NATURAL FERTILISATION OF THE MARINE ENVIRONMENT – MODELLING OF THE GLOMMA FLOOD 1995

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The flood in the Norwegian river Glomma in May-June 1995 was among the largest ones during this century. Besides being devastating for man and buildings, it implied an extra supply of nutrients to the Skagerrak. This paper will focus on the possible effects this natural fertilisation could have had on the primary production in the receiving water.

The NORWegian ECOlogical Model system (NORWECOM) has been used to quantify this effect. The model has been run three times with different runoff scenarios to isolate the effects of the flood. To investigate the dispersion and dilution of the water from Glomma, this water has been labelled in the model. The model results have also been compared with a set of field data obtained during the period.

During the flood the model gives a significant change in primary production over large areas of the Skagerrak, and all extra nutrients added from the flooded rivers were consumed by the algae. However, the flood seems to have only a small impact on the annual production.

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INTRODUCTION

Large scale artificial, but controlled, fertilising of the ocean to increase the marine production has been discussed for some years. An EU funded research project on MARIne CULTivation has been started with strong support also from industry (Hoell & al. 1995; Sakshaug & al. 1995). The goal of MARICULT is to establish the necessary information on environmental constraints and potentials for increased sustainable production of food, raw materials and energy from the ocean. In the first phase of the project, analysis in mesocosmos of possible consequences of different fertilisation strategies on the ecosystem are studied.

During the early summer of 1995, an extreme, but natural large scale fertilisation experiment of the eastern Skagerrak took place through an extreme river flood in southern Norway near the Swedish border. The hydrographical, nutrient and algae distributions were mapped before and during the flood (Danielssen & al. 1996). The flood was among the largest ones this century, and caused large destruction of land and buildings. Besides being devastating for man and animals, the water also transported a lot of extra nutrients into the sea.

There is an increasing concern about the ecological effects of increased nutrient inputs to the sea (Salomons & al. 1988; Lancelot & al. 1990; Charnock & al. 1994; Sündermann 1994). The primary production is affected by the changes in nutrient inputs, and in many areas this has caused severe problems. There seems e.g. to have been an increasing trend of harmful flagellate blooms in the coastal areas of the southern North Sea (Lancelot & al. 1991). Probably the most extreme case was the *Chrysochromolina polylepis* bloom in the spring 1988 extending as far north as the Norwegian west coast (Dundas & al. 1989; Maestrini & Graneli 1991).

Skagerrak is a transition zone between the much larger Baltic Sea and the North Sea. Since the area is very productive with a production of fish of 70 kg/hectare/year (Danielssen & al. 1997), and at the same time acts as a dustbin for most of the North Sea (Eisma & Irion 1988), it is getting the attention from many scientists. Much of the overall historic and new knowledge obtained is collected in the North Sea Subregion 8 Assessment Report (Anon. 1993) from the North Sea Task Force, and some of the major processes in physical oceanography are described in a few Ph.D. theses (Poulsen 1991; Rodhe 1992). A review of the physics of the North Sea and the Skagerrak is also given by Otto & al. (1990).

Sporadic estimates indicate in- and outflows over the boarder towards the North Sea of 0.5-1.5 Sverdrup (e.g. Danielssen & al. (1997)), while model simulation (Skogen & al. 1997a) suggests 1-3 Sv, with a clear seasonal signal (1 Sv = 10^6 m^3 s^{-1}). This variability acts on

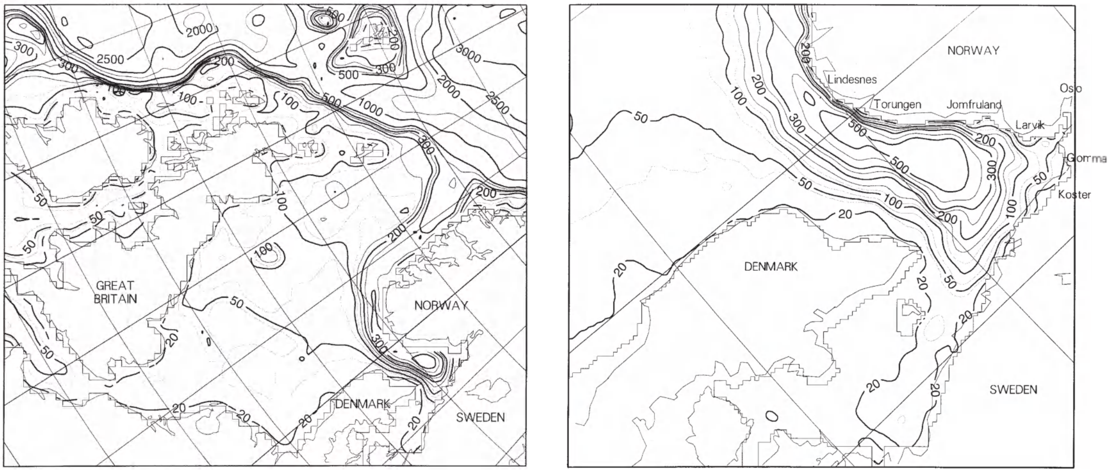

Fig. 1. Bottom topography, North Sea 20 × 20 km left, and Skagerrak 4 × 4 km right. Depths in meters.

time scales down to one day, and the inflowing water rapidly changes from mainly being Atlantic water to northern or central North Sea water, combined with water coming from the southern North Sea and the German Bight. The latter one often heavily polluted and with high nutrient concentrations (Rodhe 1992; Anon. 1993; Danielssen & al. 1997; Aure & al. 1998).

The supply of freshwater to the Skagerrak and Kattegat area is dominated by the outflow from the Baltic. This supply of freshwater is on average about 15 000 m^3 s^{-1}, compared to the river inputs of 3000 m^3 s^{-1} (Anon. 1993). Some basic work on the dynamics of the freshwater-influenced surface layer in the area is described by Gustafsson & Stigebrandt (1996). A thorough analysis of hydrographic data show strong indication of recirculation of freshwater within Skagerrak, also demonstrated by Rydberg & al. (1996) who quantifies the fluxes of water and nutrients both within and into the Skagerrak from extensive measurements. The recirculation is also clearly demonstrated in a modelling exercise by Skogen & al. (1997b). Gustafsson & Stigebrandt (1996) also concluded that although the diapycnal mixing is a major factor for increasing the volume of the freshwater influenced water circulated in the Skagerrak, the potential energy of the current system cannot be maintained by the wind driven diapycnal mixing. Instead they found that the isopycnal downwelling along the coasts provides the necessary energy. This is partly in contradiction to the conclusions by Rodhe (1992).

In this paper the focus will be on the quantified description and possible ecological effects of the flood in the largest Norwegian river, Glomma, by using a state of the art ecological model, NORWECOM (the NORWegian ECOlogical Model system) (Skogen 1993; Skogen & al. 1995). The investigation will focus both on the increased input of freshwater and the extra supply of nutrients. The main weakness of 3-D modelling activities claiming to simulate nature is the lack of comparison with adequate real data. Therefore the extensive SKAGEX dataset (Danielssen & al. 1991, 1997; Ostrowski 1994) has been used to validate (Dee 1994) the model (Svendsen & al. 1996; Skogen & al. 1997b). During the last years there have been some major model-model intercomparison activities focusing on the physics of the Skagerrak basin. This demonstrates relatively large differences between models (Gustafsson & Jönsson 1995). Some simplified modelling exercise of the effects of varying winds and fjord run-offs on the Skagerrak circulation are earlier presented by Johnson (1991), qualitatively reproducing some of the general knowledge of the circulation e.g. presented by Aure & Sætre (1981). The work on a two layer model of the Rhine Plume (de Kok 1996) and simulations of the Hudson plume in the New York bight (Oey & al. 1994) are examples of work related to realistic modelling of river plumes. However, to our knowledge our work is the first 3-dimensional modelling approach including biological effects of such plumes.

After a short model description some of the main results from the observation studies (Danielssen & al. 1996) will be presented. The main part of the paper will concentrate on the results from the model simulations. Three different model simulations have been done. One run using real 1995-data for river runoff for the flooded rivers, one using constant values (1990 mean) and one without any freshwater runoff from these rivers. The model results have been compared with the cruise data, and the dispersion and dilution of the water from Glomma have been investigated. Finally the flood is discussed in a fertilisation experiment context.

THE MODEL DESIGN

The NORWegian ECOlogical Model system (NORWECOM) is a coupled physical, chemical, biological model system applied to study primary production and dispersion of particles (fish larvae and pollution). The model is fully described in Skogen (1993). See also Aksnes & al. (1995) and Skogen & al. (1995).

In the present study a nested version of the model is used, with a coarse 20 × 20 km grid on an extended North Sea, and a fine 4 × 4 km mesh in the Skagerrak/Kattegat area (see Fig. 1). The coarse model was run initially, providing the necessary boundary and initial values for the fine grid model.

The forcing variables are six-hourly hindcast atmospheric pressure fields provided by the Norwegian Meteorological Institute (DNMI) (Eide & al. 1985), 6-hourly wind stress (translated from the pressure fields by assuming neutral air-sea stability), four tidal constituents at open boundaries (coarse model only) and freshwater runoff. In the lack of data on the surface heat fluxes, a 'relaxation towards climatology' method is used for the surface layer (Cox & Bryan 1984). During calm wind conditions, the surface temperature field will adjust to the climatological values after about 10 days (Oey & Chen 1992). The net evaporation precipitation flux is set to zero.

The biological model is coupled to the physical model through the subsurface light, the hydrography and the horizontal and the vertical movement of the water masses. The incident irradiation is modelled using a formulation based on Skartveit & Olseth (1986,1987). Due to lack of irradiance data from the period of the flood, data for global daily radiation from 1990 is taken from a station at Taastrup (Denmark) (Anon. 1991). Nutrients (inorganic nitrogen, phosphorous and silicate) are added to the system from the rivers, the open boundaries and the atmosphere (only inorganic nitrogen). Data for atmospheric nitrogen is taken from Anon. (1992).

Annual mean data for freshwater runoff, including nutrient data from the main European rivers are taken from Baliño (1993). In addition extra freshwater is added along the Norwegian and Swedish coast to fulfil requirements to estimated total freshwater runoff from these coastlines (Egenberg 1993). Several European rivers were partly flooded in the early spring of 1995. Freshwater runoff from Elbe, Ems and Weser have been made available from Bundesanstalt für Gewasserkunde, Koblenz, as monthly means up to May 1995, and for the Rhine from RIKZ, the Hague, up to March 1995. The lack of realistic runoff data may result in somewhat too high modelled salinities compared to observations in Skagerrak.

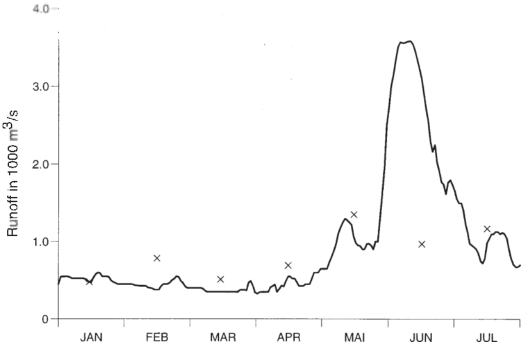

Fig. 2. Daily river runoff (m^3/s) from Glomma spring 1995 (solid line) and monthly means from 1990.

In the coarse model initial values for velocities, water elevation, temperature and salinity are taken from monthly climatologies (Martinsen & al. 1992). Interpolation between monthly fields are also used at all open boundaries, except at the inflow from the Baltic where the volume fluxes have been calculated from the modelled water elevation in Kattegat and the climatological monthly mean freshwater runoff to the Baltic, using an algorithm from Stigebrandt (1980). In the model, the water entering Kattegat from the Baltic has throughout the year a salinity near 8 psu.

The nutrient fields are derived and extrapolated/interpolated (Ottersen 1991) from data (obtained from ICES) together with some small initial amounts of diatoms and flagellates (2.75 mgN m^{-3}). Very few (continuous) time series of nutrients are available from the inflow of Atlantic water. At the open boundaries (outside the North Sea) nutrient values from station M (66°N,2°E) from 1992 (F. Rey, pers. commn. 1993) have been used and assumed valid everywhere in the inflow area. Nutrient data (climatological monthly means) measured in the Baltic (ICES) are used for the water flowing into Kattegat.

The coarse model has been run from 15 January to 1 August. The fine grid model is started on 15 March, and is initiated from the coarse grid model with interpolated data. New boundary values are read and interpolated hourly from the coarse run on the boundary facing the North Sea, and imported through an FRS-zone (Martinsen & Engedahl 1987) to the model domain. The open boundary towards the Baltic, as well as freshwater runoff, are treated as in the coarse model.

Three different model runs have been performed. First a reference run using the mean 1990 freshwater runoff from the rivers Drammenselva, Numedalslågen and Glomma, second a simulation using observed daily runoff values from 1995 provided by the Norwegian Water Resources and Energy Administration (NVE), and third a run without any freshwater inputs from these

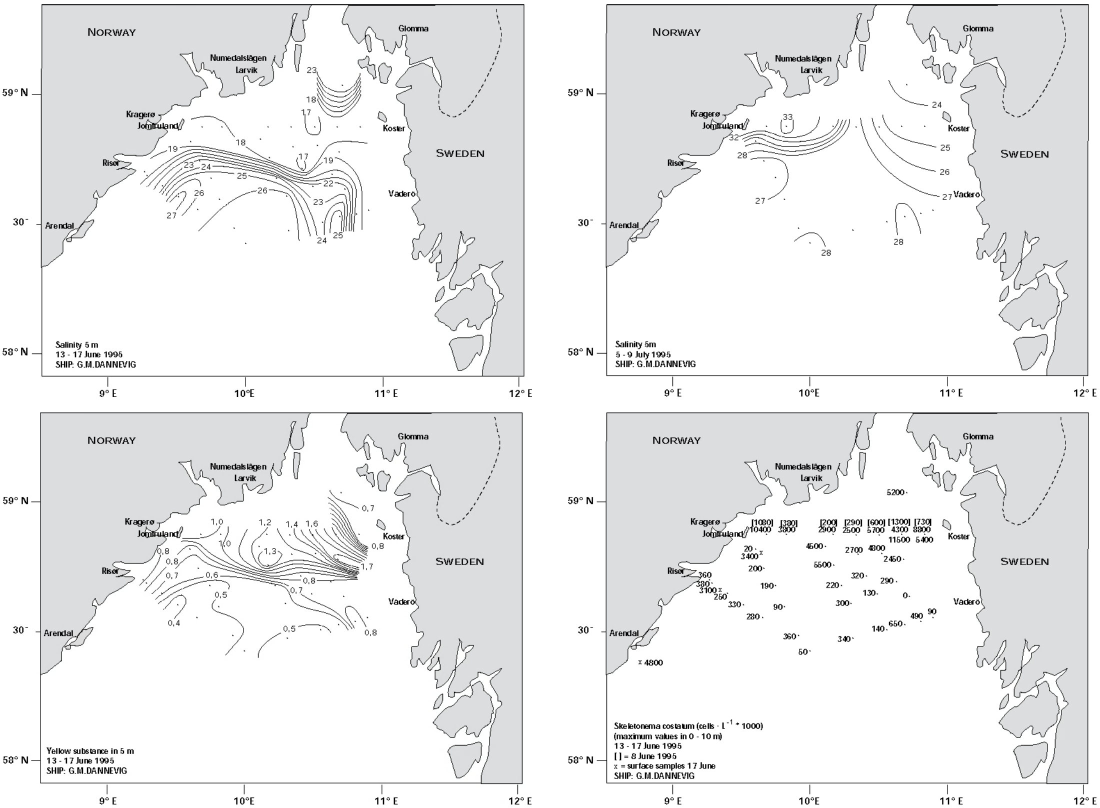

Fig. 3. Salinity at 5 meters depth in the northeastern part of the Skagerrak in June and July 1995 (upper panels), and distribution of yellow substances (lower left) and the diatom *Skeletonema costatum* (cells/l × 1000) (lower right) in June from DANIELSSEN & al. (1996).

rivers were performed. Numedalslågen and Glomma have their outlets in the outer Oslofjord (see Figs 1 and 3), while Drammenselva has its outlet inside the Oslofjord (not shown in figure). In the first run the runoffs are constant 282, 98 and 798 m^3s^{-1}, while in the second run the runoffs varies between 242-1450, 117-559 and 325-3570 m^3s^{-1}. The runoff for Glomma are shown in Fig. 2. Due to the lack of proper data for nutrients within these waters, constant values based on sporadic estimates during the flood provided by the Norwegian Institute for Water Research (NIVA) and 1990-averages (BALIÑO 1993) have been used in both runs. Thus, in the model, nutrient loads from these rivers are directly proportional to the runoffs. For Glomma the estimated nutrient concentrations are 301 mg m^{-3} (21.5 μM) for inorganic nitrogen, 8 mg m^{-3} (0.26 μM) for inorganic phosphorous and 2700 mg m^{-3} (96 μM) for inorganic silicate. Except for the river runoffs, all other forcing are identical in the three simulations.

To study in particular the dispersion and dilution of the water from Glomma, this water has also initially been labelled in the model. This is done by including an extra prognostic variable, Glommawater, with concentration one at the river outlet of Glomma. The release of this extra field is proportional to the freshwater runoff from Glomma throughout the whole model period. This Glommawater field has from this source been treated as a passive tracer by the modelled circulation and diffusion. However, the freshwater from Glomma is still included as an ordinary discharge, such that this river water also acts on the hydrodynamics like any other freshwater source.

RESULTS AND DISCUSSION

Observations during the flood

Several cruises were done in the Oslofjord and Skagerrak area in June and July 1995 (DANIELSSEN & al. 1996). The fresh-water influence from the flood created an unusually fresh surface layer with a strong halocline. The surface water with extremely low salinities was detected in June along the Norwegian coast Southwest to Risør, and east to the shore between Koster and Väderö on the Swedish west-coast. To il-

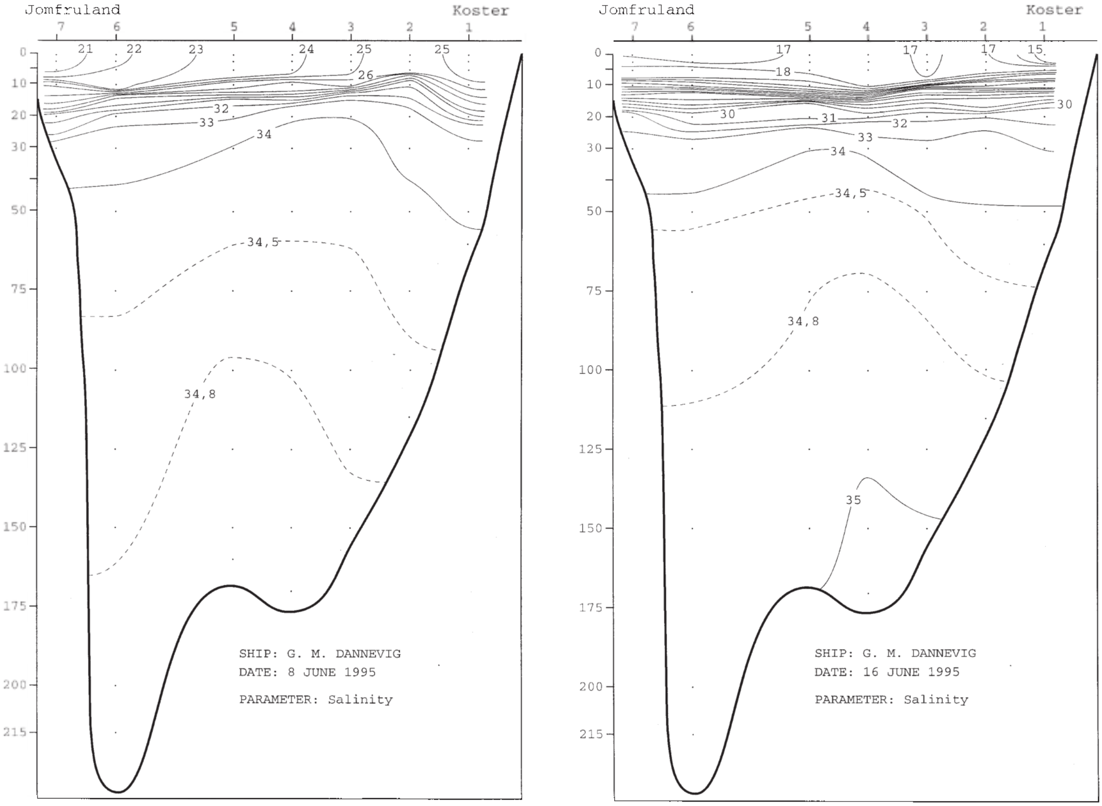

Fig. 4. Salinity along section Jomfruland - Koster. From Danielssen & al. (1996) 8 June (left) and 16 June (right).

lustrate this, horizontal distribution of salinity at 5 meters during the flood (13-17 June) and after the flood (5-9 July) are shown in the two upper panels of Fig. 3. Abnormally low salinities were also detected all along the Norwegian Skagerrak coast and across to Denmark in the central Skagerrak (Danielssen & al. 1996).

On the section Jomfruland-Koster (see Fig. 3) the effect of the flood can also clearly be seen from the salinity profiles in Fig. 4. During the one week period from 8 to 16 June the surface salinity was reduced from 22-24 psu to 17 psu. Later on 5 July (Fig. 3) the surface salinity had increased to 26 psu.

High concentrations of *chlorophyll-a* in the brackish Glomma water were observed in the middle of June along the Jomfruland-Koster section. The chlorophyll concentrations and the estimated primary production increased with a factor of three during the flood. Almost all the *chlorophyll-a* and algae concentration was found above the halocline, and the algae community was nearly a monoculture of the diatom *Skeletonema costatum* during the flood. The cause for a diatom to dominate the plankton community was probably due to excess of silicate in the surface layer. Relatively high concentrations of this algae were still present in this coastal area in the beginning of July (Danielssen & al. 1996). The distribution of the diatom during the flood is shown in the lower right panel of Fig. 3.

The brackish water along the Jomfruland-Koster section also had very high concentrations of yellow substances. This was different from the brackish water outside Väderö on the Swedish coast, and a sharp front was seen north of this point. This indicates that the Glomma water (at least under extreme flooding) is labelled with very (relatively) high concentrations of yellow substances compared to low salinity water from the Kattegat (Danielssen & al. 1996). Distribution of yellow substances during the flood are found in the lower left panel of Fig. 3.

Results from the model simulations

Focusing on the modelled velocities, there are several occasions of southward transport along the Swedish coast to Koster. However, the model does not show any signs of transports as far south as to the Väderö island. This confirms that yellow substances act as a label for the Glomma water, and that the low salinity water this

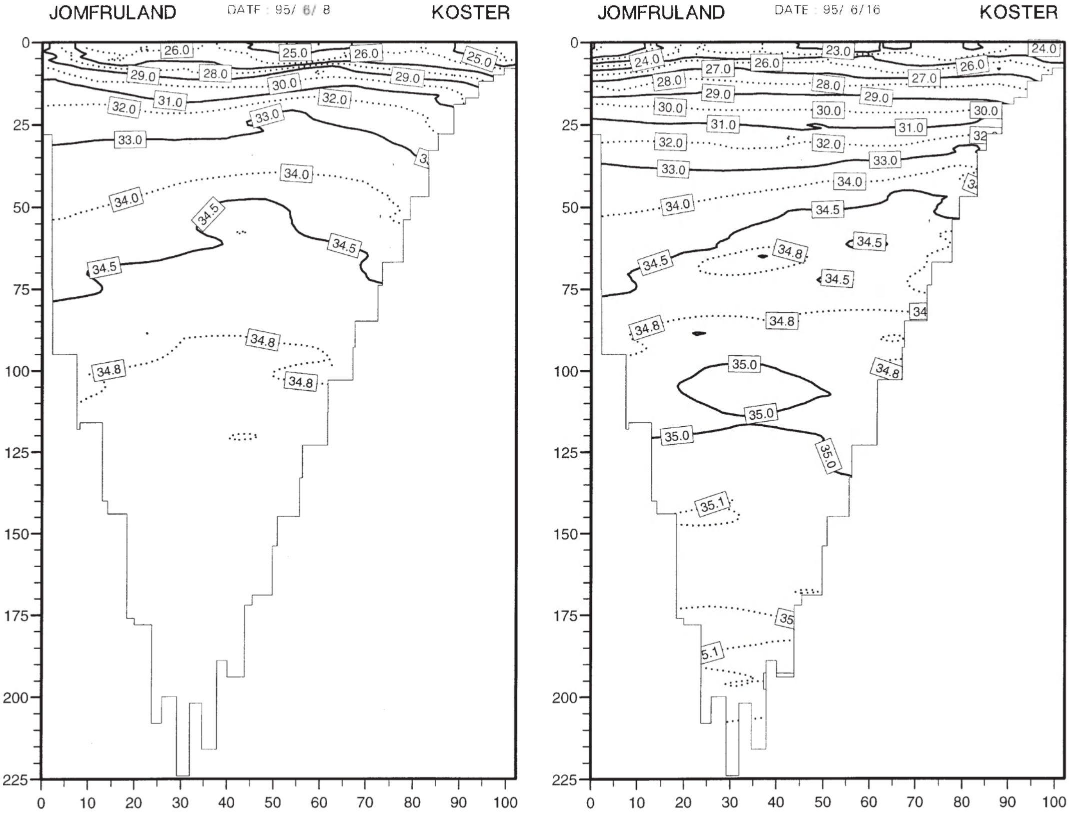

Fig. 5. Modeled salinity along section Jomfruland - Koster. 8 June (left) and 16 June (right).

far south as Väderö has its origin from other rivers with lower concentrations of yellow substances.

To compare model and data, output from the model for the Jomfruland-Koster section are given in Fig. 5. The model fails to reproduce the very fresh surface layer, even if it also gives a clear reduction in the surface salinities due to the increased input of freshwater. On 6 June the modelled surface layer has a salinity of 26 psu, while on 16 June the surface salinity has decreased to values between 22 and 24 psu. Two reasons can be seen for these too high salinities. First, there might be too much vertical mixing caused by numerical diffusion or lack of adequate vertical resolution in the model. Secondly, the freshwater from Glomma (see Fig. 6) is in the model keeping close to the coast and leaving the area in a narrow band outside Larvik (Fig. 3). The water from Glomma is (in the model) very seldom moving as far south as Koster. In the observations (Fig. 3) the fresh water is more evenly distributed over the whole area.

Further down the water column there is a better agreement between data and model, indicating a better modelling of the horizontal gradients and subsurface circulation and exchange with neighbouring domains. An interesting observation in the data is the appearance of 35 psu water below 125 meters on June 16, lifting the 34.5 and 34.8 psu isolines towards the surface. This is also seen in the modelled fields.

In Fig. 6 the freshwater height of the modelled Glommawater for selected days are given. On 1 May the amount of Glommawater in Skagerrak is by the model estimated to 1.4 × 10^9 m^3. This has increased to 3.7 on 1 June and 8.0 on 20 June. For the rest of the model period the amount is almost constant. The first six figures are every fifth day from 1-26 May, and should therefore be well before the main flood started (see Fig. 2). Nevertheless, even in these figures there are clear signs of the increased runoff in May, two times that in April. In June during the flood, the distribution maps are shown for every second day. It can clearly be seen how the Glommawater is diluted and transported Southwest along the Norwegian coast. There are also occasions of intrusion by other water masses (see e.g. 26 May). This pulsation of the Glomma water seems to be wind driven. During winds coming from the south, Glomma water are stowed in the outer Oslofjord, while winds coming from the north are transporting these

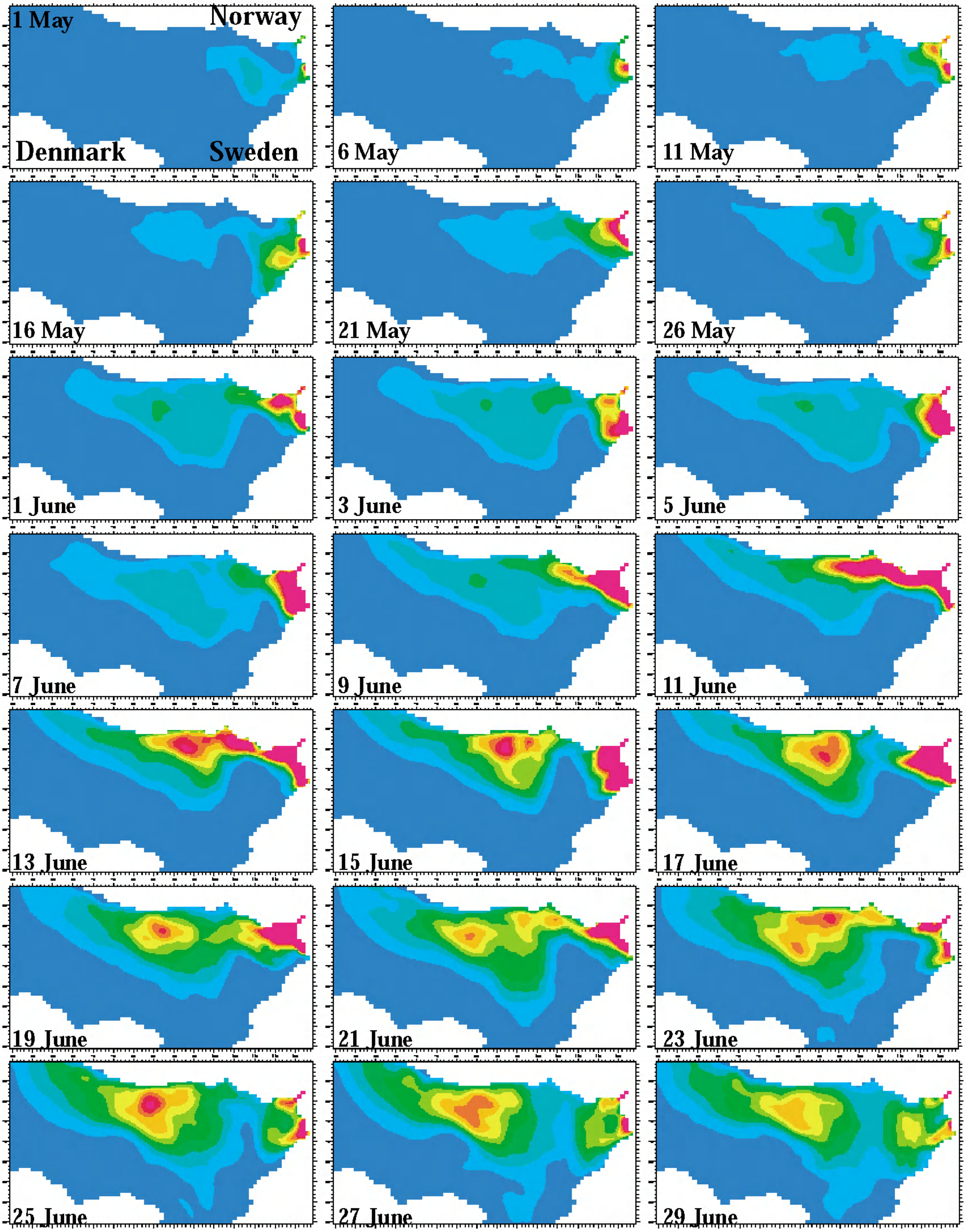

Fig. 6. Freshwater height (m) for the modeled Glomma-water 1., 6., ..., 26 May and 1, 3, 5, ...,29 June, for the 1995 flood run. Isolines range from 0.1 to 1.0 in steps of 0.1. Note the reduced view to Skagerrak only.

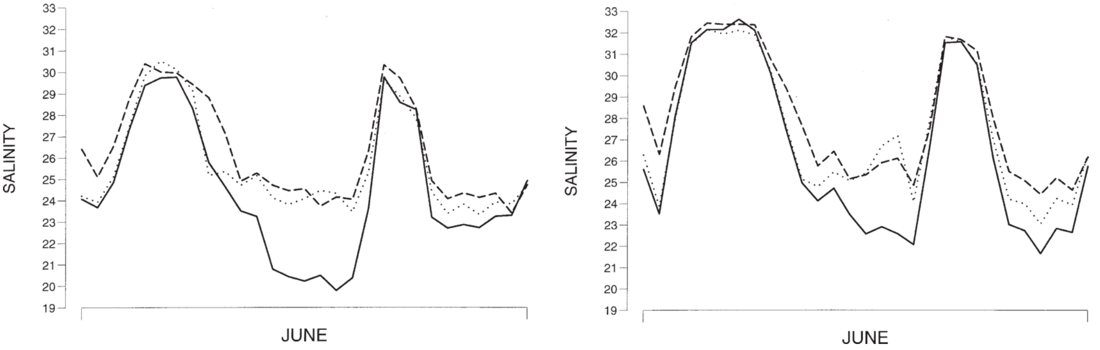

Fig. 7. Modeled salinity (2 meters) outside Jomfruland (left) and Arendal (right). With real freshwater runoffs (solid line), mean 1990 values (dotted) and without freshwater from the flooded rivers (dashed).

water masses further down along the coast (Danielssen & al. 1996).

Following one of these pulses (not shown), there is a maximum outflow of Glommawater through the section Jomfruland-Koster on 11 June (almost 6000 m^3 s^{-1}). The same maximum can be found in the model outside Arendal (Fig. 3) on 13 June and outside Lindesnes (Fig. 1), the southern tip of Norway, on 15 June. This gives an average speed of approximately 50 cm s^{-1}. These velocities in the surface layers are confirmed by observations during the *Chrysochromulina polylepis* bloom in May 1988 (Aksnes & al. 1989; Maestrini & Graneli 1991; Skjoldal & Dundas 1991), when the front was moving along the same coast with a speed of 40-50 km day^{-1} (45-55 cm s^{-1}) (Aksnes & al. 1995). The Institute of Marine Research is doing regular monitoring at Ytre-Utsira (59.20°N) on the Norwegian westcoast. At 19 June the signal from the flood could be seen in the measurements. On this date the salinity at 10 meters was found to be 28 psu (normal 32 psu). This also confirms the modelled velocities. The speed of Glomma water is not readily seen in Fig. 6 since the concentration fields do not reflect the actual water particles flushing through the system.

The distribution of high concentrations of the modelled Glomma water has its maximum on 11 June, when it reaches as far south as Jomfruland. As the flood has passed its maximum the water is more diluted and the Glomma water is being spread over large areas. At the end of June some of the water is also being spread along the Swedish coast, indicating possible effects of the flood also in these areas.

An interesting finding is the more or less permanent appearance of Glomma water in the middle of Skagerrak. This is related to a large meander and significant offshore transport and partly recirculation of coastal water. Such a semi-permanent recirculation was also seen during model studies of the SKAGEX period (Svendsen & al. 1996; Skogen & al. 1997b). That such a recirculation of Norwegian Coastal Water takes place in the region is also demonstrated by a Swedish long term monitoring program of currents and hydrography (Rydberg 1993). A topographical steered recirculation is in agreement with general theory of cyclonic circulation around deep areas (Pond & Pickard 1983). However, associated with the large meander, an anticyclonic circulation of the surface water is often set up in this central area above the underlying general cyclonic circulation. A hypothesis is that this is related to conservation of potential vorticity associated with the shallowing of the surface water layer over the general Skagerrak *dome*. This could explain the often occurrence of the *twin peaks* seen in hydrographic sections (Danielssen & al. 1997), however the theory for this is still not worked out properly.

In Fig. 7 the modelled salinity at 2 meters depth for the different simulations at a point outside Jomfruland and a point outside Arendal are shown. The figures clearly show the signal from the flood as the difference in salinity between the runs increase around 10 June. The maximum is found a week later when the difference is more than 5 psu outside Jomfruland. The increase is first seen outside Jomfruland, and a few days later outside Arendal. From around 18 June the salinity is increasing and the difference due to the extra freshwater is decreasing. At this time there is a shift in wind direction from southerly to northerly. The difference in salinity due to the flood can again be seen from 23 June, when there is another shift in the wind direction.

To investigate the possible ecological effects of the flood, we have compared the primary production in two of the simulations. In Fig. 8 the modelled daily primary production (gC m^{-2} day^{-1}) in the outer Oslofjord is given. All reported primary production results are for the total production, including remineralization. Both the sum of diatom and flagellate production, and the diatom production are given for the simulations with real 1995 and mean 1990 freshwater runoffs. For the summed pro-

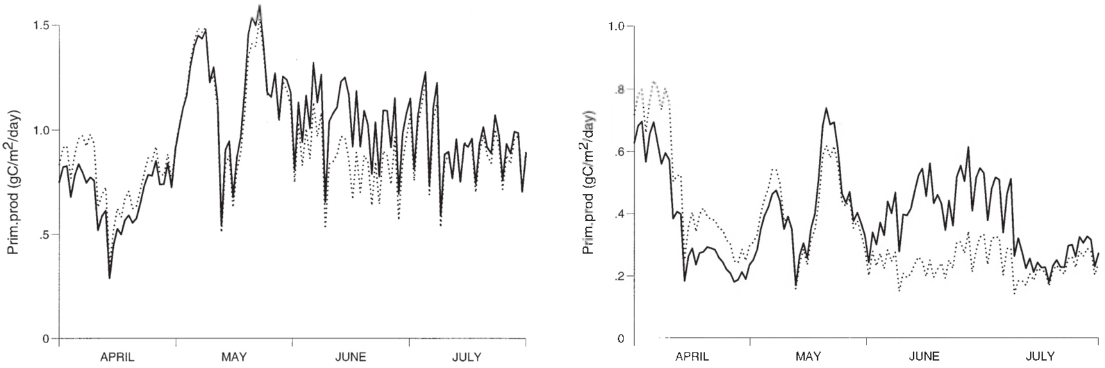

Fig. 8. Modeled daily primary production (gC/m²/day) in the outer Oslofjord. Diatom + flagellate (left) and diatom (right). With real 1995 freshwater runoffs (solid line), and mean 1990 values (dotted).

duction, there is a slight increase in June. The increase is more significant when focusing on the diatoms only. Before the flood the daily primary production is similar in the two simulations, but the extra freshwater runoff is increasing the diatom production with approximately 100 % during a one month period. However, the modelled maximum primary production is on 21 May before the flood started. In this period there were some strong winds from the north, and the model indicates that this maximum is due to an upwelling that brought large amounts of nutrients to the surface.

Field measurements of chlorophyll concentrations showed normal (1990-94) (PEDERSEN & al. 1995) concentrations on the first cruise (8 June), while on the second cruise (13-17 June) the concentrations were threefold in the outer Oslofjord. Using the chlorophyll values, and assuming similar light conditions in the whole period it is possible (MOREL & BERTHON 1989) to give an estimate of the primary production. From this, the primary production was estimated to 500 mgC m^{-2} day^{-1} on 8 June and 1400 mgC m^{-2} day^{-1} on 16 June. These numbers are comparable to those from NORWECOM (Fig. 8), even if the model only gives a doubling of the diatom production from early June. After the flood (7 July), the chlorophyll values gave a primary production of 800 mgC m^{-2} day^{-1}. The observations showed that the algae community was nearly a monoculture of the diatom *Skeletonema costatum* during the flood. In the model, flagellate and diatom production are a function of available (most limiting) nutrients, temperature and light. There are no such mechanism to prefer one species to another, or to oust one species when the other has an extreme bloom. Therefore the model only showed a weak reduction in the flagellate production being around 50 % of the primary production during the flood.

The horizontal distribution of the change in diatom production can be seen in Fig. 9. The relative increase (percentage) of the diatom production in June is shown in the left panel, and the increased production for the whole model period (15 March - 1 August) in the right. Focusing on June, the flood caused an increase in the diatom production in the outer Oslofjord of more than 100 % (maximum 144 % close to the river outlets), and at least 50 % in most areas inside the Jomfruland-Koster section. Further down along the Norwegian coast and in central Skagerrak the increase is from 10-30 %. Note also the change in primary production some distance along the Swedish coast. For the integrated primary production (the whole model period) the effects of the flood are smaller. The modelled numbers (10 % in outer Oslofjord and 2-5 % along the coast) indicate that even such a large flood gives only a minor contribution to the annual cycle. Focusing on the sum of diatom and flagellate production, the effects are between 30 and 50 % that of the diatom production.

Recently a large scientific program (MARICULT) has been initiated to study the possibilities and constraints to enhance the harvestable productivity of the marine system (HOELL & al. 1995; SAKSHAUG & al. 1995). In this context the Glomma flood can be considered a large scale marine fertilisation experiment of the surface water. The fresh water from the rivers in question contains large amounts of silicate which in this experiment can be considered as a fertiliser. During the model period an extra amount of 14 kT (kilotons) of silicate was added to the model system from the freshwater. This represents an increase of more than 50 % from these rivers compared to the simulation with constant (1990) runoffs. As a comparison less than 2 kT of extra inorganic nitrogen was added. These extra nutrients increased the modelled primary production in the whole model domain with 48 kT of carbon. Considering the whole model domain 60 % of this increase was caused by diatoms, but restricting ourselves to Skagerrak only, the model gives an increased diatom and a decreased

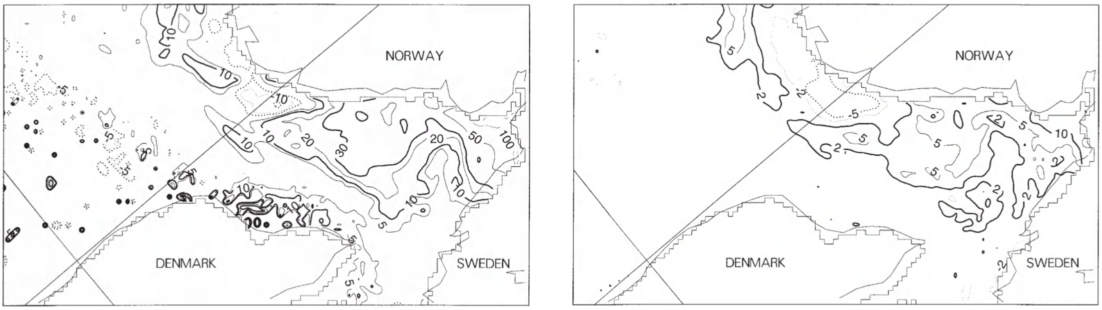

Fig. 9. Modeled change in diatom production (gC/m^2) (in percentage). June (left) and the whole model period, 15 March to 1 August, (right).

flagellate production. Using these extra amounts of silicate and carbon, it is possible to calculate the models utilisation of the fertiliser using a budget calculation. The models intercellular Si/C relationship is 0.29, thus the effectiveness is

$$E = \left(\frac{14kT}{48kT}\times\frac{1}{0.29}\right)^{-1}\times 100\% = 99.4\%$$

meaning that all extra silicate in the model were consumed by the phytoplankton. On the other hand since the amounts of extra inorganic nitrogen are much smaller, the model is now utilising inorganic nitrogen that was not available for primary production in the reference run.

As a comparison a similar model experiment, with fertilisation in a different hydrographic regime, was done as part of the MARICULT program. Outside Møre (62-63°N) in the Atlantic inflow area outside Western Norway, nutrients were released from a point source to simulate a large scale artificial marine cultivation experiment. In the experiment the idea was to lengthen the early diatom spring bloom, and silicate was added in the model as the bloom was culminating. Also in this regime with less stable conditions, all the extra silicate was consumed by the phytoplankton, and there was a shift in primary production from flagellates to diatoms. However, focusing on the sum of diatom and flagellate production the effectiveness of the fertilisation was only E = 50 %, caused by an unbalanced shift in the primary production from flagellates to diatoms (Skogen, in prep.).

CONCLUSIONS

In this paper we have modelled the flood in the Norwegian river Glomma in June 1995 using NORWECOM. To our knowledge this is the first study of this kind where a full 3D baroclinic circulation model is coupled to a primary production model, and has been used for estimates of flagellate and diatom production in a strongly stratified ocean like Skagerrak. The main focus has been on the possible ecological effects (in the model represented by primary production) of the flood. Previous works (Svendsen & al. 1996; Skogen & al. 1997b) have shown that the model is able to reproduce the Skagerrak circulation, but still the vertical density/salinity stratification is not well enough simulated. However, even if the absolute values are not fully correct, relative differences between different simulations are able to give a realistic picture of the variability in the system.

Comparisons with salinity measurements show that the model fails to reproduce the very fresh surface layer, even if the model also gives a clear reduction in surface salinity. This is probably caused by a too high vertical mixing mainly due to the lack of adequate vertical resolution. Below the surface layer the comparison indicates that the model reproduces more of the dynamics. Labelling of the water coming from Glomma in the model, enables the study of how this water is transported and diluted in Skagerrak. Following the pulses of this water along the Skagerrak coast indicates that the velocities are realistic modelled.

Comparing surface salinities between the three different simulations with varying freshwater runoffs from the flooded rivers, indicates that the flood might have resulted in a lowered surface salinity of as much as 4-5 psu as far away as Arendal.

To investigate the possible ecological effects of the flood, the primary production was compared to the simulation with normal runoffs. On a monthly basis this showed that the changes in diatom production was significant in large areas of Skagerrak. However, for the whole period even such a large flood had a small impact on the annual diatom production. Both in the model and from measurements the flood gave rise to high concentrations of diatoms. The productivity (mgC m^{-2} day^{-1}) in the outer Oslofjord are comparable although the increase in production caused by the flood seems higher in the data. The data also show a near total lack of flagellates, while in the model 50 % of the production in this area are from the flagellates.

Looked upon as a large scale marine fertilisation experiment the flood proved a success. All extra nutrients that were added to the system were used by the phytoplankton, and the effectiveness (Si/C) was almost 100 %. In the inner regions of Skagerrak this resulted in a shift from flagellate to diatom production. This shift is similar to an artificial model fertilisation experiment that were performed outside Møre on the Norwegian west coast. However, in this experiment, even if all the extra silicate were consumed by the diatoms, the effectiveness including the flagellate production was only around 50 %.

The present model represents a tool for getting new insight in the complex dynamics between physics and biology in nature. However, limitations have to be taken into consideration when interpreting the results. There are no zooplankton eating the algae, and no 'particle' bottom settlement and resuspension routines are incorporated in the model. Neither are there at present routines for regeneration of silicate. A clear limitation is also the lack of realistic light attenuation due to riverine inputs of gelbstoff, suspended particulate matter and resuspended sediments.

Clearly the horizontal resolution is a limiting factor with respect to correct simulation of, for example, nearshore and mesoscale processes. The model does not incorporate *real* surface heat fluxes, and 1990 data for surface irradiance were used when modelling 1995. Large supplies of freshwater have a great impact on the Skagerrak circulation. The Baltic outflow dominates this discharge, and a prescribed climatological fresh water run off to the Baltic is therefore an oversimplification. A more or less constant salinity of the Baltic outflow might also contribute to bias of model results.

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