24 years by at least 10 different persons!

Chlorophyll a

If the mean annual chlorophyll *a* concentration of the whole time-series were included in the correlation analysis, a significant negative trend of decreasing chlorophyll in the surface water at Släggö was evident (Tab. 6). However, during the years 1986-1988 some very large blooms with a huge biomass, mainly made up by large species of the dinoflagellate *Ceratium*, occurred during autumn (Lindahl and Hernroth, 1988). Further, in May 1988 the large bloom of the toxic *Chrysochromulina polylepis* also contributed to the high annual mean of the chlorophyll concentration (Rosenberg et al., 1988). If these anomalies of chlorophyll concentration were excluded from the time series, the rest of the curve shows a clear correspondence with the development of the primary production over time (Fig. 24). The mean annual chlorophyll concentration during the first half of 1990s was circa 2.2 µg l^{-1} and increased to almost 3 µg l^{-1} between 1995 and 2000, where after it decreased to around 2 µg l^{-1} from about 2005 and onwards.

Figure 24: The annual mean chlorophyll *a* concentration 1985 – 2008 in the surface water at Släggö.

Regime shift analysis

he regime shift index (RSI) analysis detected two periods of major changes in primary production; between 1994-1995 and 1999-2000 (Fig. 25).

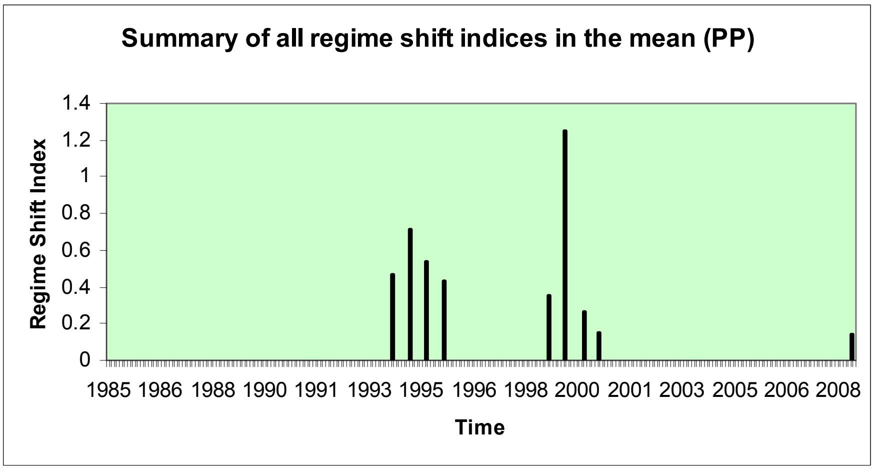

Fig. 25. Summary of all regime shift indices in the monthly mean primary production significant at the 0.01 level (2-tailed).

From table 4 it was evident that the RSI shifts in 1994 and 1995 corresponded to prolonged periods of increased summer production and to a higher set of values in the primary production which occurred in 1999 (Fig. 26).

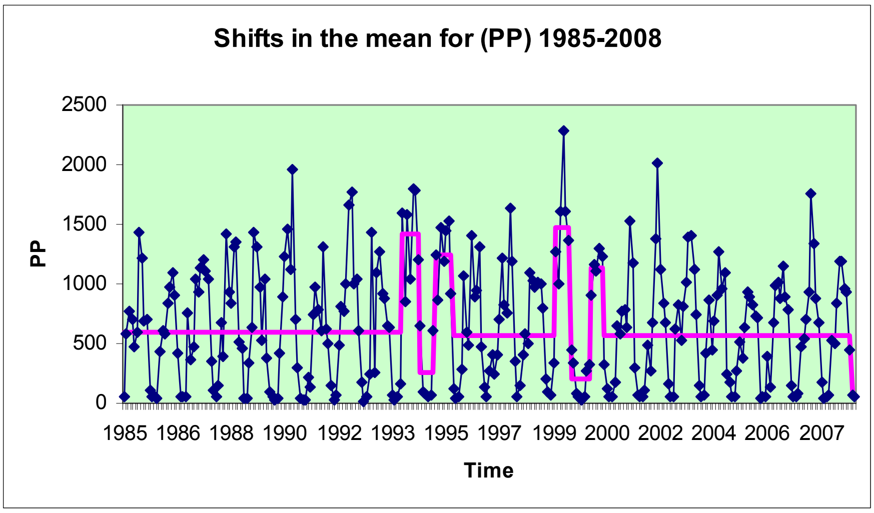

Fig. 26. Shifts in monthly mean primary production (mgC m^{-2} day^{-1}); purple line indicate the regime shift index (RSI).

Pearson´s correlation tests

The correlations between primary production and nutrients concentrations from the Örekil River at the far inner end of the Gullmar Fjord were tested using a Pearson's correlation test and the results are reported in Table 4. A significant negative correlation was found between years and *NO_3 (r= -0.139)* but positive for *PO4 (r= 0.3);* negative between primary production and *NO_3 (r= -0.221)* but positive for *PO4 (r= 0.158)* and positive between *NO_3* and *PO_4 (r= 0.223)*.

Table 4: Pearson's correlation between the primary production and Örekil River nutrients. *correlation was significant at the 0.05 level (2-tailed). **correlation was significant at the 0.01 level (2-tailed).

	Years	PP	NO_3	$P0_4$
Years	1	-.029	-.139(*)	.300(**)
PP	-.029	1	-.221(**)	.158(*)
NO_3	-.139(*)	-.221(**)	1	.223(**)
$P0_4$	.300(**)	.158(*)	.223(**)	1

The Pearson's correlations of the Örekil River nutrients indicated that nitrate had decreased while phosphate had increased over time. Over the whole time span primary production at the Gullmar Fjord mouth area had first increased and then decreased and it was concluded that the nutrient supply from the Örekil River had no clear influence on the primary production in the mouth area of the fjord.

The analysis of the primary production time series using the annual value was related to the deep nutrients regime in the central Skagerrak and to the NAO index. Significant positive correlations between total nitrogen (Tot-N) and the NAO *(r= 0.430* significant at the 0.05 level, 2-tailed), between the primary production and *NO_3 (r= 0.691* significant at the 0.01 level, 2-tailed) and primary production and dissolved inorganic nitrogen (DIN) *(r= 0.561* significant at the 0.01 level, 2-tailed) were found (Table 5).

Table 5: Pearson's correlation between primary production (PP) and Skagerrak deep water nutrients. * correlation was significant at the 0.05 level (2-tailed). ** correlation was significant at the 0.01 level (2-tailed).

	Year	PP	Temp.	Salt	PO_4	tot-P	NO_3	DIN	tot-N	NAO
Year	1	-.092	.916(**)	.046	-.591(**)	-.689(**)	-.201	-.406(*)	-.729(**)	-.137
PP	-.092	1	-.202	.021	-.098	-.080	.691(**)	.561(**)	.259	.292
Temp.	.916(**)	-.202	1	.003	-.498(*)	-.587(**)	-.297	-.433(*)	-.667(**)	-.032
Salt	.046	.021	.003	1	-.050	-.187	-.086	-.229	-.214	.060
PO_4	-.591(**)	-.098	-.498(*)	-.050	1	.777(**)	.185	.362	.687(**)	.106
tot-P	-.689(**)	-.080	-.587(**)	-.187	.777(**)	1	.186	.412(*)	.799(**)	.285
NO_3	-.201	.691(**)	-.297	-.086	.185	.186	1	.902(**)	.530(**)	.378
DIN	-.406(*)	.561(**)	-.433(*)	-.229	.362	.412(*)	.902(**)	1	.703(**)	.305
Tot-N	-.729(**)	.259	-.667(**)	-.214	.687(**)	.799(**)	.530(**)	.703(**)	1	.430(*)
NAO	-.137	.292	-.032	.060	.106	.285	.378	.305	.430(*)	1

Table 6: Pearson's correlation between the primary production (PP) and Släggö surface water nutrients and chlorophyll. * correlation was significant at the 0.05 level (2-tailed). ** correlation was significant at the 0.01 level (2-tailed).

	Year	PP	Temp.	Salt	PO_4	tot-P	NO_3	DIN	tot-N	Chl-*a*	NAO
Year	1	-.092	.220	.175	-.195	-.401	.243	-.003	-.552(**)	-.501(*)	-.137
PP	-.092	1	-.053	.118	-.276	-.250	.542(**)	.553(**)	-.026	.003	.292
Temp.	.220	-.053	1	.166	.083	-.104	.247	.289	-.298	-.366	.335
Salt	.175	.118	.166	1	.207	-.118	.231	.272	-.312	-.687(**)	.209
PO_4	-.195	-.276	.083	.207	1	.577(**)	.249	.248	.531(**)	-.171	.461(*)
tot-P	-.401	-.250	-.104	-.118	.577(**)	1	-.017	.065	.776(**)	.198	.307
NO_3	.243	.542(**)	.247	.231	.249	-.017	1	.929(**)	.191	-.403	.645(**)
DIN	-.003	.553(**)	.289	.272	.248	.065	.929(**)	1	.281	-.416(*)	.727(**)
Tot-N	-.552(**)	-.026	-.298	-.312	.531(**)	.776(**)	.191	.281	1	.331	.341
Chl-a	-.501(*)	.003	-.366	-.687(**)	-.171	.198	-.403	-.416(*)	.331	1	-.436(*)
NAO	-.137	.292	.335	.209	.461(*)	.307	.645(**)	.727(**)	.341	-.436(*)	1

Further to confirm the hypothesis that Skagerrak deep water nutrients supplies the surface water of the Gullmar Fjord mouth area, we analyzed the primary production time series using the annual value in relation to the nutrient concentrations of the coastal water using data from Släggö covering the period 1985-2008. The Pearson's correlation between primary production and Släggö surface nutrients (Table 6), confirmed the positive link between the primary production and *NO_3 (r= 0.542* significant at the 0.01 level, 2-tailed) and primary production and dissolved inorganic nitrogen (DIN) *(r= 0.553* significant at the 0.01 level, 2-tailed). Also the influence of climate variability (NAO) showed to be positively related with the nutrients regime pattern at Släggö. The Pearson's correlation between NAO and *NO_3 (r= 0.645* significant at the 0.01 level, 2-tailed);

NAO and dissolved inorganic nitrogen (DIN) *($r= 0.727$* significant at the 0.01 level, 2-tailed); NAO and PO_4 *($r= 0.461$* significant at the 0.05 level, 2-tailed) were all positively significant.

The negative significant correlation between the chlorophyll *a* concentration at Släggö and years indicated a decrease over time. Further, the significant negative correlations between salinity and DIN was most likely a result of reversed seasonality between winter values of high salinity and DIN concentrations on one hand and summer values of high chlorophyll concentrations. However, the negative and significant correlation between chlorophyll concentration and NAO was not possible to directly explain, but was likely an effect seasonal miss-match.

It should be pointed out that the effect of grazing to zooplankton on the primary production or any relation between the primary production and zooplankton biomass was not included in this study due to that there are no long-term zooplankton data available.

Discussion and conclusions

The analysis of the five-year running means of the primary production time-series from 1985 to 2008 revealed that the primary production in the Gullmar Fjord increased and peaked during the five-year period 1992 – 1996, followed again by a decrease in production. The increase in production, as calculated from the first annual running mean and compared with the maximal mean, was 20 % and the decrease of the last annual mean was 25 %. The total result was that the mean annual primary production was 3.8 % lower when the difference between the first and the last 5-year running means compared to the over-all mean production of the whole period of time.

Heath and Beare (2008) studied through GAM-modeling (General Additive Models) spatial and temporal patterns from 1960 to 2003 in annual potential new primary production of the NW European shelf seas. Their results indicated an exceptional flux of nitrate-rich ocean water onto the shelf in early 1990s, which resulted in a pulse of potential new production concomitant with a well-documented “regime shift” in the pelagic food web. They further found that the positive time series correlation between the winter NAO index and the estimates of the proportion of potential new production accounted for by the vertical flux of nitrate in seasonally stratified waters gave a hint as to one of the ways in which climatic factors may effect the potential new production. The precise link between the winter NAO index and the estimates of vertical flux were obscure, since the barometric pressure data upon which the NAO index is based are seasonally disconnected from the timing of the vertical fluxes of nitrate. The high NAO index phase during the mid 1990s coincided with a period of when vertical fluxes contributed a particularly large fraction of annual potential new production according to Heath and Beare (2008).

Mean nitrate concentrations in January – April at Helgoland in the German Bight was 28 µmol l^{-1} during the period 1980 – 1985, 35 µmol l^{-1} 1985 - 1990 and further increased to maximum of 42 µmol l^{-1} during 1990 – 1995, where after the concentration decreased to 26 µmol l^{-1} 1995 – 2000 and 24 µmol l^{-1} 2000 – 2006 (Aure and Magnusson, 2008). During almost the same period of time, 1975 – 2003, the loads of both nitrate and phosphorus from the big rivers Rhine-Maas and Elbe-Weser clearly decreased as reported by van Beusekom et al. (2005). The observed decrease in nitrate concentrations in the German Bight from the 1990s was reflected in the Norwegian Coastal Current, where the mean nitrate concentration in the upper 30 m was reduced half way back to the situation in the 1970s (Aure and Magnusson, 2008).

There was, on the other hand, no sign of a stable and long-term decrease in the nutrient supply from Swedish rivers into the Kattegat and Skagerrak Sea areas although large efforts, especially concerning nitrogen coming from agriculture operations in the nutrient leakage sensitive SW Sweden has been performed (Anon., 2005). The observed inter-annual observations in nutrient supply were related to variations in precipitation and run-off and no trend during the period 1985 – 2004 was detected. Rydberg et al. (2006) studied long-term trends in phytoplankton primary production by analyzing data from the Kattegat and the Belt Sea (Baltic entrance region). The study employed the core of Danish monitoring data-sets from the past 20 – 50 years. Rydberg et al. (2006) found that it was obvious that mean annual production had increased considerably since the 1950s, but also that this increase took place before 1980. For data after 1980 a co-variation between annual nutrient loads and regional mean primary production was found; years of low total nitrogen and total phosphorus input to the region coincide with low primary production and vice versa. Further that waste-water treatment and measures in agriculture had reduced the land-based input of total nitrogen by about 1/3 and input of total phosphorus by about 2/3 since 1980s, enough to cause a substantial decrease in the surface water nutrient concentrations. Concerning the primary production of the Kattegat and Belt Sea area, a simultaneous but weak downward trend in the regional production was seen up to 1997, after which the trend was broken and replaced by higher production. However, this trend-shift was most likely due to a change in the method used for the determination of the primary production (Rydberg et al., 2006).

An estimation of the primary production over time in the Gullmar Fjord from 1960 to 2000 was made by Lindahl (2003) by assuming that the production over time of the Gullmar Fjord has developed more or less in parallel with the production in Kattegat. The “natural” level of production was set to 100 gC m^{-2} $year^{-1}$, which was somewhat higher according to what Steeman Nielsen (1958) calculated for the southern Kattegat area for the period 1954-1960 (Fig 27). The higher value was based on methodological and site differences. The development of the daily mean production in the Kattegat area (EEA report no 4, ref. Richardson and Ærtebjerg, 1991) together with estimates on the annual production of the Kattegat area calculated by Heilman et al. (1994) and Richardsson and Heilman (1995) was used to estimate the production from 1960 to 1985. The increase in production during this period was explained by eutrophication (Richardson and Ærtebjerg, 1991), since the increase took part during the summer half of the year when nutrients were the limiting factor for phytoplankton growth.

The final part in figure 27 was made up by data from the actual measurements carried out 1985-2008. This increase in production from 1985 to mid 1990s was related to a period of a positive NAO index during 1990s (Belgrano et al., 1999).

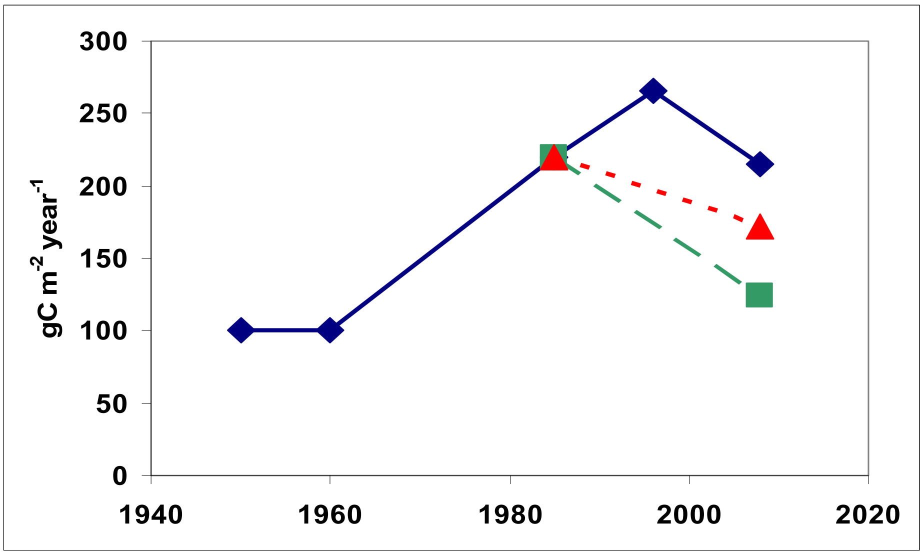

Figure 27: The blue curve from 1950 to 1985 represents as estimate over time of the primary production in the Gullmar Fjord, while the part from 1985 to 2008 is according to the reported time series. The green and red curves represent different scenarios excluding the impact of climate variability (NAO) on the primary production.

The total decrease in primary production from 1996 to 2008 was 19 % of mean annual production, or about 4 gC m^{-2} year^{-1}. As also shown in the present evaluation, the increase in production 1985 – mid 1990s was most likely triggered by the strong positive winter NAO during the same period of time. It can be speculated what the development of the primary production over time would have been without this NAO anomaly. If it is assumed that the mean decrease in production which actually occurred between 1996 and 2008 (4 gC m^{-2} year^{-1}) would have been ongoing since e.g. 1985, then the annual production would have been around 125 gC m^{-2} year^{-1} in 2008, or almost back to level of the 1960's (Fig. 27, green line)! However, this decrease in production was from a high level of production and it was more likely to assume a slower decrease of 2 gC m^{-2} year^{-1} (Fig. 27, red line), which would have resulted in an annual production around 170 gC m^{-2} year^{-1} in 2008.

In summary, it may be concluded that there was a direct link between primary production and nitrate concentrations in the mouth area of the Gullmar Fjord. Further, there was no influence from local runoff on the long term development of the primary production. Also that long-term co-variation in primary production of the Kattegat and Belt Sea area and the Gullmar Fjord not was evident when literature data was compared.

The overall results suggested that the primary production in the mouth area of the Gullmar Fjord during 1985 – 2008 has been controlled by the coupling of large climatic decadal patterns such as the NAO and the subsequent changes in the nutrient regime both in the central Skagerrak and at a regional scale. It may further be concluded that the anomaly of an exceptional flux of nitrate-rich ocean water onto the NW European shelf most likely extended its distribution also into the mouth area of the Gullmar Fjord, which in turn triggered and was the and key variable for the 19 % rise in annual primary production during the mid 1990s.

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An evaluation of the 1985 – 2008 time series

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The environmental state of the seas around Sweden are monitored through regular observations of physical, chemical and biological variables that each or jointly indicate environmental changes over time. The length of many Swedish time series are in many cases unique.

One main challenge for the Swedish environmental authorities is to combat the eutrophication of coastal and open sea areas caused by inputs of nutrients that stimulates the over-production of plant biomass. Primary production measurements performed in the water column are used to determine the rate of phytoplankton growth and to gauge any needs to reduce excessive nutrient inputs to a recipient.

This report describes a 24-year time series of primary production measurements in the Gullmar Fjord on the Swedish Skagerrak coast. The author evaluates alternative climate-drive mechanisms and processes that could explain the production variations in this sea area.

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