International Council for
the Exploration of the Sea

ICES CM 1998/Q:3

Validation of a 3-D Biophysical Model using Nutrient Observations in the North Sea

By
Henrik Søiland and Morten D. Skogen
Institute of Marine Research
P.O. Box 1870
N-5024 Bergen, Norway

ABSTRACT

A 3-dimensional coupled physical-chemical-biological model (NORWECOM) is validated using observed nutrient fields in the North Sea. The observations used in this study are aggregated nutrient data for the period 1980-89 obtained from the ICES. The data has been grouped in winter, early summer and late summer data, and mean values and the standard deviations are given for 0.5° latitude x 1.0° longitude boxes spanning the North Sea. The nutrient fields from the NORWECOM is used to produce an aggregated model data set that is compared with the observed values. Results on both the model's ability to reproduce the mean observed nutrient concentrations and the spatial variability are presented. Since the differences are typically larger in areas with high variability, a cost function approach, i.e. the differences between observations and model data weighted with the standard deviation, are used in the comparison study.

INTRODUCTION

Increased inputs of anthropogenic derived nutrients to the North Sea have caused elevated nutrient levels and adverse eutrophication effects in some areas (Anon., 1993). The most obvious changes in the nutrient concentrations and in the primary production has taken place in the continental coastal waters, but effects are also seen farther away from the major nutrient sources (Anon., 1997). In situ measurements have documented these changes (Radach et al., 1990), but to increase the understanding of the eutrophication issue coupled physical-chemical-biological models have been constructed (Aksnes et al., 1995, Moll and Radach, 1994). The models have proved to be useful tools to study the anticipated area influenced by increased anthropogenic nutrient supplies, and also to study the effects on primary production for different reduction scenarios for anthropogenic nutrient loads (Skogen et al., 1995). However, even though some comparisons with observations have been carried out (Anon., 1998), there is a lack of objective quantified validation. NORWECOM has recently gone through a development in order to be able to do multiyear simulations of primary production and nutrient concentrations in the North Sea. In this development process we first focus the validation on the mean yearly cycle of nutrient concentrations for the 10 year period 1980-89. Actually because of the limited amount of observations available, we have chosen to compare 10 year means for three periods of the year to be able to do a comparison that encompass most of the North Sea. It is important to keep in mind that all the chemical-biological model parameters are from the literature (Aksnes et al. 1995), and has not been tuned or calibrated.

MATERIAL AND METHODS

The Model

The NORWegian ECOlogical Model system (NORWECOM) is a coupled physical, chemical, biological model system (Aksnes et al. 1995; Skogen et al. 1995) applied to study primary production, nutrient budgets and dispersion of particles (fish larvae and pollution). In the present study the model is used with a horizontal resolution of 20x20 km on an extended North Sea (see Figure 1), and in the vertical 12 bottom following sigma levels are used. The physical model is based on the Princeton Ocean Model (Blumberg and Mellor, 1987),and the chemical-biological model is coupled to it through the subsurface light, the hydrography and the horizontal and the vertical motion of the water masses. The prognostic variables are inorganic nitrogen, phosphorous and silicate, two different types of phytoplankton (diatoms and flagellates), detritus (dead organic matter), diatom skeletal (biogenic opal), inorganic suspended particulate matter (ISPM), oxygen concentration and light. Particulate matter has a sinking speed relative to the water and may accumulate on the bottom if the bottom stress is below a certain threshold value and likewise resuspension takes place if the bottom stress is above a limit. Regeneration of the organic particulate matter takes place both in the watercolumn and in the sediments. The bottom stress is due to both currents (including tides) and surface waves. The forcing variables for the hydrodynamical model are six-hourly hindcast atmospheric pressure fields and 6-hourly wind stress provided by the Norwegian Meteorological Institute (DNMI), four tidal constituents at the lateral boundaries and freshwater runoff. Initial values for velocities, water elevation, temperature and salinity are taken from monthly climatologies (Martinsen et al. 1992). Interpolation between monthly fields are also used at all open boundaries, and a 7 gridcell "Flow Relaxation Scheme" (FRS) zone (Martinsen and Engedahl, 1987) is used. To calculate the wave component of the bottom stress, data from DNMI's operational wave model ,WINCH, are used

Nutrients (inorganic nitrogen, phosphorous and silicate) are supplied to the modelled area from the rivers, monthly data for nutrient loads, from the atmosphere (only inorganic nitrogen) and from the open boundary through the FRS zone. The initial nutrient fields are derived from data obtained from ICES together with some small initial amounts of algae.

To produce the model fields used, NORWECOM was run for the period 1980-89 with one spin up year (i.e. 1980 was run twice). Monthly mean fields of the physical and chemical biological variables were saved, and the 10 year means for the three periods winter (January-February), early summer (May-July) and late summer (July-September) were calculated from those fields.

The Data

The field data used in this model validation was provided by the ICES, and the data set covers the North Sea south of the Shetlands including the Skagerrak-Kattegat. All the temperature, salinity, nitrate, phosphate, silicate and oxygen measurements available in the ICES data base for the years 1980-89 was used to calculate averages for three periods of the year, January-February, May-June-July and July-August-September. The data was averaged in boxes with two layers , the surface layer of 0-20 m and a lower layer of 20 m to the bottom, and the boxes had a lateral size of 0.5° latitude x 1.0° longitude. The standard deviation based on all the measurements that was used to calculate the averages for each box was also supplied together with the number of observations. The averages were assumed to represent temporal averages for the boxes even though it is possible that the averages in some boxes are based on measurements from only one single year. Since the data was supplied in aggregated form, we do not have specific information on this.

Method

Berntsen et al. (1996) proposed to quantify the discrepancies between models and measurements using a costfunction, relating the difference to the normal variation of the field variable. This is done by normalising the difference between the mean (in time) fields from model and measurements with the standard deviation. Let **F** be either a temporal average model field, $\mathbf{F}_{model}$, or the corresponding temporal average measured field, $\mathbf{F}_{data}$, and let $\mathbf{SD}_{data}$ be the standard deviation field from the temporal average of the measured field. Then the costfunction field (point-to-point) is defined by:

$$\mathbf{D}_F = (\mathbf{F}_{data} - \mathbf{F}_{model}) / \mathbf{SD}_{data}$$

The cost function , $< D_F >$, is the area average of the absolute values of the costfunction field and is computed as the sum over all grid points. Before the computation is done, the model results are interpolated onto the of 0.5° latitude x 1.0° longitude data grid. Note that the costfunction is a positive number whereas the costfunction field has both positive and negative values as defined by the formula above.

Even for a 10-year period, the number of observations in some areas of the North Sea are low, for some variables even zero. For some data there are also many identical observations, thus the standard deviation is zero. To avoid using a standard deviation calculated from a non-representative selection of data, a minimum number for the standard deviation has been introduced, and the point is set to undefined if the number of observations are too low. This means that we have recalculated the standard deviation as $\mathbf{SD}_{data} = \max(\mathbf{SD}_{data}, \mathbf{SD}(\mathbf{F},n))$, where **F** is the parameter in question, and *n* the number of observations. The values for $\mathbf{SD}(\mathbf{F},n)$ are given in Table 1.

The costfunction technique is exemplified in Figure 2. In the upper left panel the mean observed salinity field for May, June and July (1980-89) in the upper 20 meters is given. The corresponding model field, before interpolation to the same grid as the measurements, is given in the upper right panel. Subtracting the model field from the measurement field gives to the difference field depicted in the middle left panel, while normalising with the standard deviation field (middle right) gives the costfunction field shown in the lower panel. The mean of the absolute values of this field is 0.49 (see Table 2), telling that the model on average is less than 0.5 standard deviation off the measured salinity.

RESULTS

A summary of the main results are given in Table 2. For each of the three seasons the mean values of the observations, the model, the absolute value of the differences (data-model) and the costfunction are given for the upper 20 meters and from 20 meters to the bottom. As can be seen there are large differences between the different parameters, and the discrepancy between model and observations also changes with season.

The best results, in the context of a low costfunction, are seen in the salinity fields with an overall (all seasons) mean of 0.70. This means that the modelled salinity is well within one standard deviation of the observed field. Nitrate, on the other hand, gives a very high costfunction (more than 13 in the upper 20 meters in late summer), but the cost function for this parameter shows a large seasonal variability, with much lower values in winter. In the winter field it is interesting to note the large mean of the absolute values of the difference field (4.18 µM in upper 20 meters). With a mean of the modelled nitrate less than 1 µM off the observations, this indicates both large positive and negative anomalies.

For the other parameters, the costfunction is mainly between 1 and 2. For temperature, silicate and chlorophyll(A), the results for the summer seasons are better than for the winter, while the opposite is true for oxygen and phosphate. Generally there is a consistency between the results for the upper 20 meters and the bottom layers through the seasons. The main exception for this is the change in summer oxygen, with a significant lower costfunction in the bottom layer in the early summer, changing to a lower value in the surface layer in the late summer.

To get a picture of the spatial variation of the costfunction fields, the results for the early summer period (May-June-July) are given in Figures 3 and 4. In the left panels the horizontal distribution of the 10-year modelled means are shown, while the corresponding costfunction fields are given in the right panels. All results, except for the oxygen field, are for the upper 20 meters. It should be noted that for large areas there were none (or too few) datapoints available for calculation of the costfunction (white areas in the costfunction field). The scale for the costfunction fields in the figures are linear from -3 with step 1 to +3.

The large values for the costfunction for nitrate is seen to be due to large discrepancies in the central and northern part of the North Sea. The coastal areas however, gives a costfunction between -1 and +1. The reason for these low costfunction field values is the large standard deviation in these areas. Looking on the difference field (not shown), the absolute error is higher at the coast than in the central and northern North Sea. The temperature shows a similar pattern with a high costfunction in the northern North Sea, and low values in the rest of the area. Again this is due to a higher variability in the southern parts. For the other parameters the picture are more scattered, with small areas with a high costfunction surrounded by larger areas where the costfunction is between -1 and +1. This scattered pattern can partly be explained by a much lower density of measurements for the biological and chemical parameters than the physical ones, and thus may partly be due to uncertain estimates of both the measurement averages and standard deviations.

DISCUSSION

With the large import of nutrients to the North Sea from the Atlantic Ocean, and the short and long term variability in this transport (Laane et al.,1996), a proper representation of the physical processes becomes essential when modelling nutrient fluxes and primary production. In fact, model studies (Skogen and Moll, 1998) indicates that the interannual variability of the primary production to a large extent (70 - 90 %) can be explained from either variations in the vertical mixing or the Atlantic exchange. In Skogen et al. (1997) and Svendsen et al. (1996) the models ability to reproduce the short term variability in Skagerrak was demonstrated. The low costfunction (Table 2) for the salinity field in both the top and bottom layers, combined with the temperature results, also indicate a proper representation of the climatological mean of these fields. The modelled underlying physics, including the short term variability and the large,scale circulation, is therefore assumed to be a proper forcing for the nutrient cycles.

Aside from the low costfunction values for salinity it is the high values for nitrate in the two summer periods that strikes one when the Table 2 is examined. This is partly due to the fact that in the model it is the inorganic nitrogen that is a state variable and this is compared to the measured nitrate concentrations not including ammonia. In the surface layer (0-20 m) in summer, ammonia concentrations may even be higher than the nitrate values (Radack and Gekeler, 1997). If we look at the bottom layer (20 m - bottom) the inorganic nitrogen values in the model remain fairly constant throughout the year, whereas the measured values show a marked decrease (less than half). This indicates that the primary production in the model does not penetrate deep enough and thus we do not have reduced concentration in this layer. The same is seen for phosphate, and to some extent for silicate. This may be attributed to the light formulation either through too strong damping of light with depth or the value of the light affinity parameter. The winter silicate concentrations in the model are too low, and this may be due to a too slow regeneration of biogenic opal (diatom skeletal). An increased regeneration speed will however not only increase the silicate concentrations in winter, but also lead to an increased diatom production. Above we have pointed to possible model limitations in order to explain differences between observed and modelled concentrations. In addition we should not overlook the importance of proper lateral boundary conditions and river loads.

Even though there are clear limitations in both the data set and the cost function method used in this validation, the exercise has pointed to several processes in the model that can be improved in future versions. At the same time the technique gives evidence of the higher quality parts of the model, ensuring that resources are being spent in the right way for such further model development. We also believe that the costfunction approach can be an important tool in the process towards an objective and standardised method for model validation and model-model intercomparison.

REFERENCES

Aksnes, D.L., Ulvestad, K.B., Balino, B., Berntsen, J., Egge, J. and Svendsen, E, 1995. Ecological modelling in coastal waters : Towards predictive Physical-Chemical-Biological simulation models. Ophelia, 41, 5-36.

Anon., 1993. North Sea quality status report, 1993. North Sea Task Force

Anon.,1997. Kyststrekningen Jomfruland-Stad. Vurdering av eutrofitilstand. Rapport 2 fra ekspertgruppe for vurdering av eutrofiforhold i fjorder og kystfarvann

Anon., 1998. Workshop report "Modelling of Eutrophication Issues". Workshop organized by ASMO of OSPARCOM. In print.

Berntsen, J., Svendsen E. and Ostrowski, M., 1996. Validation and sensitivity study of a sigma-coordinate ocean model using SKAGEX dataset. ICES CM 1996/C:5.

Blumberg, A. F. and Mellor G. L., 1987. A description of a three-dimensional coastal circulation model. In Heaps, Three-Dimensional Coastal Models. AGU, Washington, 4, 1-18.

Laane, R.W.P.M., Svendsen, E., Radach, G., Groeneveld, G., Damm, P., Pätsch, J., Daniellsen, D., Føyn, L., Skogen, M., Ostrowski, M. and Kramer, K.J.M., 1996. Vairiability in fluxes (N, P, Si) of nutrients into the North Sea from the Atlantic Ocean and Skagerrak caused by variability in water flow. Deutsche Hydrographishe Zeitschrift, 48 (3/4), 401-419.

Martinsen, E. A. and Engedahl, H., 1987. Implementation and testing of a lateral boundary scheme as an open boundary condition in a barotropic ocean model. Coast. Eng., 11, 603-627.

Martinsen, E. A., Engedahl, H., Ottersen, G. and Ådlandsvik, B., Loeng, H. and Balino, B., 1992. Metocean Modeling project, Climatological and hydrographical data for hindcast of ocean currents. Norwegian Meteorological Institute, Technical Report 100.

Moll, A. and Radach, G., 1994. Phytoplankton modelling in the central North Sea during ZISCH 1986. In Sundermann J (ed.), Circulation and contaminat fluxes in the North Sea. Springer-Verlag, Berlin, 403-433.

Radach, G., Berg, J. and Hagmeier, E., 1990. Long-term changes of the annual cycles of of meteorological, hydrographic, nutrient and phytoplankton time series at Helgoland and at LV Elbe 1 in the German Bight. Continental Shelf Research, 10, 305-328.

Radach, G. and Gekeler, J, 1997. Gridding of the NOWESP data sets. Annual cycles of horizontal distributions of temeperature and salinity and of concentrations of nutrients, suspended particulate matter and chlorophyll on the north-west European shelf. Berichte aus dem Zentrum fur Meeres- und Klimaforschung, B 27: 1-375.

Skogen, M. D., Svendsen E., Berntsen J., Aksnes D. and Ulvestad K., 1995. Modelling the Primary Production in the North Sea using a Coupled Three-dimensional Physical-Chemical-Biological Ocean Model. Estuarine, Coastal and Shelf Science, 41, 545-565.

Skogen, M., Svendsen E. and Ostrowski, M, 1997. Quantifying volume transports during SKAGEX with the Norwegian Ecological Model system. Continental Shelf Research, Vol. 17, No. 15, pp. 1817-1837

Skogen, M. D. and Moll, A., 1998. Natural variability of the North Sea primary production. Submitted to Cont Shel Res..

Svendsen, E. , Berntsen, J., Skogen, M., Ådlandsvik, B. and Martinsen E., 1996. *Model simulation of Skagerrak circulation and Hydrography during Skagex*. J. Mar. Syst., Vol. 8, 219-236.

	$n < 10$	$10 \le n < 100$	$n \ge 100$
Phosphate	undef	0.05	0.01
All other parameters	undef	0.10	0.01

Table 1: The function $SD(\mathbf{F}, n)$

	JAN-FEB				MAY-JUN-JUL				JUL-AUG-SEP			
	Obs	Mod	Diff	Cost	Obs	Mod	Diff	Cost	Obs	Mod	Diff	Cost
T_{0-20}	5.73	7.56	1.85	2.07	11.70	11.05	1.18	0.65	14.05	12.77	1.31	1.36
T_{20-b}	6.15	8.05	1.91	2.36	8.39	9.08	0.97	0.70	10.57	10.56	1.21	0.94
S_{0-20}	33.98	34.12	0.39	0.76	33.48	33.72	0.43	0.49	33.55	33.83	0.42	0.70
S_{20-b}	34.69	34.72	0.21	0.73	34.64	34.61	0.20	0.70	34.60	34.59	0.19	0.83
O_{0-20}	6.87	6.70	0.19	1.00	6.72	6.15	0.57	1.53	5.82	5.86	0.19	1.13
O_{20-b}	6.71	6.61	0.15	1.05	6.50	6.17	0.42	0.93	5.61	5.93	0.36	2.16
P_{0-20}	0.75	0.69	0.17	0.90	0.22	0.28	0.13	1.25	0.24	0.28	0.17	1.50
P_{20-b}	0.71	0.71	0.10	0.93	0.43	0.63	0.21	1.68	0.44	0.61	0.20	1.27
Si_{0-20}	5.50	3.22	2.58	1.44	1.10	0.54	0.70	0.76	1.29	0.57	0.84	1.28
Si_{20-b}	4.50	3.32	1.51	1.37	2.34	2.20	0.79	0.82	2.92	2.11	1.09	0.80
N_{0-20}	10.23	9.29	4.18	1.74	2.03	3.76	3.03	9.57	0.98	3.70	3.25	13.57
N_{20-b}	8.33	9.50	2.32	2.03	3.53	8.57	5.10	8.29	3.46	8.24	4.85	8.11
Chl_{0-20}	0.92	0.55	0.44	1.61	2.13	1.31	1.19	1.50	1.89	0.73	1.20	1.17
Chl_{20-b}	0.77	0.52	0.32	2.27	2.02	0.68	1.38	1.48	1.51	0.54	1.00	1.10

Table 2: Statistics for the for the mean seasonal (1980-89) North Sea fields of Temperature ($^\circ C$), Salinity (psu), Oxygen (ml/l), Phosphate (μM), Silicate (μM), Nitrate (μM) and Chlorophyll(A) (mg/m^3). The table gives the mean value of the observations, the model, the absolute value of the difference (data-model) and the costfunction, $< D_{\mathbf{F}} >$, in both the upper 20 meters and from 20 meters to the bottom

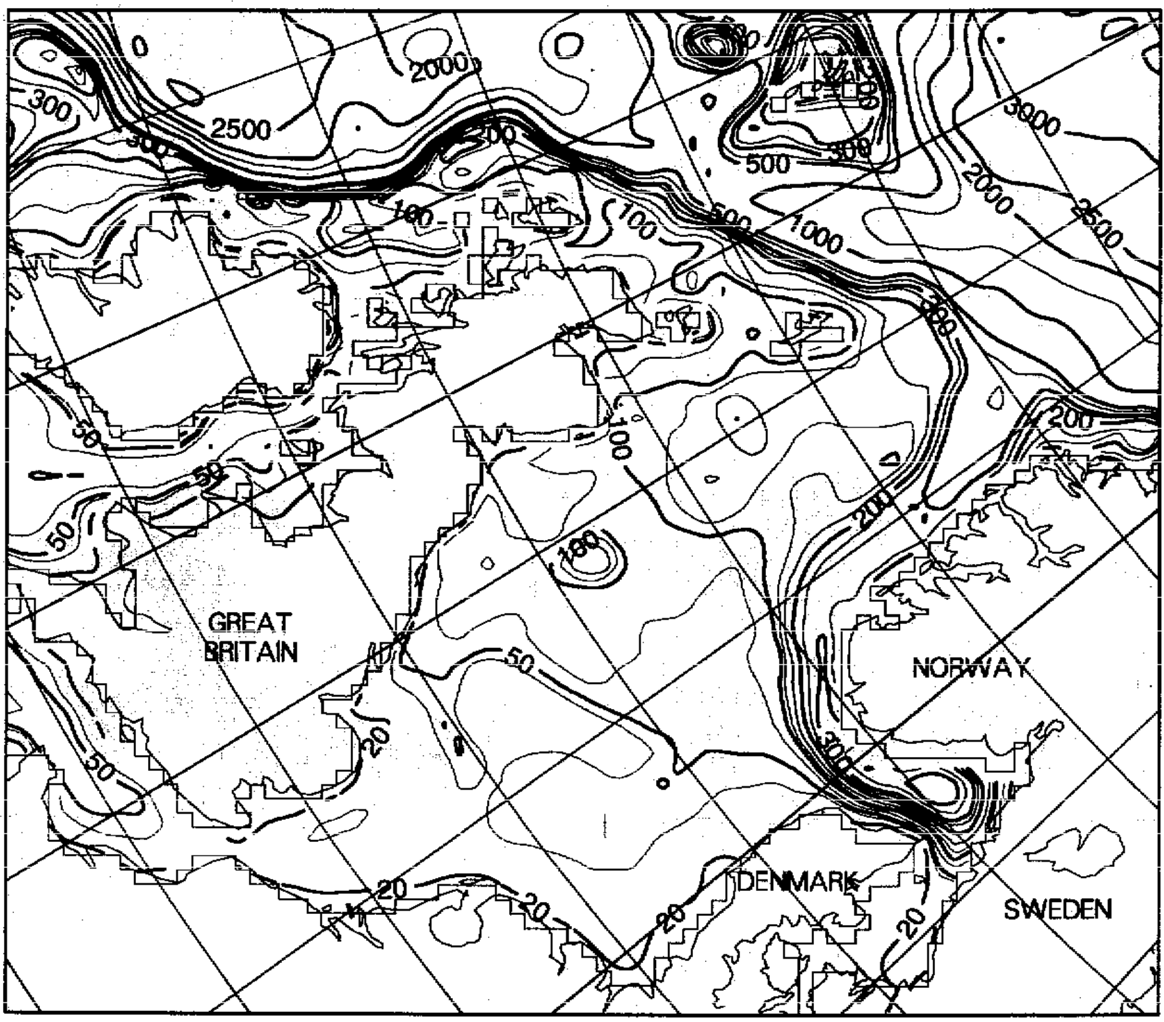

Figure 1: North Sea model bottom topography

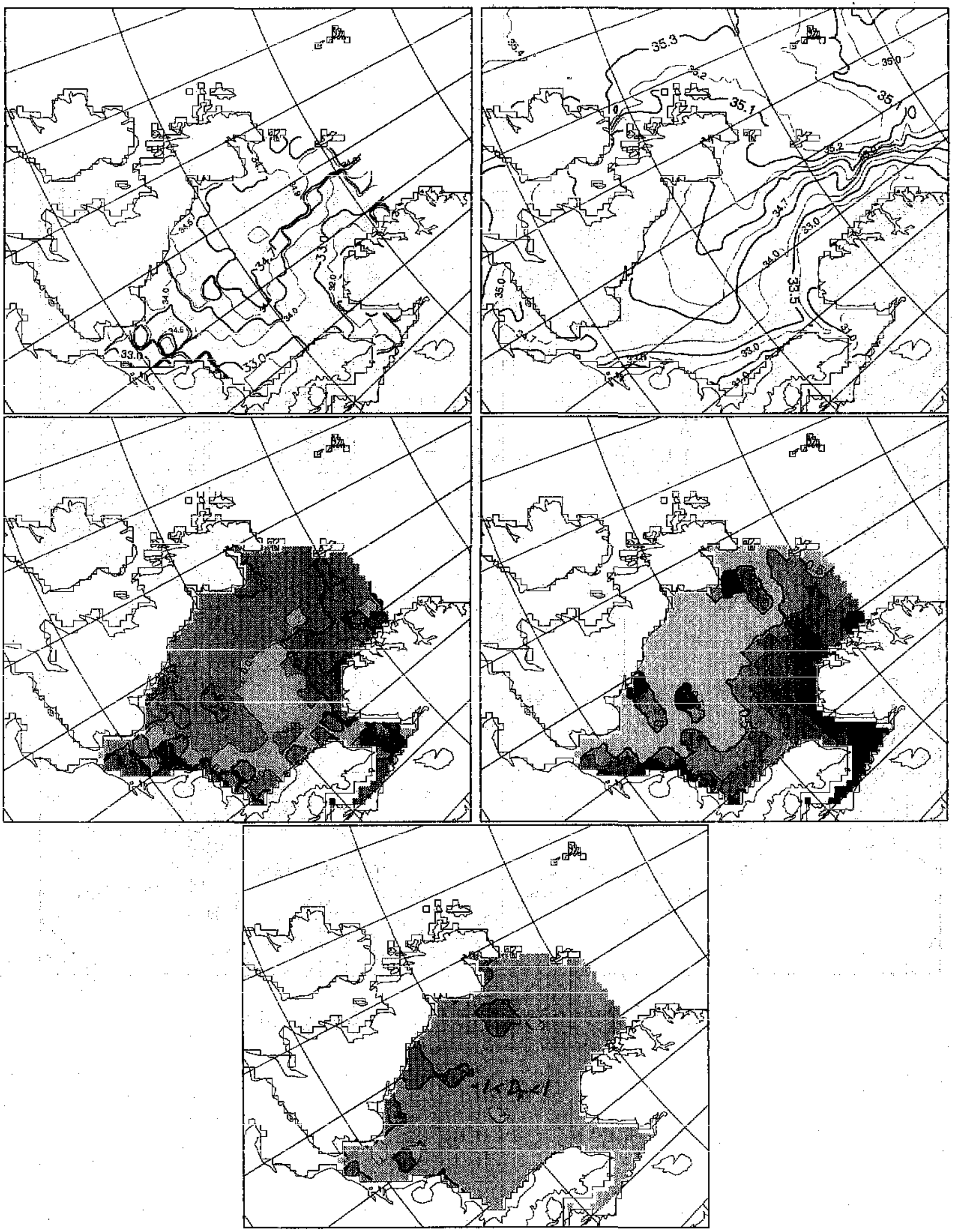

Figure 2: Observed mean salinity (upper left), modelled mean salinity (upper right), the difference (data-model) field (middel left), the standard deviation of the observed salinity (middel right) and the costfunction field (lower). All results are mean (1980-89) for May, June and July in the upper 20 meters

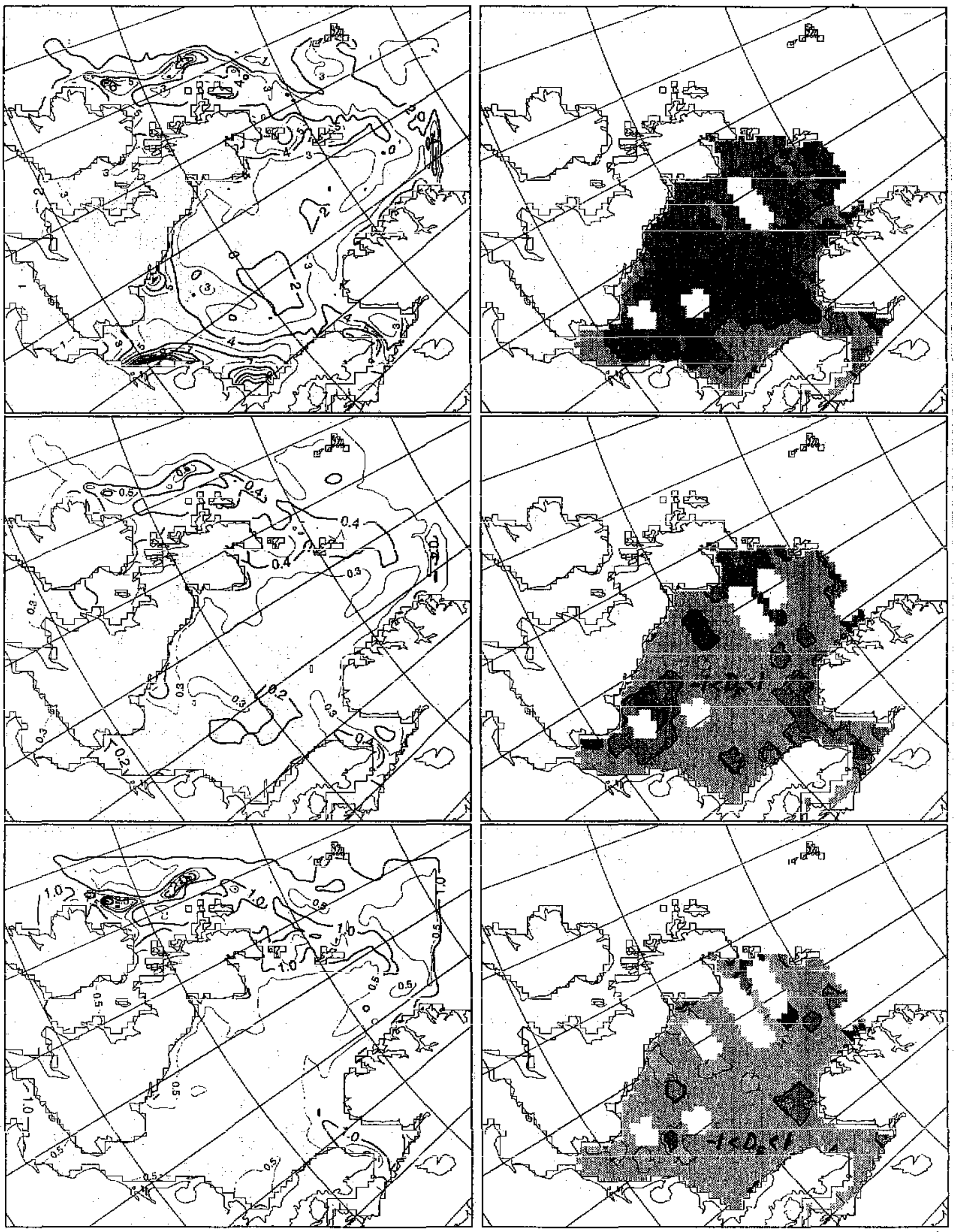

Figure 3: Mean (1980-89) model (left) and costfunction (right) field for inorganic nitrogen (upper), phosphate (middle) and silicate (lower). The results are for May-June-July in the upper 20 meters. The nutrient fields are in (μM), while the isolines in the costfunction field are -3, -2, -1, +1, +2 and +3

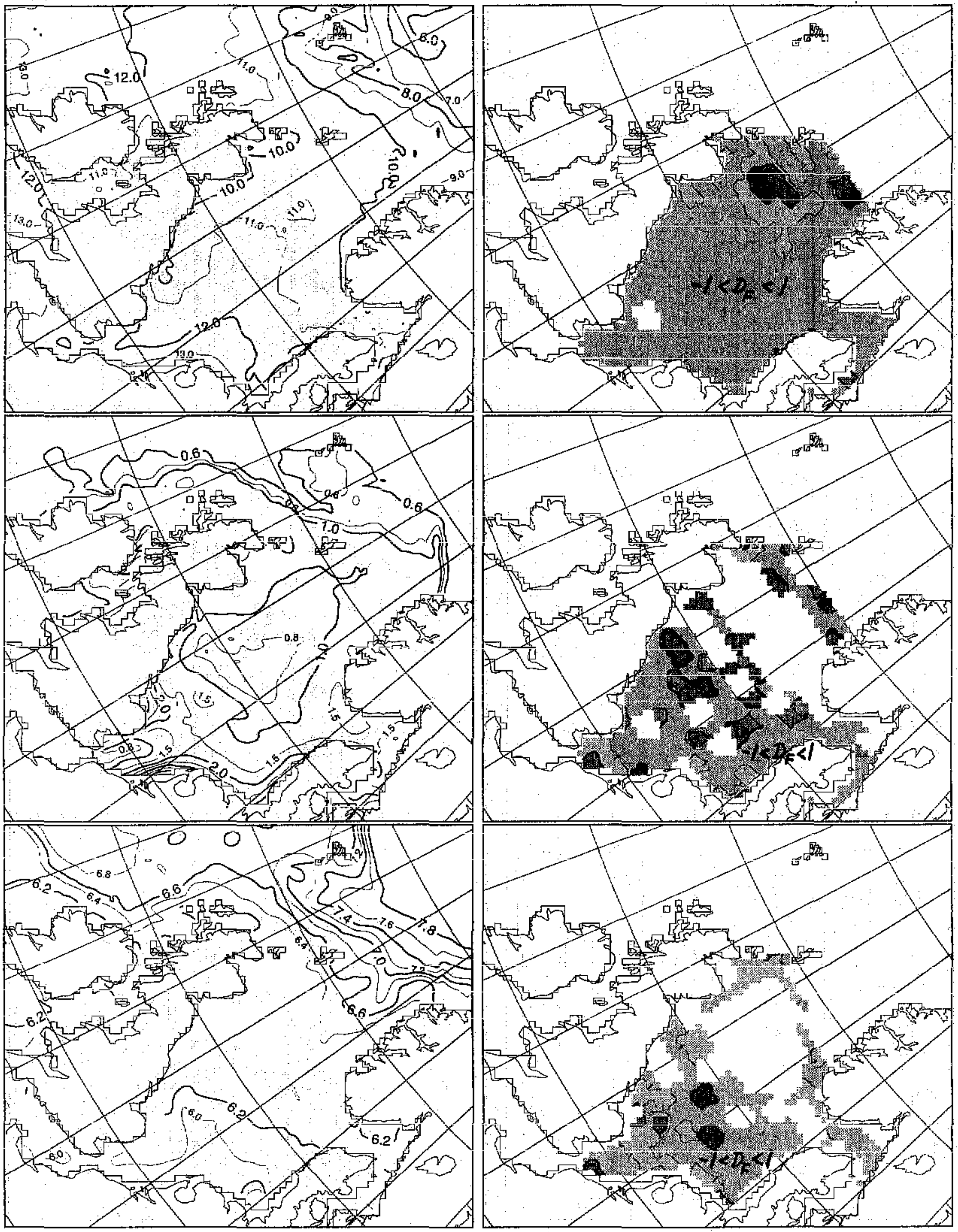

Figure 4: Mean (1980-89) model (left) and costfunction (right) field for temperature (upper), chlorophyll(A) (middle) and oxygen (lower). The results are for May-June-July, in the upper 20 meters for temperature and Chl(A), and from 20 meters to bottom for oxygen. Chl(A) is given in (mg/m^3), and oxygen in (ml/l), while the isolines in the costfunction field are -3, -2, -1, +1, +2 and +3