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Sensitivity analysis with regard to variations of physical forcing including two possible future hydrographic regimes for the Öregrundsgrepen

A follow-up baroclinic 3D-model study

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Keywords: Numerical model, 3D, sensitivity analysis, baroclinic, cascaded coupling, C-grid, water exchange, retention time, SAFE, SFR, surface ecosystem, biosphere, Öregrundsgrepen, Baltic Sea.

Abstract

A sensitivity analysis with regard to variations of physical forcing has been performed using a 3D baroclinic model of the Öregrundsgrepen area for a whole-year period with data pertaining to 1992. The results of these variations are compared to a **nominal** run with unaltered physical forcing. This nominal simulation is based on the experience gained in an earlier whole-year modelling of the same area; the difference is mainly that the present nominal simulation is run with identical parameters for the whole year. From a computational economy point of view it has been necessary to vary the time step between the month-long simulation periods. For all simulations with varied forcing, the same time step as for the nominal run has been used. The analysis also comprises the water turnover of a hypsographically defined subsection, the BioModel area, located above the SFR depository. The external forcing factors that have been varied are the following (with their found relative impact on the volume average of the retention time of the BioModel area over one year given within parentheses):

- atmospheric temperature increased/reduced by 2.5 °C (-0.1% resp. +0.6%),
- local freshwater discharge rate doubled/halved (-1.6% resp. +0.01%),
- salinity range at the border increased/reduced a factor 2 (-0.84% resp. 0.00%),
- wind speed forcing reduced 10% (+8.6%).

The results of these simulations, at least the yearly averages, permit a reasonably direct physical explanation, while the detailed dynamics is for natural reasons more intricate.

Two additional full-year simulations of possible future hydrographic regimes have also been performed. The first mimics a hypothetical situation with permanent ice cover, which increases the average retention time 87%. The second regime entails the future hypsography with its anticipated shoreline displacement by an 11 m land-rise in the year 4000 AD, which also considerably increases the average retention times for the two remaining layers of the BioModel area when simulated with the same forcing as for the nominal run.

Sammanfattning

En känslighetsanalys med avseende på variationer för den fysiska drivningen har utförts med en baroklin 3D-modell över Öregrundsgrepen för en hel årscykel med data avseende 1992. Resultatet av dessa variationer jämförs med en **nominell** körning med oförändrad fysisk drivning. Denna nominella simulering har baserats på erfarenheterna från en tidigare utförd helårsmodellering av samma område. Av numeriska effektivitetsskäl har det varit nödvändigt att variera tidssteget mellan de månadslånga simuleringsperioderna. För samtliga simuleringar med varierad drivning har samma tidssteg som för den nominella körningen använts. Analysen omfattar även vattenutbytet för en av den hypsografiska utformningen definierad delarea, BioModell-området, beläget ovanför SFR-förvaret. De externa drivande faktorerna som har varierats är följande (med deras beräknade påverkan på volymsmedelvärdet för uppehållstiden under en årscykel angiven inom parentes):

- Atmosfärstemperaturen ökad/minskad 2,5 °C (-0,1 % resp. +0,6 %).
- Sötvattenavrinningen dubblerad/halverad (-1,6 % resp. +0,01 %).
- Salinitetssvinget på modelranden ökad/minskad en faktor 2 (-0,84 % resp. 0,00 %).
- Vindfarten minskad 10 % (+8,6 %).

Dessa simuleringar tillåter åtminstone för helårsgenomsnitten rimligt enkla fysikaliska förklaringar av resultaten. Den detaljerade dynamiken är av naturliga skäl mer svårtolkad.

Dessutom har två ytterligare helårssimuleringar av möjliga framtida hydrografiska strömningstillstånd genomförts. Den första efterliknar en hypotetisk situation med permanent istäcke, vilket visar sig öka den genomsnittliga uppehållstiden med 87 %. Det andra beräkningsfallet omfattar den förväntade framtida hypsografin med en förskjutning av strandlinjen, som beräknas uppgå till 11 m genom landhöjning vid år 4000. Detta innebär också en avsevärd ökning av uppehållstiden för de två återstående lagren i BioModell-området när simulering genomförs med samma drivning som för den nominella körningen.

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1 Introduction

1.1 Relationship to "SAFE" reporting context

This report is a part of the SKB project "SAFE" (Safety Assessment of the Final Repository of Radioactive Operational Waste). The aim of project SAFE is to update the previous safety analysis of SFR-1. The analysis should be presented to the Swedish authorities not later than during year 2000. SFR-1 is a facility for disposal of low- and intermediate-level radioactive waste, which is situated in bedrock beneath the Baltic Sea, 1 km off the coast near the Forsmark nuclear power plant in the northern part of the province of Uppland.

The two SKB reports "Project SAFE – Update of the SFR-1 safety assessment Phase 1" /Andersson et al., 1998a/ and "Project SAFE – Update of the SFR-1 safety assessment Phase 1 Appendices" /Andersson et al., 1998b/ present both an overview of the SAFE project and the work that should be performed in order to achieve the project goal.

In addition to the water exchange model study in Engqvist and Andrejev /1999/ on which the present study is based, several results have been reported concerning various but systematically chosen aspects of the local ecosystems. The shore-level displacement in historical times back to a few thousand years BP and the corresponding projection into the future have been presented in Brydsten /1999a/. The changes in sedimentation have been estimated by Brydsten /1999b/. The characteristics of contemporary existing lakes and the anticipated development of future lakes have further been described in Brunberg and Blomqvist /1999; 2000/. A diving survey describing the structure of the marine ecosystem has been presented in Kautsky et al. /1999/. Kumblad /1999/ presented an ecosystemmodel of the coastal area and anticipated future changes, including radiation dose estimates, will be described in Kumblad /in manus/. Finally, the terrestrial ecosystem and the future vegetation will be exposed in Jerling et al. /in manus/. The information in the present study and the above-mentioned reports will be summarised and used in dose estimates for possible releases from the repository.

1.2 Sensitivity analysis considerations

In an earlier model study /Engqvist & Andrejev, 1999/ the water exchange of the Öregrundsgrepen (ÖG) area was studied using a cascaded coupled 3D model approach. The arrangement of these models was such that first the large-scale dynamics of the entire Baltic was run for one year. This grid had a horizontal resolution of 5 nautical miles, (Figure 1-1), sufficient to resolve the major circulation and stratification. Subsequently the densimetric variables along the interfacial border to the ÖG area (Figure 1-2), with a considerably refined grid resolution of 0.1 nautical miles (Figure 1-3) was allowed to be driven by these saved border data. These data consisted of the salinity, temperature and sea level distribution along the border, including the narrow opening to the south. One month (December, 1991) was assigned to serve as a so-called 'spin-up' period. These two models were run with a time step and with a hydrodynamic parameter set-up that were deemed appropriate based on experience from other similar simulation tasks /Andrejev and Sokolov, 1989; 1990; 1997/.

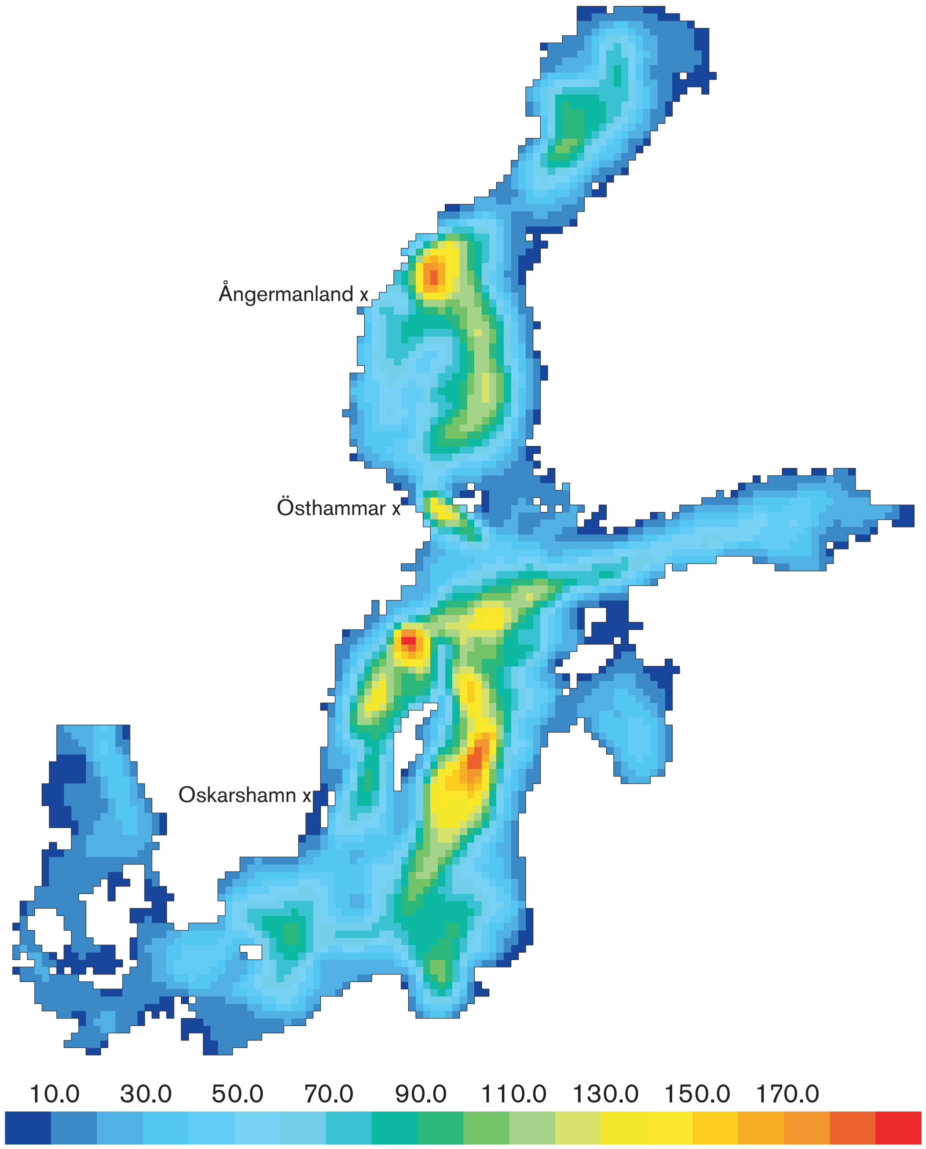

Figure 1-1. *The hypsography of the Baltic as used for all runs taking place in recent time, i.e. 1992. The legend indicates depth in meters. The approximate locations used for prognosis of the shoreline displacement are also indicated.*

Coastal embayments are normally strongly forced systems, meaning that if the forcing such as the wind ceases, the water movement and hence the exchange rapidly subsides. The necessity of sensitivity analysis arises from determining to what extent the different forcing factors influence the water exchange. This is the central theme of this report. The ambient forcing factors that have been varied are listed in Table 1-1.

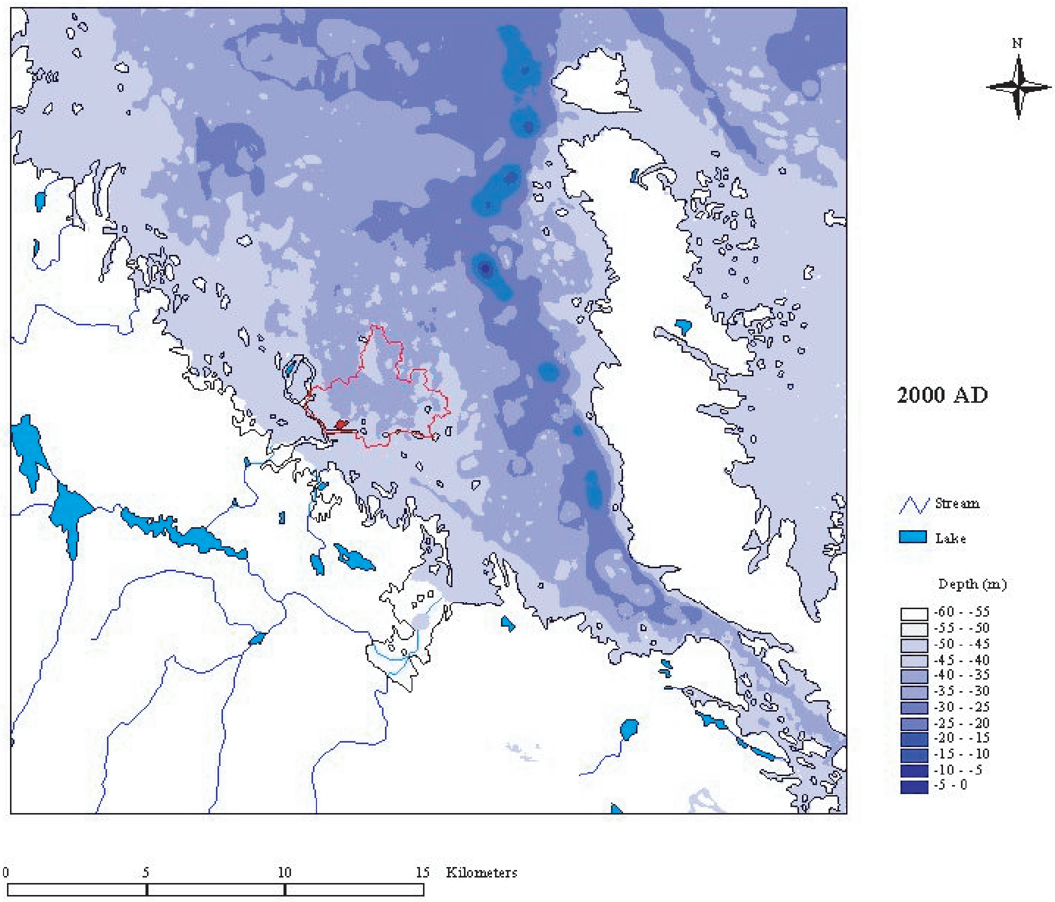

***Figure 1-2.** The present time (year 2000 AD) shoreline of the Öregrundsgrepen (ÖG) area. The location of the BioModel (BM) area is outlined. Map provided by Lars Brydsten.*

Table 1-1. Nine whole-year simulations with varied ambient forcing factors. The ninth simulation differs from the others in that it does not take place in the present hypsographical shape of the Baltic and the ÖG basins, but in radically altered ones that can be anticipated to arise 2000 YAP by the land rise and the ensuing shoreline displacement. The columns to the right indicate which simulations also include a rerun of the entire Baltic circulation with the same altered forcing.

		Baltic model	ÖG-model
0.	Nominal run (accounted for in SKB-TR-99-11)	X	X
1.	Temperature change +2.5°C	X	X
2.	Temperature change -2.5°C	X	X
3.	River runoff: Increase a factor 2		X
4.	River runoff: Decrease a factor 2		X
5.	Salinity: Increase a factor 2 of the border amplitude range		X
6.	Salinity: Decrease a factor 2 of the border amplitude range		X
7.	Wind variation: Decrease 10 %; otherwise unchanged	X	X
8.	Ice-cover regime: wind reduced 90 % permanently	X	X
9.	Land rise regime	X	X

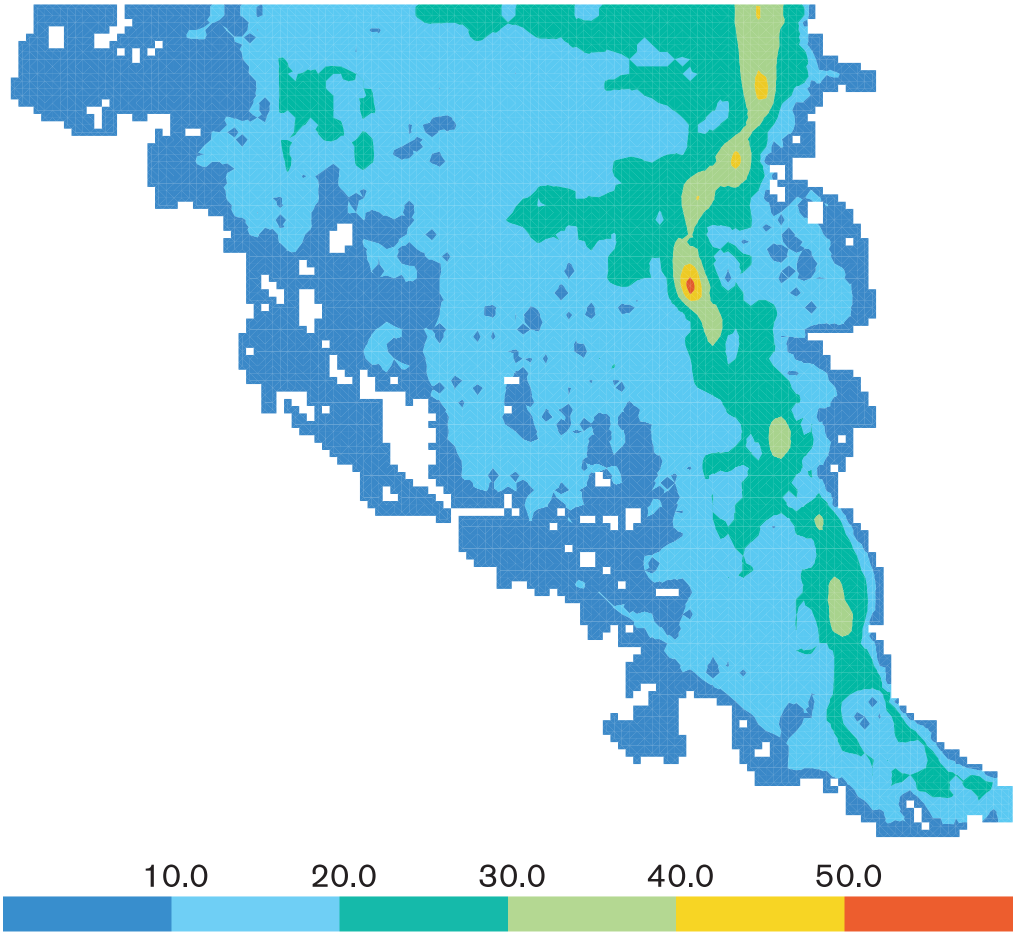

Figure 1-3. *The ÖG grid in present time (1992). The legend indicates depth in meters.*

The procedure by which to achieve the aspired intercomparability is to first rerun the *nominal* simulation with a time step that is short enough to permit uninterrupted monthly run suites and then to compare each of these simulations with varied forcing to this referential nominal run. With the exception of the *land rise regime* few, if any, numerical surprises were apprehended. The project has mainly been characterised by intense computing and the handling, analysis and presentation of these massive sets of data.

2 Variability of ambient conditions

To the present authors' knowledge, there have never been any attempts from representatives of the scientific society to claim that the long-term climate development of a randomly prespecified area could be foretold with a significant level of confidence. The IPCC third assessment report for example discusses the contingency of "rapid climate change" but the preliminary status of this report expressly precludes citing. Notwithstanding implicit reasons for caution, long-term climate projections founded on variations of paleogeological records can be compiled /e.g. SKB, 1999/ which was based on Morén and Påsse /1999/. However, these efforts must be regarded to be mainly of scenario character relying on the perpetuation of astronomically determined climate cycles, rendering such projections devoid of the known subtle mechanisms in the earth's dynamically linked atmosphere and hydrosphere. The bottom line is thus that the long-term climate development remains essentially unknown.

Against this background, the present modeling policy has been adopted to vary the contemporary forcing such that a substantial offset from its nominal values results. These nominal values that are used for comparison were chosen to correspond to the forcing of the actual year 1992 /Engqvist and Andrejev, 1999/.

2.1 Single forcing factor variations

The first forcing factor to be varied is the *atmospheric temperature*. From a climatic point of view, an average increase of only one degree Celsius means a considerable change of climate corresponding in present time to a displacement of approximately 100 km in north/south direction /e.g. Vedin, 1995/. Since the vertical heat exchange of both the fine (ÖG area) and the coarse (Baltic) resolution models is driven mainly by the atmospheric temperature variation, it was decided that this should be altered ± 2.5 °C, thus encompassing even more extreme deviations from the present climate. The interannual variation of present time averages is one order of magnitude smaller /Vedin, 1995/. These changes are imposed in the form of a systematic temperature addition or subtraction from the measured temperatures. The insolation component of the heat transfer may in comparison be treated as constant in time.

The next forcing factor is the *local stream discharge*. Whether the development in the future is towards an arid or wet climate is also genuinely uncertain. If a large-scale intensified precipitation were to become predominant and encompass a large part of the entire Baltic catchment area, the salinity in the entire Baltic most likely would be lowered. According to estimates given by Westman et al. /1999/ the variations of the paleosalinity the past 8500 years could be explained by the freshwater run-off having been decreased or increased a factor 2. The same authors also give an indication for the spin-up time of the order of 100 years for the Baltic, if a new freshwater discharge regime were to be introduced. This statement effectively discourages the possibility to involve the entire Baltic model in this analysis. Presently only the discharge of the two local streams are increased/decreased a factor 2. This range coincides quite closely with the observed 1 standard deviation (S.D.) fluctuation found for the coastal catchment areas analysed in Engqvist /1999/ for a ten-year period.

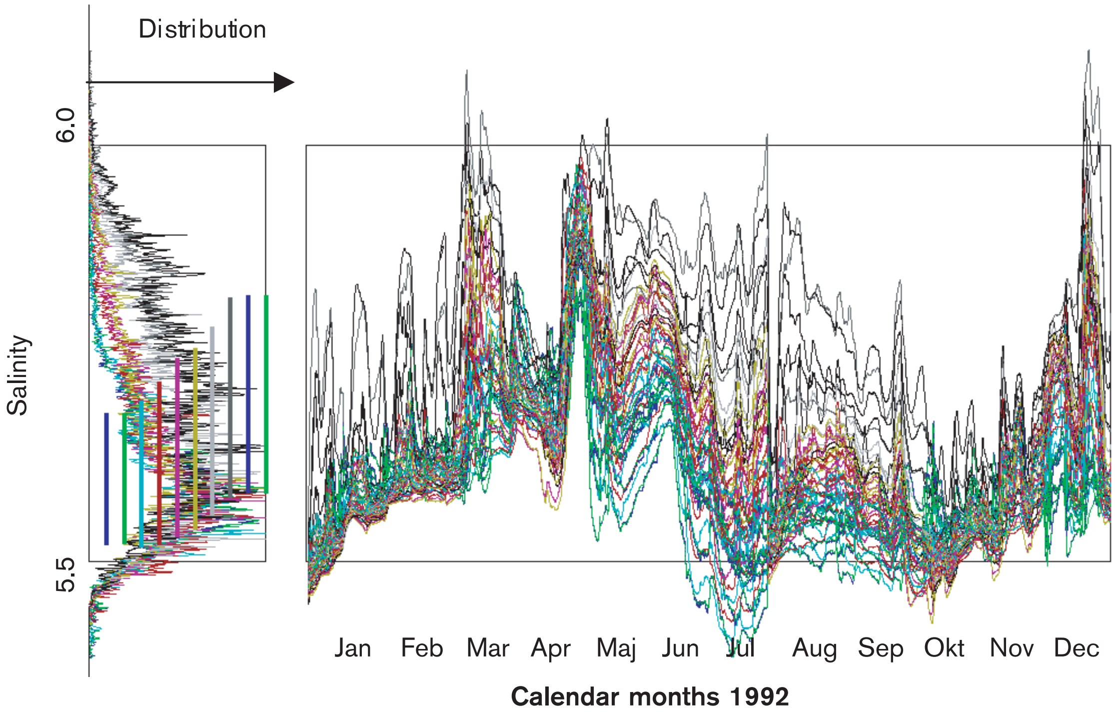

Figure 2-1a. *Salinity distribution at the ÖG border. The right diagram presents the salinity development for the various layers on all locations along the model border. The left diagram gives the density distribution for the respective layers. The variation range in the form of the average retention time (± 1 S.D.) for each layer has also been added to the picture. Note the complicated drift of the layer averages with depth. The averages between the layers increase steadily toward bottom; and reflect the stable stratification.*

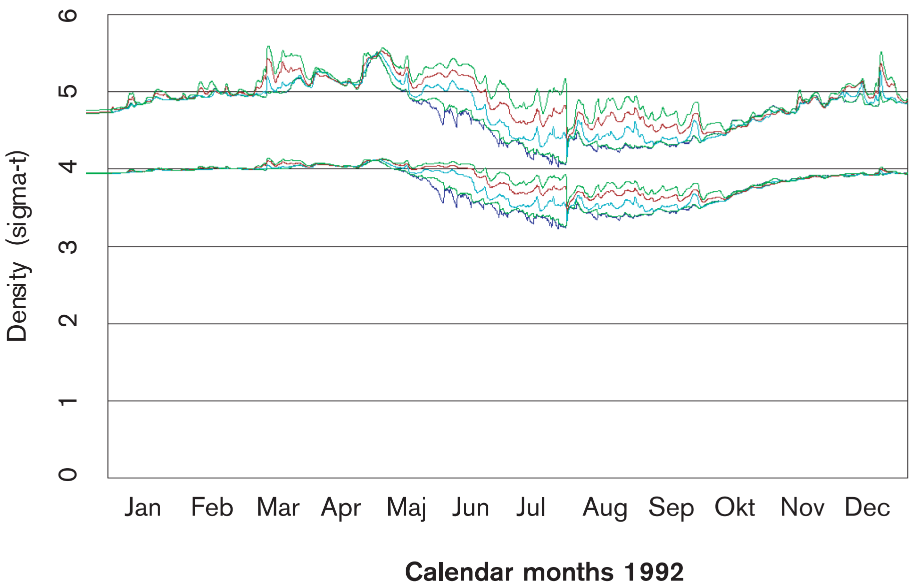

Figure 2-1b. *Density development displayed for the manipulated border salinity data. The upper set of curves are the ones with increased (doubled) salinity range while the S.D. of the lower group is decreased (halved). The two sets of curves have been graphically separated ±0.5 σ_t unit in the vertical.*

Salinity variations that enhance the difference between the surface water and the bottom water would to the contrary contribute to accentuate the so-called intermediary circulation. To arrange for such an enhanced vertical salinity difference, the distribution along the border interfacing the two models has been analysed (Figure 2-1a). From the salinity distribution with its inherent S.D., a linear transformation may be performed so that the transformed border data display twice or half of the value of the original S.D.

Concerning the *wind forcing*, one would be tempted to pursue the same procedure as for the above-mentioned forcing factors, i.e. increase and decrease the wind speed the same constant factor. Since the time step of the simulations is determined by the maximal wind speed, it would not be possible to retain the same time step as for the nominal simulation. An excessively small time step is costly from a numerical efficiency point of view. It was therefore decided that the wind should only be reduced 10% while maintaining the wind direction.

The density of water near the surface is determined not only by the salinity but also by the temperature and to a negligible extent by the pressure. In order to judge the total impact on the density forcing variation, the corresponding diagram is presented in Figure 2-1b. The difference between the enhanced and the lowered border salinity variation is obviously diminished during the summer season due to the natural heating-related density changes.

2.2 Future regime-type variations

If a greater wind speed reduction of 90% is combined with an imposed sea surface temperature that corresponds to the freezing point, then this hydrographic condition would mimic the situation of a permanent ice cover regime. This represents one possible – however extreme – outcome if a hypothetical ongoing climate deterioration were to prevail in Fennoscandia for an extended period. This condition will subsequently be referred to as the **'ice cover regime'**.

Finally, it has been of interest to estimate the water exchange at a future time when the land rise and subsequent shoreline displacement have considerably altered the hypsography of the ÖG area and the Baltic. The location and hypsography of these areas may be seen in Figures 1-1, 1-2 and 1-3 and further details may also be found in Engqvist & Andrejev /1999/. It was also decided that the future should be chosen so that the BioModel area would still be in contact with the coastal water. A suitable time was found to be the year 4000 AD /Brydsten, 1999a/ when the shoreline according to Påsse /1997/ would have been displaced 11.02 m below its present position (Figure 2-2). With such radical change of the local bathymetry, one is lead to believe that the general circulation of the Baltic would also be changed. To be sure, this simulation endeavour, projected far into the future, also included the modified hypsography of Baltic model, and will subsequently be referred to as the **'land rise regime'**.

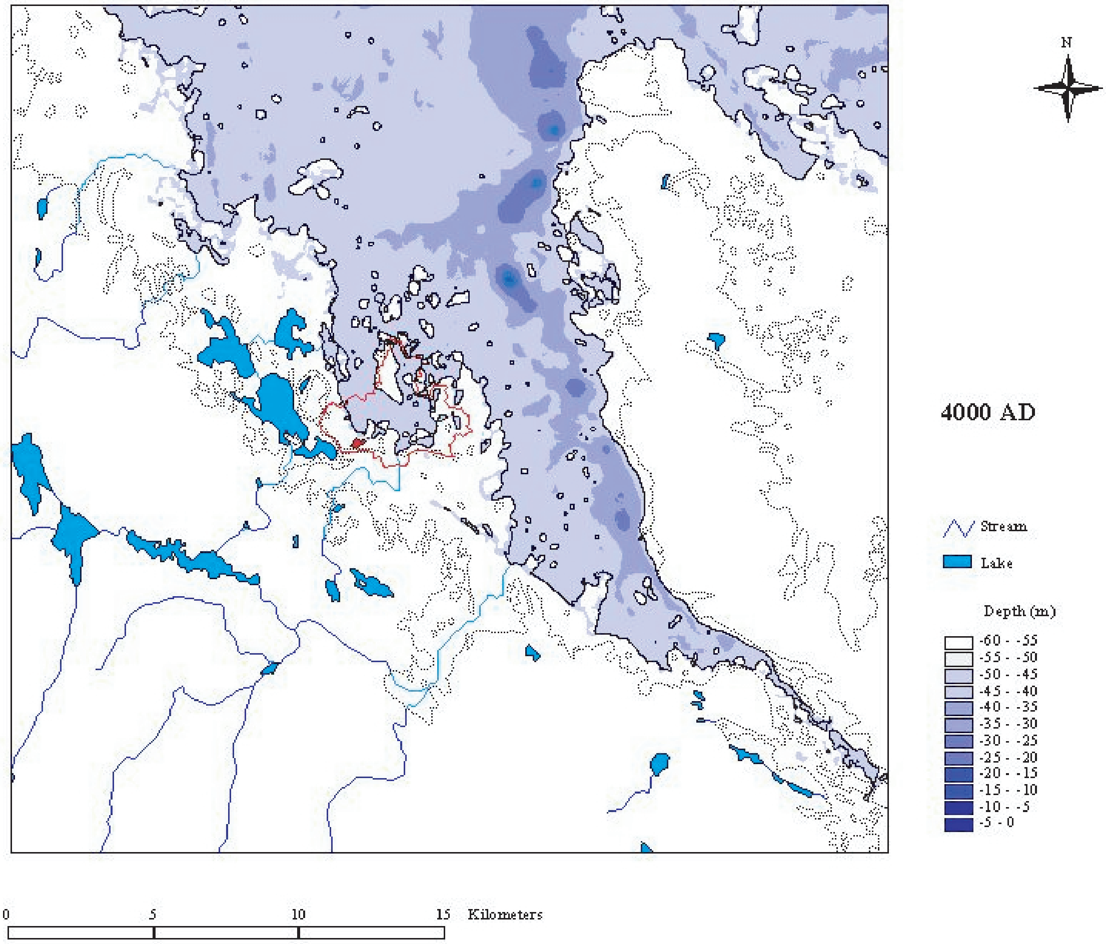

Figure 2-2. *Anticipated shoreline position of the ÖG area in the year 4000 AD compiled by Lars Brydsten.*

2.3 Choice of comparison variables

The water exchange can either be expressed in flow rates (m^3/s) or in retention times. These are not fully equivalent, since there cannot exist any functional relationship that is constant in time between those variables. When accounting for the ventilation of a predefined geographical area, only a full description of the entire flow field in space and time would give a fully adequate picture. This is of course highly unpractical if one wants to assess long-term differences. Any form of averaging the flows will lead to loss of detailed information as does relying on the transit retention analysis /*sensu* Bolin and Rodhe, 1973/. Even though this retention time measure is strictly defined, the averaging process is inherently built in. A distinct advantage of performing the analysis in transit retention time terms is that the storing effect with varying sea level necessitates no extra concern. To the contrary, analysis based on volume flows immediately yields a difference between entering and exiting flows. For these reasons the analysis and comparisons will consistently be performed with the above mentioned '*volume-specific retention time*' measure, i.e. invariably in the present context with the physical dimension (days/m^3). In spite of some inherent shortcomings, discussed in Engqvist and Andrejev /1999/ this method of analysis has won acceptance among oceanographers /Engqvist, 1996; Mattson, 1996; Gustafsson, 1999/ and lately also by biologists /e.g. Kumblad, 1999/ who welcome it for their modelling purposes.

3 Numerical realisation of the analysis

The weather data encompass geostrophically resolved wind flow fields and atmospheric temperatures and are both organised in month periods. This has been the determining factor when planning these simulations. Ideally one would prefer to use the same time step for all simulations but this was counterbalanced by the obvious desire to also efficiently use computer resources. In preliminary test runs it was established that a time step of 3 minutes could be used for most of the months, but for the five months (April, July, October, November and December) with occurrences of strong winds, this nominal time step must be halved.

To assure full intercomparability, the nominal simulation /Engqvist and Andrejev, 1999/ was rerun with this set of time steps attributed to the respective months. The oversight in the earlier study by not allowing the water retention time dynamics be started on December 1, 1991 (i.e. on the beginning of the spin-up month) was also corrected. This improved policy produced a difference between the earlier evaluated retention times in Engqvist & Andrejev /1999/ and produces an initial small discrepancy between the earlier and the present simulations. This discrepancy is of little consequence, however, since these differences are progressively diminished for each instance of elevated wind that occurs. Other aberrations occurred as well. The marked differences revealed occur only for the five months with elevated winds, and are accounted for by the explorative attempts then deployed to overcome the ensuing numerical hazards.

While rapid water exchange diminishes retention time, the contrary is true for stagnation periods, when in principle the water may age indefinitely in confined and secluded portions of the flow domain. Since stagnation periods represent a hazard in this context, it is advantageous that the measure is maximally sensitive for such events.

The central point of the analysis is the BioModel (BM) area (see Figure 1-2) because this is the primary receiving water body for possible leak-outs from the SFR repository. Accordingly the statistical analysis will be more articulated for this area while the ÖG area, as an intermediary link to the Baltic, will also be given appropriate attention.

3.1 Climate change-oriented variations

The climatic temperature variations were the first simulations to be performed. The desired variations were performed by increasing/decreasing the atmospheric temperatures ±2.5 °C, systematically and evenly distributed over the whole year. This was performed both for the Baltic and the ÖG area simulations.

The second simulations were the variations of the discharge rates of the two streams. This was straightforward; the estimated monthly discharge data were merely multiplied and divided by the advocated factor two. For reasons given above, the analysis was restricted to the ÖG area.

The variation of the salinity was to the contrary more problematic. First the salinity distributions of the different layers along the border for the nominal run were inspected. The depicted curves (Figure 2-1a) represent each location along the ÖG-model border for each of the 10 layers, using the full actual temporal resolution (i.e. 2-h time step) of the Baltic model. From these time series, the temporal salinity distribution curves over the year 1992 were extracted and the average density and their standard deviations were calculated for each layer. These computed averages differed somewhat in that they slightly but systematically increased downward, reflecting a stable stratification. The intermediary circulation /*sensu* Stigebrandt, 1990/ is driven by the density fluctuation in time. A natural way to express these variations is by their S.D. /Stigebrandt and Aure, 1990/. The dependency on salinity variations could therefore be evaluated by manipulating the border salinity data in such way that the S.D. would be altered, while mainly maintaining the average salinity level. It could be suspected, however, that a separate manipulation of the individual layers risked producing strange results since unnatural unstable vertical stratification might occur. It seemed safer to treat all layers in the same way and thus a grand average for all the layers was computed and a linear transformation of all the border data was performed accordingly. This seemingly exaggerated caution was motivated by the lack of time margins to make corrections if the simulation should go awry.

Finally, the realisation of the *wind reduction* simulations was easy to implement. While consistently maintaining its direction, the wind speed was reduced 10%. Even though this would allow for a shorter time step, the nominal set-up was retained.

3.2 Future regime-type simulations

The *ice cover regime* case was performed by reducing the wind speed 90%, while simultaneously maintaining the water temperature at a temperature close to the freezing point. The numerical implementation was the following: the atmospheric temperature was lowered to a constant –30 °C, provoking a rapid cooling of the surface water during the spin-up month. When the surface water temperature reached the freezing point of 0.2 °C /Omstedt, 1998; 1999/, the heat exchange with the atmosphere was numerically shut off, mimicking the insulating capacity of the ice cover. In order to avoid a mismatch between the local ÖG water temperatures and those on its Baltic interfaces, this procedure was also required to entail the Baltic model.

Finally, the simulation of the projected *future hypsographic* conditions that according to Påsse /1997/ would prevail in the year 4000 AD was taken on. Geological analysis gives that the shoreline displacement will be only marginally affected by the wave action, biological transformation and sediment accumulation in the future 2000 years according to Brydsten /1999a; 1999b/. The main reason for this is that the bottom area where sediments accumulate will mainly be subjected to land rise and thus will be eliminated as a factor altering the bottom topography. The shoreline is further in present time already so forcibly shaped by wave-induced erosion, that further modification of future storm events will give only marginal contributions. The details of the geometrical transformations that have been employed are deferred to section 4.7. The altered hypsography of the Baltic and the ÖG area can be seen in Figures 3-1 and 3-2.

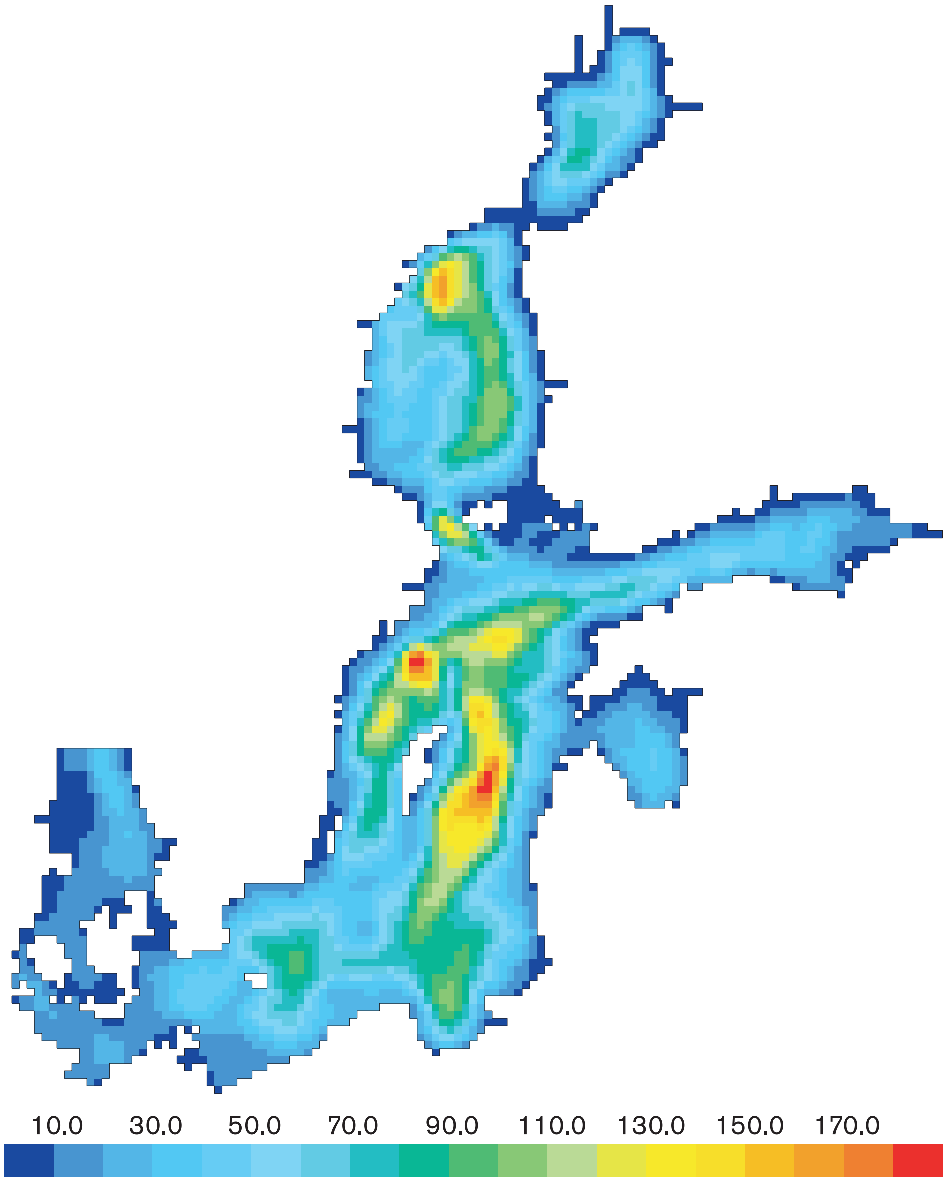

__Figure 3-1.__ A projection of the Baltic hypsography into the year 4000 AD. The shoreline displacement is based on data from Påsse /1997/. Note that the Gulf of Bothnia is on the verge of becoming a major lake. In order to make the major rivers properly discharge into the newly formed coastal zone, virtual canals have been dug in the grid. These are seen as the blue horizontally or vertically oriented blue stripes.

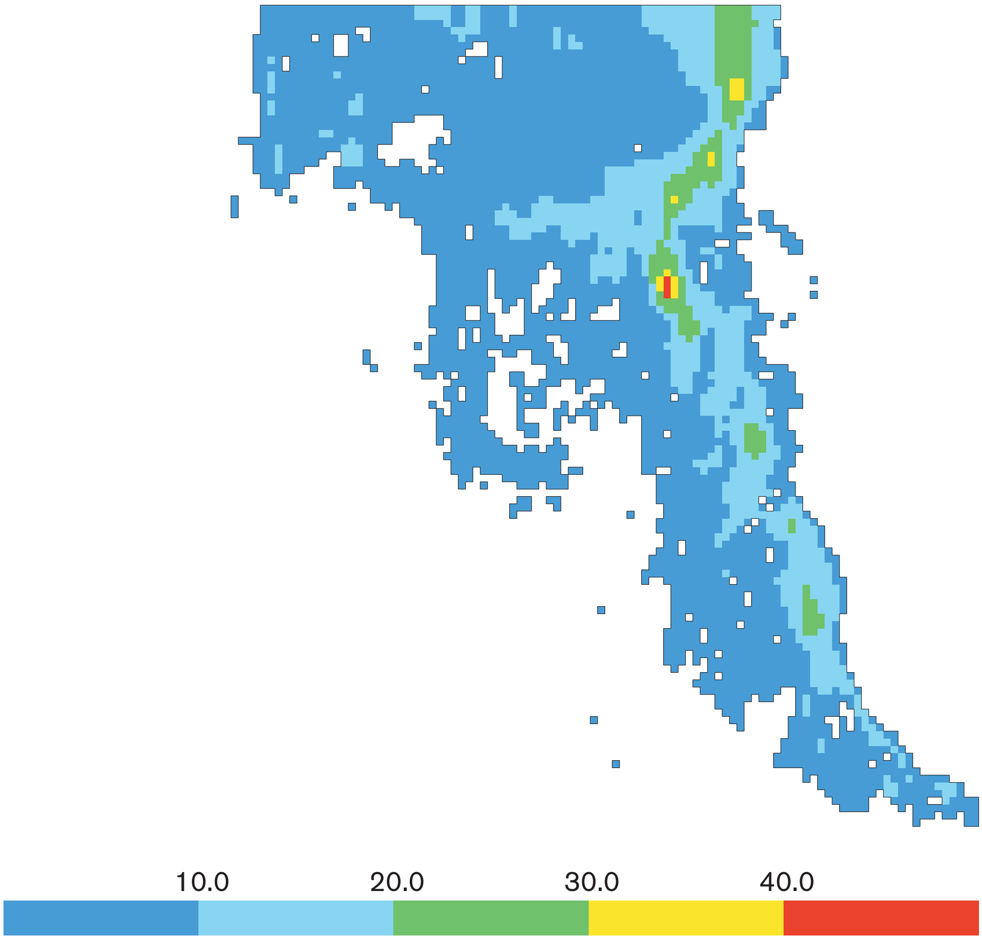

Figure 3-2. *Hypsographic gridded map of the ÖG area in the year 4000 AD, corresponding to Figure 2-2. This is obtained by lowering the sea level in Figure 1-3 exactly 11 m below the present mean sea level.*

4 Numerical results

The simulations to achieve the present sensitivity analysis results have taken approximately one working day to compute for each simulated month. The massive amount of data thus generated calls for orderly handling in the ensuing analysis. In order to present the results in a clear and communicative manner, a comparison of the nominal run to each simulation with varied forcing should preferably be performed. For conspicuous differences, standard contouring diagrams suffice. When the differences are small, the minute deviations relative to the nominal run will be presented as the deviant monthly averages relative to the nominal run. This will be done both for the entire ÖG and the BM areas. An overview of all the simulations will also be presented in Section 5.

4.1 The nominal run

The simulation with the nominal parameters as presented in Engqvist & Andrejev /1999/ was first rerun on two separate computers independently (with different Fortran compilers) and the results were checked to be coincidental within the precision of the numerical representation. This measure was taken to certify that the results coincide exactly and to assure that the choice of time step for the respective months would permit all simulations to be run in an identical manner. The appropriate time steps were next to be determined and the acceptable length is a matter of the peak occurrences of elevated wind. The months with accentuated wind peaks were April, July and October through December. For these months the assigned time step was 1.5 minutes. For the other months, twice this time period was used. The resulting monthly averages of the retention times for both the BM and the ÖG areas are given in Table 4-1. Corresponding contour plots of the retention times (i.e. the average retention time each day) for each of the 366 days in the leap year 1992 are presented in Figures 4-1a and 4-1b.

Table 4-1. Monthly averages of the ÖG and the BM area transit retention times for each layer with nominal parameters and unaltered physical forcing.

	ÖG Depth (m)										BM Depth (m)			
Month	**1**	**5**	**10**	**15**	**20**	**25**	**31**	**40**	**50**	**60**	**1**	**5**	**10**	**15**
1	2.35	2.41	2.32	2.45	2.84	3.57	3.74	3.58	5.66	12.5	0.272	0.360	0.512	0.670
2	3.60	3.65	3.50	3.65	4.16	5.35	5.69	5.60	8.84	11.6	0.400	0.486	0.669	0.885
3	5.90	5.91	5.77	5.95	6.35	7.57	7.43	6.71	11.8	19.2	0.496	0.552	0.732	0.993
4	7.74	7.61	6.93	6.63	6.84	8.02	7.94	7.03	12.8	26.1	0.489	0.560	0.723	0.936
5	7.88	7.73	7.37	7.16	7.24	7.90	7.27	6.18	14.7	25.2	0.598	0.671	0.993	1.54
6	16.5	16.3	15.1	13.6	12.8	12.8	10.7	7.78	29.1	37.0	0.714	0.810	1.20	2.06
7	12.4	12.5	12.2	11.7	12.0	13.3	11.8	8.96	27.7	42.7	0.605	0.686	0.941	1.53
8	8.53	8.51	8.27	8.19	8.19	9.33	8.64	7.51	18.7	33.2	0.600	0.665	0.948	1.50
9	8.80	8.86	8.57	8.85	10.1	13.2	13.8	13.2	23.7	37.0	0.567	0.654	0.904	1.32
10	6.05	5.97	5.43	5.20	5.40	6.41	6.41	5.73	9.62	15.1	0.522	0.601	0.752	0.944
11	6.20	6.08	5.55	5.32	5.32	6.02	5.66	4.73	8.23	9.05	0.485	0.528	0.654	0.830
12	4.67	4.65	4.5	4.66	5.04	5.75	5.49	4.69	8.44	9.58	0.380	0.438	0.592	0.781
Avg.	**7.55**	**7.52**	**7.12**	**6.95**	**7.19**	**8.26**	**7.88**	**6.81**	**14.9**	**23.2**	**0.511**	**0.584**	**0.801**	**1.17**

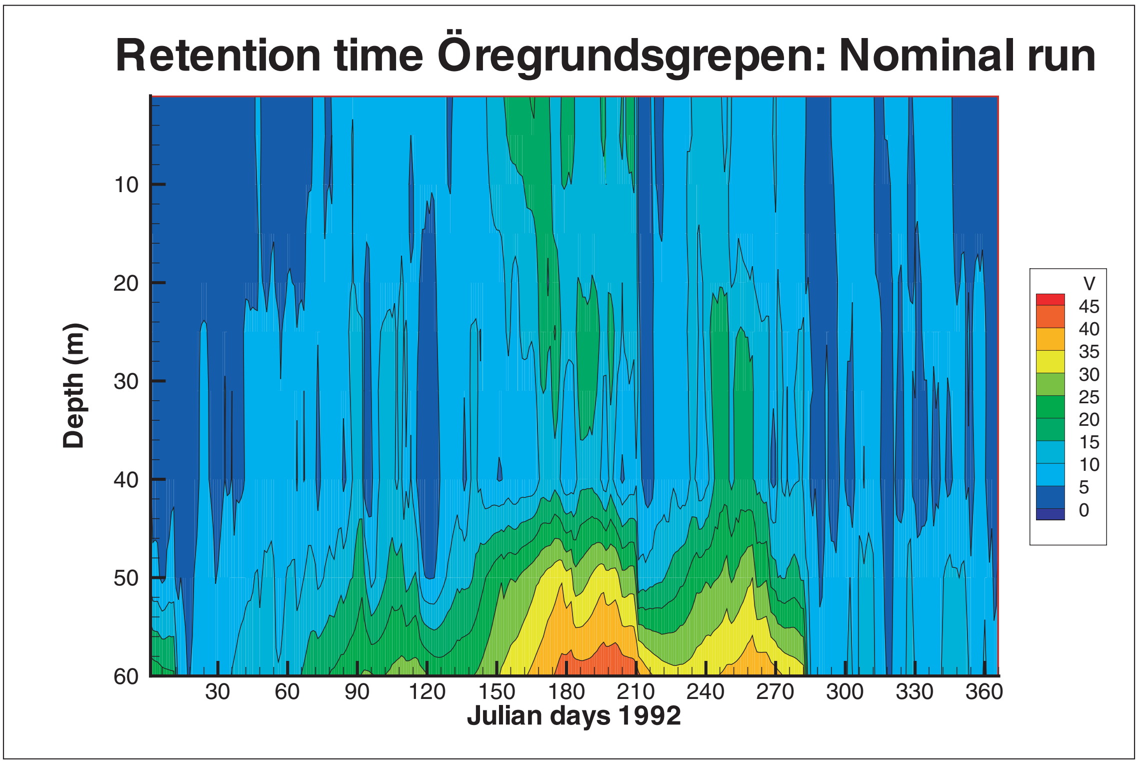

Figure 4-1a. *Contour plot of ÖG area with the **nominal** parameter set-up. The legend indicates retention time in (day/m³).*

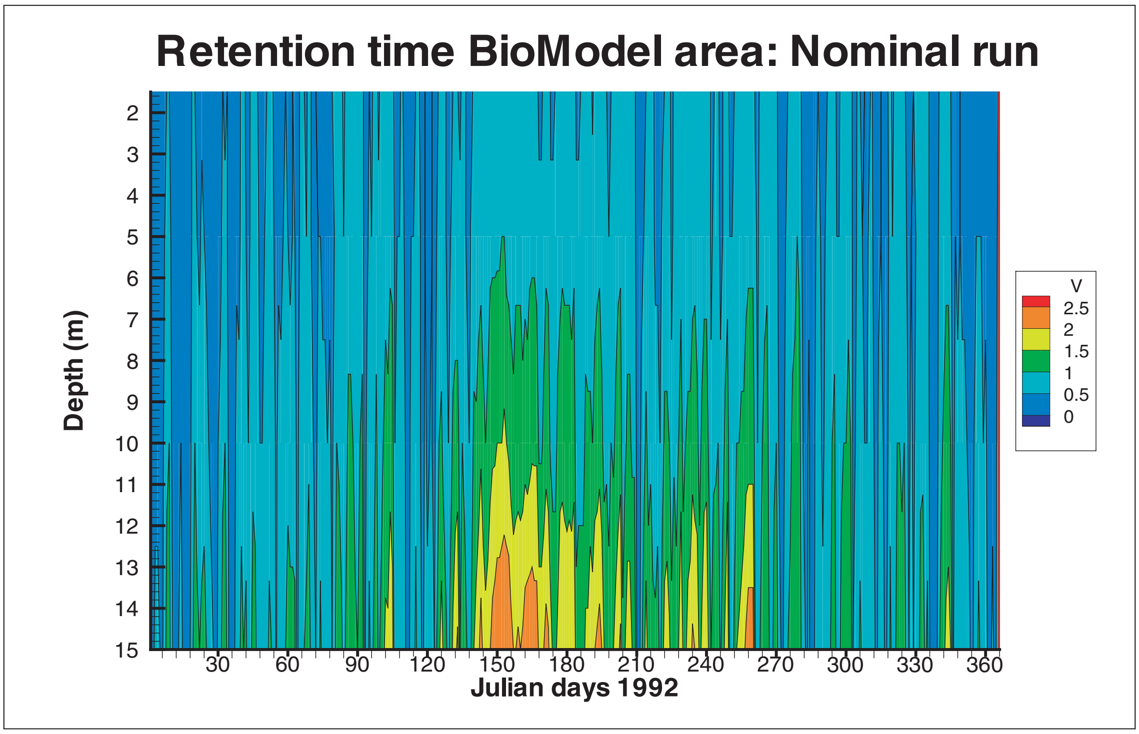

Figure 4-1b. *Contour plot of BM area with the **nominal** parameter set-up. The legend indicates retention time in (day/m³).*

For both Öregrundsgrepen and the BioModel area it is clearly seen from Figures 4-1a and 4-1b that the episodic fluctuations dominate the water renewal. During the summer months, the intensified stratification retains water in the bottom layers. This process is temporarily interrupted during the storm event in July.

Another way of displaying the same data is by depicting the (average) retention time for each layer. When the variational simulations deviate only slightly from the nominal run, this method is preferred over the contouring presentations. The nominal run for each of the layers will then be consistently depicted in **yellow colour** when displayed together with the other simulations for comparison. This reference nominal simulation will thus run like "a red thread", (however, in yellow colour) throughout these comparative presentations, all with a daily temporal resolution.

4.2 Temperature variations

The results of the **low temperature** atmospheric forcing are presented in Table 4-2 for each of the ten layers for the ÖG area and four for the BM area. It is obvious that the deviations compared to the nominal run are minor – on the order of hours – for the ÖG area and yet an order of magnitude lower for the BM area. The most notable effect reflected in the yearly average of the ÖG area is a general increase of the retention time for all layers. The only exception is for the bottom-most layer, that from the beginning of the accounting period has a considerably lowered relative retention time. Decreased retention times occur for the months when the atmospheric heat exchange is intense.

Since these simulations also involve the Baltic model, there are several effects that must be invoked to explain these results in more detail. The first is that decreasing surface temperatures lead to shallower positioned and weaker thermoclines both in the Baltic and in the coastal embayments as well, acting to diminish the thermal component of the baroclinically driven exchange. Denser water in the top layers would also be less susceptible to wind-induced slushing, which could explain the noted increase in retention time. For the shallower BM area the same mechanisms apply even though the resulting differences in retention times are even smaller.

Table 4-2. The monthly averages of *differential* retention time (days) relative to the nominal run for low temperature atmospheric forcing with regard to depth.

	ÖG Depth (m)										BM Depth (m)			
Month	**1**	**5**	**10**	**15**	**20**	**25**	**31**	**40**	**50**	**60**	**1**	**5**	**10**	**15**
1	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.01	-5.46	0.000	0.000	-0.001	0.000
2	0.51	0.48	0.38	0.24	0.11	0.15	0.25	0.44	0.66	0.31	0.022	0.027	0.047	0.083
3	0.09	0.07	0.04	0.04	0.05	0.04	0.02	-0.03	-0.08	1.97	0.001	0.001	-0.001	-0.011
4	0.11	0.12	0.11	0.10	0.08	0.05	0.01	-0.04	-0.07	0.08	0.001	0.001	0.001	-0.001
5	-0.06	-0.06	-0.04	-0.02	-0.01	-0.02	0.02	0.06	-0.03	-0.03	0.001	-0.001	-0.001	-0.004
6	0.02	0.10	0.41	0.76	0.91	1.25	1.17	0.95	0.27	0.09	-0.004	-0.002	0.016	0.049
7	0.35	0.43	0.66	0.98	1.25	1.84	1.84	1.51	1.52	0.97	-0.004	-0.002	0.019	0.040
8	-0.24	-0.24	-0.19	-0.08	0.04	0.26	0.47	0.68	0.58	0.92	-0.001	-0.002	-0.002	-0.015
9	0.05	0.05	0.01	-0.05	-0.10	-0.18	-0.23	-0.32	-1.42	-0.43	0.003	0.002	-0.009	-0.052
10	0.12	0.12	0.13	0.14	0.16	0.18	0.14	0.09	0.18	-0.76	0.000	0.001	0.005	0.012
11	-0.03	-0.04	-0.03	-0.03	-0.03	-0.03	-0.01	0.01	0.07	0.12	-0.001	-0.001	0.002	0.004
12	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.01	0.01	0.05	0.13	0.000	-0.001	0.002	0.005
Avg.	**0.08**	**0.09**	**0.12**	**0.17**	**0.20**	**0.30**	**0.31**	**0.28**	**0.15**	**-0.17**	**0.002**	**0.002**	**0.007**	**0.009**

For the case with **high temperature** atmospheric forcing, the yearly averages of the retention times are decreased (see Table 4-3), again except for the bottom-most layer of the ÖG area. That the ice-covered period in the beginning of the year is reduced in duration is evident, but still the insulation capacity of the ice cover reveals itself as preserving *status quo* in the retention times. Possibly the most direct way to explain both the results of this present and the previous case is by invoking the mechanism that Söderqvist /1997/ stressed. The heating/cooling of the shallower areas produces local thermally driven estuarine type of circulation. With elevated atmospheric temperatures this intensifies the ventilation of the coastal embayments which will thus act to reduce the retention time.

The daily variations for each layer compared to the nominal run can be seen in Figures 4-2a and 4-2b. The dynamics of the bottom layers are for reasons cited clearly the most visible.

Table 4-3. The monthly averages of *differential* retention time (days) relative to the nominal run for high temperature atmospheric forcing with regard to depth.

	ÖG Depth (m)										BM Depth (m)			
Month	**1**	**5**	**10**	**15**	**20**	**25**	**31**	**40**	**50**	**60**	**1**	**5**	**10**	**15**
1	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.01	0.10	6.36	0.000	0.000	0.002	0.004
2	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	-0.01	0.53	0.000	0.000	0.000	0.001
3	-0.01	-0.02	-0.01	0.00	0.00	0.01	0.02	0.05	0.17	0.20	0.000	-0.001	0.003	0.006
4	-0.12	-0.12	-0.12	-0.11	-0.11	-0.12	-0.09	-0.06	-0.09	0.02	0.000	0.000	-0.001	0.002
5	0.05	0.03	0.02	0.00	0.00	0.00	-0.02	-0.07	-0.01	-0.01	0.000	0.000	-0.003	-0.003
6	-0.11	-0.18	-0.44	-0.64	-0.67	-0.81	-0.68	-0.49	-0.17	-0.15	0.001	0.002	-0.014	-0.037
7	-0.46	-0.53	-0.70	-0.91	-1.04	-1.32	-1.24	-0.93	-0.82	-0.50	0.003	0.001	-0.014	-0.032
8	0.18	0.18	0.13	0.02	-0.10	-0.29	-0.45	-0.60	-0.81	-0.76	0.001	0.001	-0.002	0.001
9	-0.09	-0.08	-0.06	-0.03	-0.01	0.02	0.01	0.07	1.11	0.07	-0.003	-0.001	0.008	0.042
10	-0.12	-0.12	-0.13	-0.14	-0.15	-0.17	-0.14	-0.09	-0.12	0.46	-0.001	-0.001	-0.004	-0.010
11	-0.12	-0.13	-0.12	-0.10	-0.02	0.07	0.11	0.15	-0.02	-0.08	0.002	0.002	-0.001	-0.004
12	-0.06	-0.06	-0.05	-0.05	-0.02	0.00	0.01	0.02	-0.06	-0.08	-0.001	-0.001	-0.002	-0.004
Avg.	**-0.07**	**-0.09**	**-0.12**	**-0.16**	**-0.18**	**-0.22**	**-0.21**	**-0.16**	**-0.06**	**0.51**	**0.000**	**0.000**	**-0.002**	**-0.003**

4.3 Freshwater discharge variations

The local freshwater discharge rate, given with monthly resolution /Engqvist and Andrejev, 1999/, was first halved and then doubled. The effects of these variations according to Tables 4-4 and 4-5 are small to the point of being barely noticeable for the BM area in the yearly average. The overall effect is consistent with what may be expected when considering the estuarine component of the circulation. Moreover these two tables express their positive and negative signs mainly in a complementary pattern. For month and depths with positive retention times (relative to the nominal run) in one table, the other table shows the opposite sign. This is a strong indication of the main effect being directly caused by the estuarine circulation mechanism.

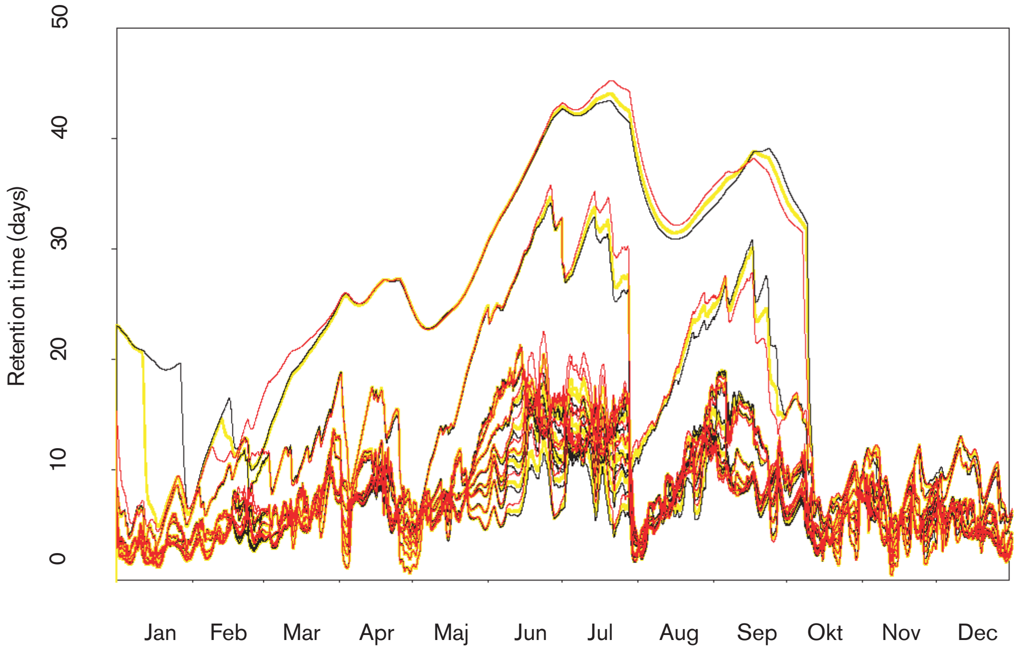

Figure 4-2a. *Retention time for the ten layers of the ÖG area with daily resolution. The colours denote:* ***Low temperature*** *(red),* ***high temperature*** *(black) and for comparison the* ***nominal run*** *(yellow). The last line is also drawn coarser.*

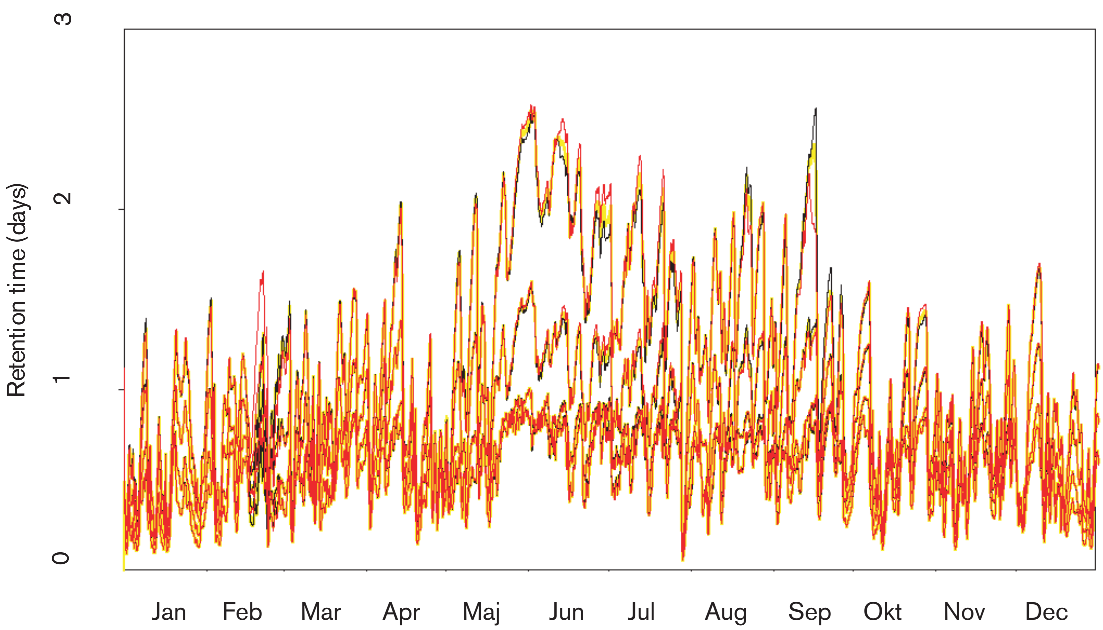

Figure 4-2b. *Retention time for the four layers of the BM area with daily resolution. The colours denote:* ***Low temperature*** *(red),* ***high temperature*** *(black) and for comparison the* ***nominal run*** *(yellow). The last line is also drawn coarser.*

Table 4-4. The monthly averages of *differential* retention time (days) relative to the nominal run for low freshwater discharge forcing with regard to depth.

	ÖG Depth (m)										BM Depth (m)			
Month	**1**	**5**	**10**	**15**	**20**	**25**	**31**	**40**	**50**	**60**	**1**	**5**	**10**	**15**
1	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.02	-0.03	0.000	0.000	0.000	0.000
2	0.00	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.01	0.00	-0.16	0.000	-0.001	0.000	0.001
3	-0.02	-0.03	-0.02	-0.01	0.00	0.03	0.06	0.09	0.07	0.02	-0.001	-0.001	0.000	0.001
4	-0.12	-0.12	-0.10	-0.09	-0.09	-0.06	-0.01	0.07	0.10	0.10	-0.001	-0.001	-0.001	0.002
5	0.05	0.05	0.09	0.12	0.12	0.17	0.20	0.22	0.18	0.11	0.000	-0.001	0.003	0.008
6	0.39	0.43	0.51	0.58	0.60	0.73	0.62	0.46	1.06	0.72	0.000	0.000	0.004	0.011
7	0.14	0.15	0.17	0.17	0.19	0.26	0.22	0.13	0.52	0.77	-0.001	0.000	0.001	0.001
8	-0.01	-0.01	0.00	0.01	0.01	0.04	0.05	0.07	0.12	0.25	0.000	-0.001	-0.001	-0.001
9	-0.06	-0.06	-0.06	-0.07	-0.07	-0.08	-0.07	-0.03	0.01	0.07	-0.001	-0.001	-0.001	-0.002
10	-0.02	-0.02	-0.02	-0.02	-0.01	0.00	0.01	0.03	0.04	0.02	-0.001	0.000	0.000	0.001
11	0.00	-0.01	0.00	0.01	0.02	0.03	0.03	0.04	0.06	0.06	0.000	-0.001	0.001	0.000
12	0.04	0.04	0.04	0.04	0.06	0.09	0.09	0.08	0.01	0.01	0.000	0.000	0.002	0.003
Avg.	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.10**	**0.10**	**0.10**	**0.18**	**0.16**	**0.000**	**-0.001**	**0.001**	**0.002**

Table 4-5. The monthly averages of *differential* retention time (days) relative to the nominal run for high freshwater discharge forcing with regard to depth.

	ÖG Depth (m)										BM Depth (m)			
Month	**1**	**5**	**10**	**15**	**20**	**25**	**31**	**40**	**50**	**60**	**1**	**5**	**10**	**15**
1	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	-0.01	-0.09	0.000	0.000	-0.001	0.000
2	0.02	0.02	0.03	0.02	0.03	0.04	0.03	0.01	0.01	0.13	0.000	0.000	0.000	0.001
3	0.03	0.03	0.03	0.01	0.00	-0.08	-0.13	-0.18	-0.16	-0.16	0.003	0.002	-0.001	-0.002
4	0.13	0.15	0.13	0.10	0.06	-0.08	-0.22	-0.39	-0.50	-0.36	0.002	0.002	-0.002	0.008
5	-0.16	-0.16	-0.21	-0.26	-0.29	-0.41	-0.40	-0.39	-0.42	-0.40	0.111	0.113	0.263	0.591
6	-0.70	-0.73	-0.83	-0.89	-0.90	-1.05	-0.88	-0.60	-1.60	-1.18	0.116	0.139	0.194	0.500
7	-0.30	-0.31	-0.33	-0.35	-0.39	-0.47	-0.40	-0.24	-0.91	-1.23	-0.110	-0.124	-0.255	-0.536
8	0.03	0.03	0.04	0.03	0.02	-0.01	-0.04	-0.07	-0.18	-0.39	-0.005	-0.021	0.006	-0.024
9	0.09	0.10	0.10	0.09	0.11	0.12	0.08	0.02	-0.05	-0.12	-0.033	-0.011	-0.044	-0.184
10	0.05	0.05	0.05	0.03	0.03	0.02	0.00	-0.03	-0.06	-0.03	-0.045	-0.053	-0.151	-0.377
11	0.00	0.00	0.00	-0.01	-0.02	-0.05	-0.06	-0.08	-0.13	-0.09	-0.037	-0.072	-0.101	-0.114
12	-0.08	-0.08	-0.07	-0.09	-0.10	-0.12	-0.11	-0.09	-0.27	-0.26	-0.104	-0.089	-0.062	-0.053
Avg.	**-0.07**	**-0.07**	**-0.09**	**-0.11**	**-0.12**	**-0.17**	**-0.18**	**-0.17**	**-0.36**	**-0.35**	**-0.009**	**-0.010**	**-0.013**	**-0.016**

Examining the results in more temporal detail, one notes that for the spring months with intensified run-off, it would have been expected that the increased freshwater flow would manifest itself as an imminently increased estuarine circulation and would thus yield a lowered retention time. However, this is evidently not the case, either for the entire ÖG area, or for the BM area. Again the effect is most evident in the ÖG area bottom layers (see Figure 4-3a), but is also unexpected since one would presume that the altered freshwater admission would in the first place affect the surface layers. An explanation may start from taking into consideration the uneven discharge distribution over the year. It is

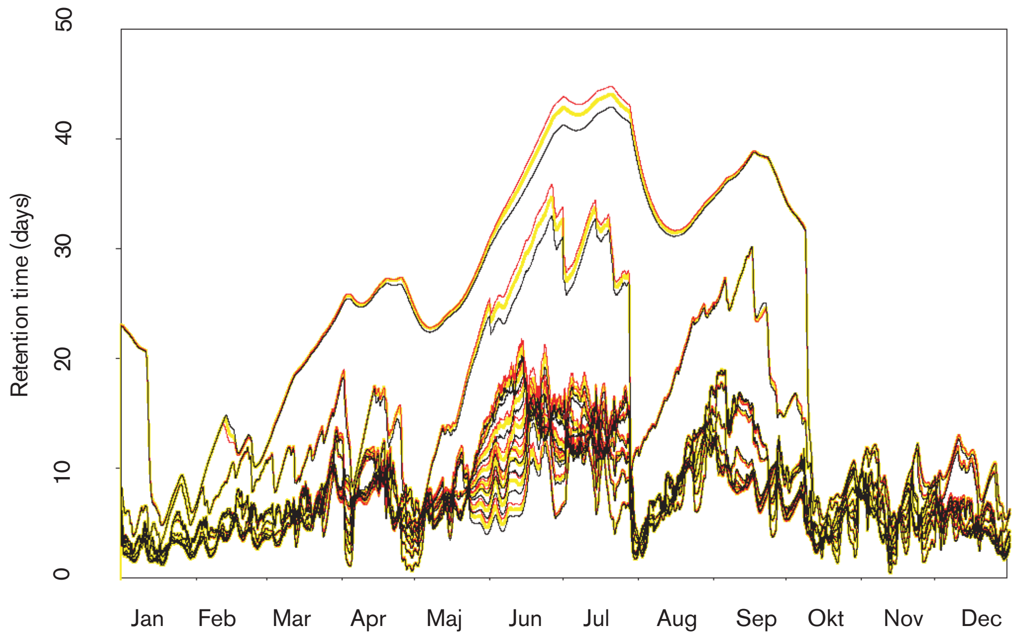

Figure 4-3a. *Retention time for the ten layers of the ÖG area. The colours denote:* ***Low freshwater discharge*** *(red),* ***high freshwater discharge*** *(black) and for comparison* ***the nominal run*** *(yellow). The last line is also drawn coarser.*

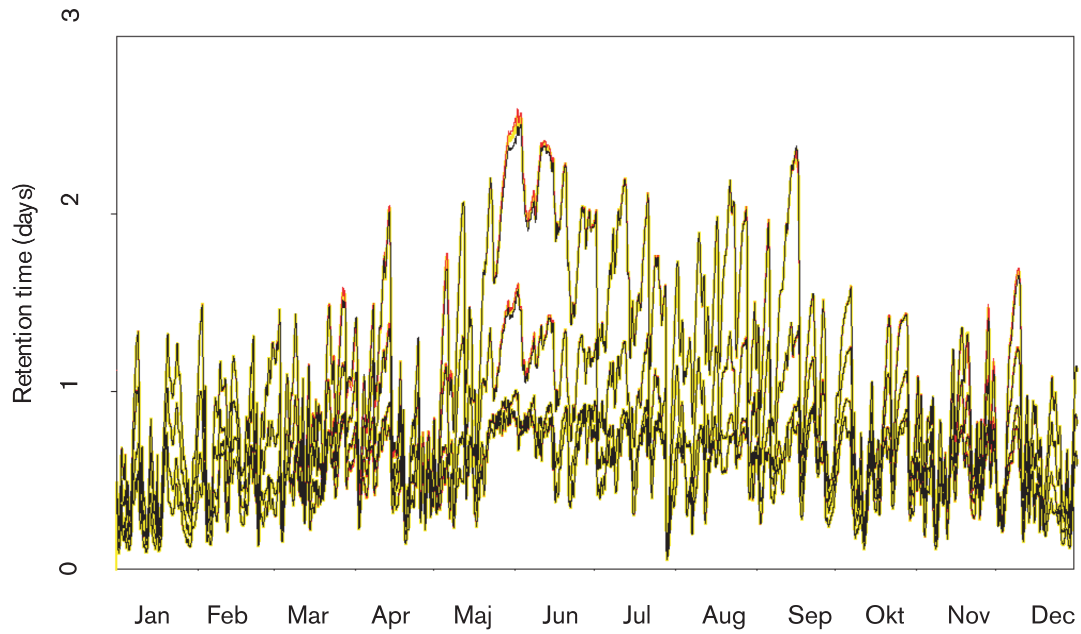

Figure 4-3b. *Retention time for the four layers of the BM area. The colours denote:* ***Low freshwater discharge*** *(red),* ***high freshwater discharge*** *(black) and for comparison the* ***nominal run*** *(yellow). The last line is also drawn coarser.*

plausible that during the summer stagnation period, the retention time increases and becomes of the order of one month. The slow but existing vertical mixing would lower the density of the bottom layers, making those in turn more susceptible to subsequent events of baroclinically induced intermediary exchange. For the shallower BM area (Figure 4-3b) it seems that for the first half year with a positive heat balance, more intense freshwater discharge means that the stratification effect dominates. This increases the retention time, while for the last (cooling) half year the penetrative convection effects dominate, increasing first the vertical and then the horizontal circulation.

4.4 Border salinity manipulations

The intended result of enhancing the fluctuations around the mean salinity of the border was to facilitate the induced baroclinical forcing thereby increasing the intermediary circulation /Stigebrandt and Aure, 1990/. For the manipulated border salinity data when the standard deviation was increased a factor two – giving a **high** (doubled) **salinity range** – the expected decreased retention time for the ÖG area also occurred for most of the months, see Table 4-6. The first two months and the autumnal months September and October are exceptional, however. As the mean average of all layers fluctuates throughout the year, an increase of the retention time would occur at times when the density rate of change at the border is marked. This is not the case for the exceptional months that are characterised by a stable stratification lasting in time. Moreover, the exchange due to the cooling process during the autumnal months acts against the baroclinical border forcing.

Table 4-6. The monthly averages of *differential* retention time (days) relative to the nominal run for high-salinity range fluctuation forcing with regard to depth.

	ÖG Depth (m)										BM Depth (m)			
Month	**1**	**5**	**10**	**15**	**20**	**25**	**31**	**40**	**50**	**60**	**1**	**5**	**10**	**15**
1	0.03	0.04	0.06	0.07	0.10	0.10	0.05	-0.04	0.05	-1.48	-0.002	-0.002	0.002	0.013
2	0.04	0.04	0.07	0.09	0.14	0.18	0.13	0.04	0.31	8.16	0.000	-0.001	0.000	0.022
3	-0.40	-0.43	-0.49	-0.54	-0.49	-0.44	-0.26	-0.03	-0.44	3.91	-0.003	-0.002	-0.003	-0.001
4	-1.15	-1.14	-1.08	-1.06	-1.19	-1.27	-0.98	-0.24	-0.83	-3.27	-0.010	-0.010	-0.003	0.058
5	-0.36	-0.45	-0.75	-0.96	-1.00	-0.84	-0.50	-0.14	-2.66	-1.51	0.008	0.004	-0.053	-0.122
6	-1.54	-1.63	-1.72	-1.10	0.19	2.34	2.85	2.52	-4.00	-4.20	0.001	-0.007	-0.008	-0.003
7	-3.04	-3.27	-3.54	-3.57	-3.65	-4.63	-4.45	-4.10	-15.16	-11.68	0.016	0.008	-0.052	-0.190
8	-0.56	-0.65	-0.97	-1.38	-1.60	-2.82	-3.40	-3.99	-10.49	-11.76	0.016	0.014	-0.038	-0.216
9	1.25	1.23	1.08	0.55	-0.30	-2.79	-4.93	-7.25	-11.00	-18.57	0.025	0.021	-0.006	-0.146
10	0.56	0.55	0.49	0.41	0.37	0.10	-0.39	-1.10	-1.16	-3.10	0.000	0.001	0.030	0.054
11	-0.11	-0.12	-0.08	-0.02	0.08	0.12	0.16	0.25	0.35	1.95	-0.001	-0.001	0.003	0.021
12	-0.27	-0.29	-0.30	-0.29	-0.22	-0.13	-0.02	0.08	-0.06	2.24	-0.010	-0.009	-0.001	0.021
Avg.	**-0.46**	**-0.51**	**-0.60**	**-0.65**	**-0.63**	**-0.84**	**-0.98**	**-1.17**	**-3.76**	**-3.28**	**0.003**	**0.001**	**-0.011**	**-0.041**

It is somewhat surprising that the complementary simulation with a **low** (halved) **salinity range** for most of the year the water turnover is almost exactly as intense the nominal run, see Table 4-7. An attempt to explain this would be that the border forcing consists of both a barotropic (sea level-related) part and a baroclinic (mainly determined by the salinity) part. These are not independent but linked as to meet the requirement of being geostrophically compatible. When the salinity range is increased, the two involved forces act together and thus the circulation is intensified; when lowered the barotropic part becomes dominant so that no or only minute changes occur. This result indicates that the methodology presented by Stigebrandt & Aure /1990/ cannot be applied to wide-entrance basins without due caution for these second-order effects.

These arguments also apply to the BM area retention times. For the two top layers the water exchange is essentially identical to the nominal run, while a relative decrease can be seen for the bottom layers some months. Reassuringly the average ventilation rates of all layers are greater for the high-salinity range case. See also Figures 4-4a and 4-4b.

Table 4-7. The monthly averages of *differential* retention time (days) relative to the nominal run for low range salinity fluctuation forcing with regard to depth.

	ÖG Depth (m)										BM Depth (m)			
Month	**1**	**5**	**10**	**15**	**20**	**25**	**31**	**40**	**50**	**60**	**1**	**5**	**10**	**15**
1	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.06	0.000	0.000	0.000	0.000
2	0.00	-0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.02	0.000	-0.001	0.000	0.001
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.000	0.000	0.000	0.000
4	0.00	0.00	0.00	0.00	-0.01	-0.03	-0.04	-0.06	-0.06	-0.03	0.000	0.000	0.000	0.002
5	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.01	-0.01	0.00	-0.02	0.000	0.000	-0.001	-0.001
6	0.00	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.00	-0.01	0.000	0.000	0.000	0.001
7	-0.02	-0.02	-0.02	-0.02	-0.02	0.00	0.00	0.00	-0.04	-0.02	-0.001	0.000	0.001	0.000
8	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	-0.01	0.00	0.000	0.000	-0.001	-0.002
9	-0.01	0.00	-0.01	-0.01	-0.01	0.00	-0.01	-0.01	-0.06	-0.03	-0.001	0.000	-0.001	-0.003
10	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	-0.02	-0.001	0.000	0.000	0.000
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.000	0.000	0.000	0.000
12	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.02	-0.09	-0.09	0.000	0.000	0.001	0.001
Avg.	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**-0.02**	**-0.01**	**0.000**	**0.000**	**0.000**	**0.000**

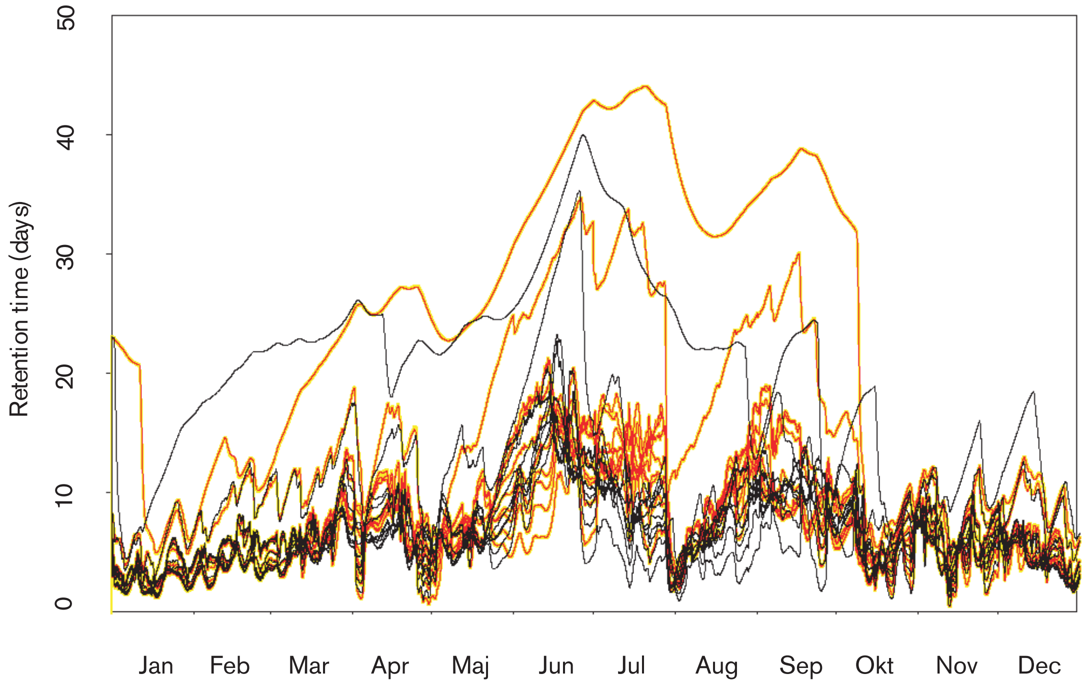

***Figure 4-4a.** Retention time for the ten layers of the ÖG area. The colours denote: **Low border salinity range** (red), **high border salinity range** (black) and for comparison the **nominal run** (yellow).*

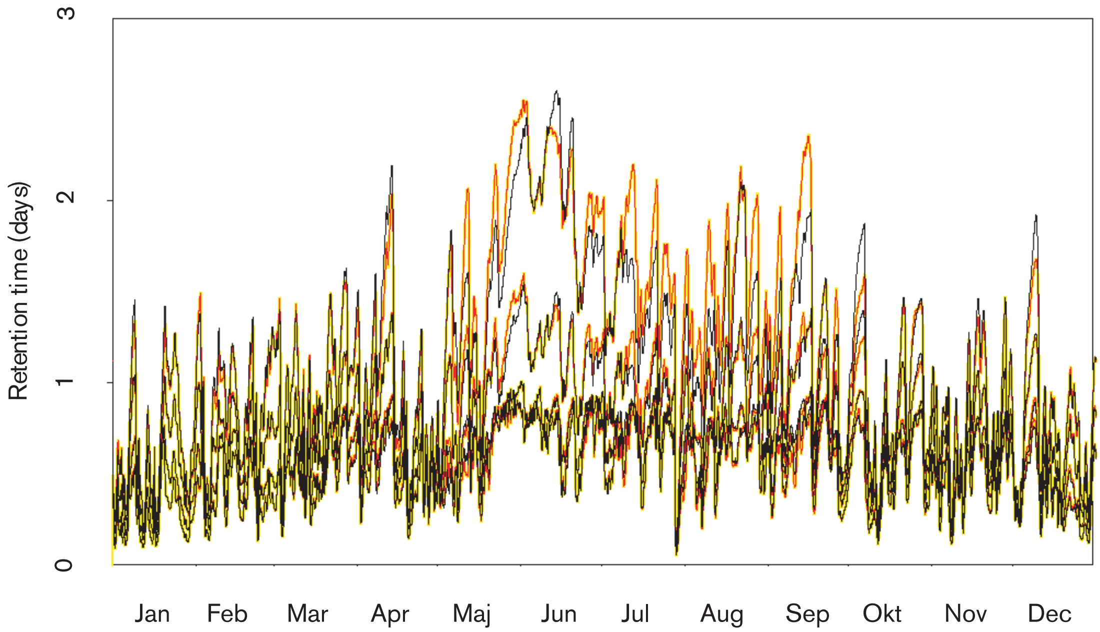

***Figure 4-4b.** Retention time for the four layers of the BM area. The colours denote: **Low border salinity range** (red), **high border salinity range** (black) and for comparison the **nominal run** (yellow). The last line is also drawn coarser.*

4.5 Wind speed reduction

The effect on the retention time when reducing the wind speed 10% – while maintaining its direction – can be seen in Table 4-8 and in Figures 4-5a and 4-5b. For both the ÖG and the BM areas the result is unanimous: for all layers and throughout the entire year, the retention time is increased. This is clear evidence of the dominant role the wind forcing plays. One part is the direct influence by friction stress exerted on the surface layer, the other part stems from the up-/downwelling brought about by the large-scale wind patterns over the near-coast Baltic. The reduced intensity of the ensuing intermediary exchange component is responsible for the noticeable increase in retention time for the bottom layers that would otherwise be out of reach from being influenced by the local wind.

Table 4-8. The monthly averages of *differential* retention time (days) relative to the nominal run for 10% reduced wind forcing with regard to depth.

	ÖG Depth (m)										BM Depth (m)			
Month	**1**	**5**	**10**	**15**	**20**	**25**	**31**	**40**	**50**	**60**	**1**	**5**	**10**	**15**
1	0.25	0.25	0.23	0.23	0.27	0.41	0.43	0.43	0.74	5.89	0.029	0.040	0.065	0.095
2	0.75	0.77	0.79	0.85	1.01	1.34	1.38	1.27	2.10	2.37	0.040	0.050	0.080	0.114
3	1.08	1.11	1.14	1.21	1.30	1.50	1.41	1.24	2.82	2.57	0.043	0.050	0.082	0.140
4	2.17	2.17	2.05	1.95	1.98	2.26	2.04	1.48	3.42	3.25	0.046	0.051	0.074	0.132
5	1.57	1.62	1.62	1.59	1.63	1.69	1.44	0.93	2.43	2.72	0.032	0.043	0.078	0.140
6	2.19	2.33	2.49	2.56	2.51	2.71	2.61	2.52	5.39	3.88	0.019	0.033	0.090	0.143
7	2.45	2.48	2.26	1.73	1.37	0.84	0.44	0.16	6.19	6.26	0.042	0.048	0.060	0.092
8	1.32	1.35	1.31	1.16	1.03	0.93	0.67	0.49	3.41	4.39	0.036	0.047	0.090	0.192
9	2.12	2.20	2.28	2.43	2.73	3.43	3.36	2.97	7.09	5.20	0.036	0.048	0.087	0.153
10	1.18	1.16	1.05	0.99	1.07	1.34	1.32	1.09	2.13	4.25	0.038	0.043	0.053	0.061
11	1.55	1.54	1.46	1.40	1.41	1.55	1.39	1.06	1.70	1.67	0.046	0.052	0.072	0.095
12	1.06	1.08	1.10	1.14	1.26	1.46	1.38	1.14	1.97	1.97	0.038	0.045	0.064	0.084
Avg.	**1.47**	**1.51**	**1.48**	**1.44**	**1.46**	**1.62**	**1.49**	**1.23**	**3.28**	**3.70**	**0.037**	**0.046**	**0.075**	**0.120**

For the BM area the same overall slowing of the water movements occurs. This retardation is more marked for the bottom layers, indicating that the dampened general circulation of the ÖG area is also reflected by a slower local baroclinic ventilation of the BM area.

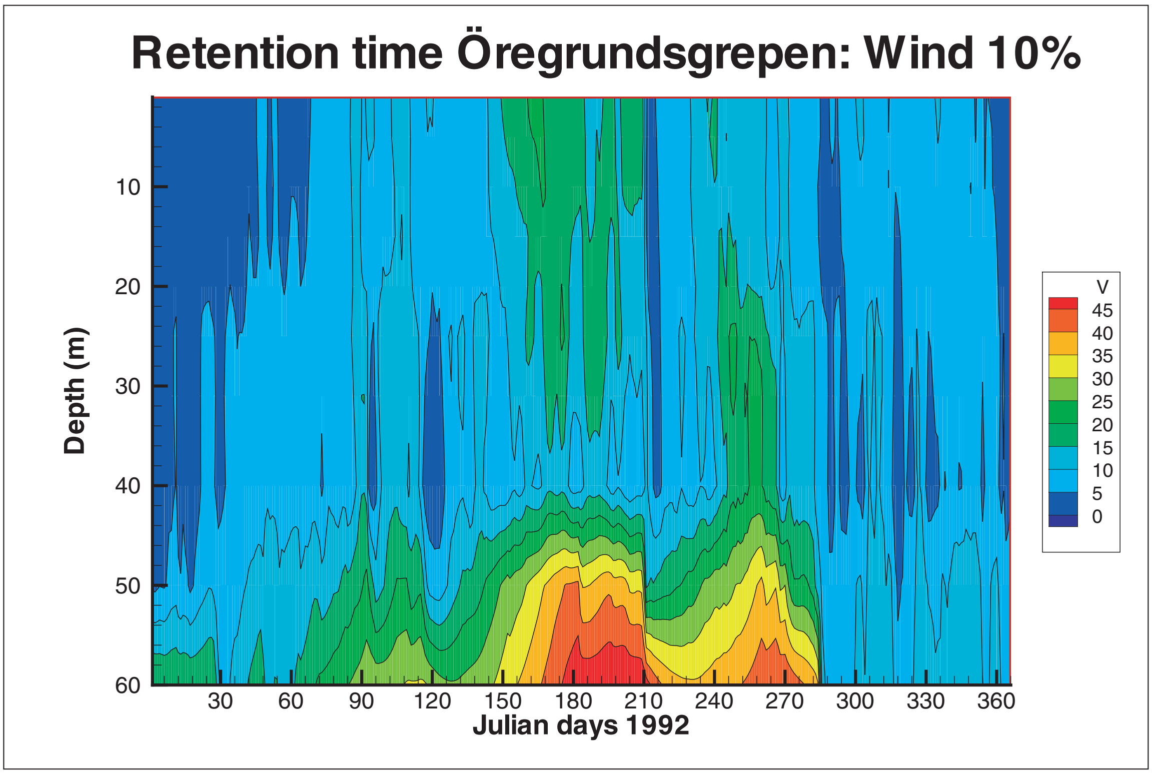

*Figure 4-5a. Contour plot of ÖG area with the **wind forcing reduced 10%**. In comparison to Figure 4-1a the general pattern remains mainly the same but the retention time is generally increased.*

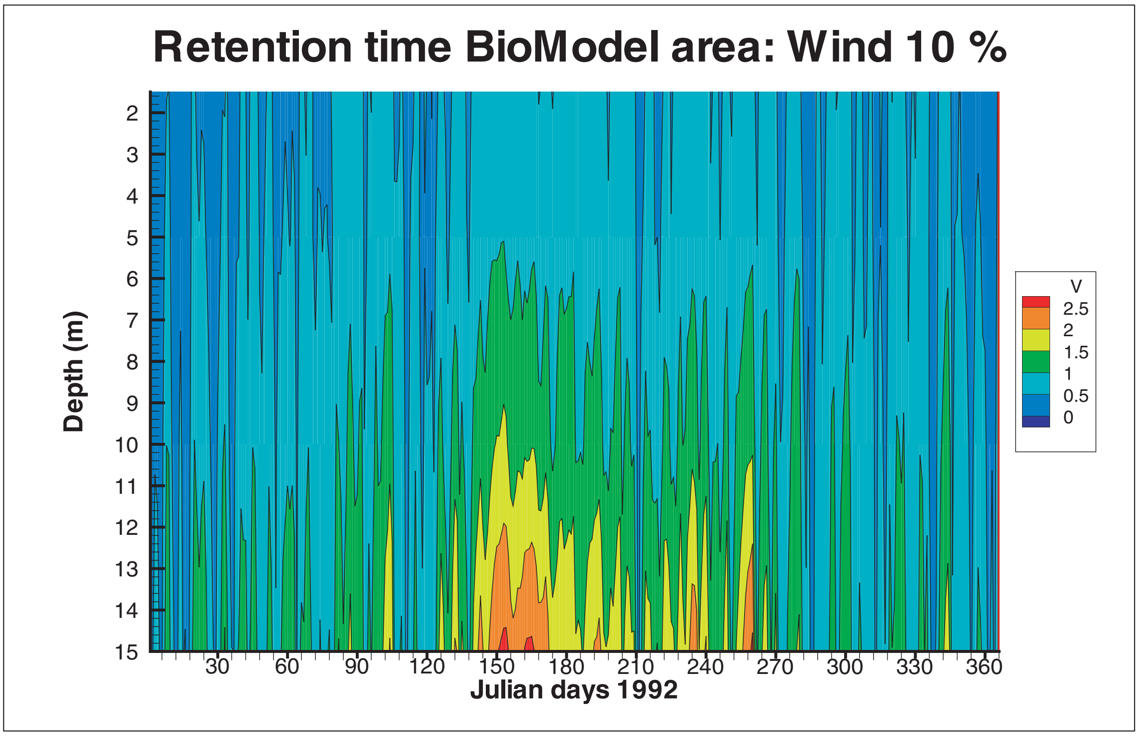

*Figure 4-5b. Contour plot of BM area with the **wind forcing reduced 10%**. The same observation as for the upper diagram applies.*

4.6 Permanent ice cover regime

The formation of a permanent ice cover situation is mimicked in the simulation by first reducing the wind speed 90% when the surface temperature reaches 0.2 °C and below. When the temperature is further lowered to 0.0 °C, the vertical heat exchange with the atmosphere is shut off. The surface temperature is thus kept at a temperature just above the freezing point for the time duration while the heat exchange with the atmosphere is negative. The neglected reduction of the freezing point temperature due to the salinity amounts only to a fraction of one °C and is deemed negligible in comparison to the crude model formulation of the ice formation process /e.g. Omstedt, 1998; 1999/. These measures effectively reduce two of the major processes that set water in motion. The result of wind speed reduction has been exposed in the previous section and the effect is now even more pronounced (Table 4-9).

The elimination of the heating and cooling surface processes has two direct consequences that reduce the circulation. First, the differential warming and cooling between the shallower and deeper areas are virtually eliminated. These processes drive the local thermically induced baroclinic horizontal currents /Söderqvist, 1997/, which in turn account for the increase in retention time relative to the nominal simulation during spring and autumn (Figures 4-6a and 4-6b). Second, the summer stagnation situation does not occur, and is manifested as a lowered retention time in comparison to the nominal run.

Table 4-9. The monthly averages of *differential* retention time (days) relative to the nominal run for 90% reduced wind forcing with regard to depth.

	ÖG Depth (m)										BM Depth (m)			
Month	**1**	**5**	**10**	**15**	**20**	**25**	**31**	**40**	**50**	**60**	**1**	**5**	**10**	**15**
1	13.21	13.74	13.48	12.59	11.22	12.93	14.17	15.14	20.52	15.34	0.507	0.605	1.098	1.486
2	12.23	12.91	13.20	12.97	11.44	12.36	13.43	14.40	20.24	19.55	0.360	0.465	0.968	1.516
3	10.49	11.10	11.28	11.00	9.23	10.08	11.73	13.46	25.43	20.02	0.263	0.404	0.926	1.415
4	7.87	8.34	8.77	9.16	7.72	8.52	10.19	12.57	37.68	28.69	0.268	0.394	0.995	2.173
5	4.98	5.06	4.22	4.39	4.42	6.06	7.92	10.44	32.19	37.18	0.168	0.280	0.704	1.596
6	-5.28	-5.22	-5.52	-4.50	-3.37	-0.81	2.30	6.16	-0.92	11.39	0.079	0.152	0.381	0.982
7	-0.91	-1.12	-2.17	-2.15	-2.14	-1.02	1.46	5.18	-2.93	-3.70	0.191	0.283	0.578	1.290
8	3.32	3.26	2.07	1.74	2.01	3.31	5.02	7.15	7.67	5.76	0.194	0.304	0.575	1.299
9	3.06	2.86	1.60	0.83	-0.06	-0.46	0.01	1.64	3.12	2.88	0.230	0.316	0.619	1.616
10	6.04	5.88	4.79	4.50	4.70	6.52	7.69	9.42	17.22	24.78	0.278	0.371	0.769	2.000
11	6.35	6.02	4.75	4.45	4.95	7.28	8.92	10.88	20.05	31.64	0.316	0.448	0.887	2.167
12	8.44	7.87	6.11	5.37	5.54	8.03	9.70	11.53	21.01	32.51	0.422	0.541	0.979	2.268
Avg.	**5.82**	**5.89**	**5.22**	**5.03**	**4.64**	**6.07**	**7.71**	**9.83**	**16.77**	**18.84**	**0.273**	**0.380**	**0.790**	**1.651**

The same reasoning applies to the BM area that adopts an even retention time all through the year with only minor fluctuations. The only remaining movement-inducing forces are the reduced local wind and the also much reduced densimetric fluctuations on the Baltic border driving a substantially weakened intermediary circulation.

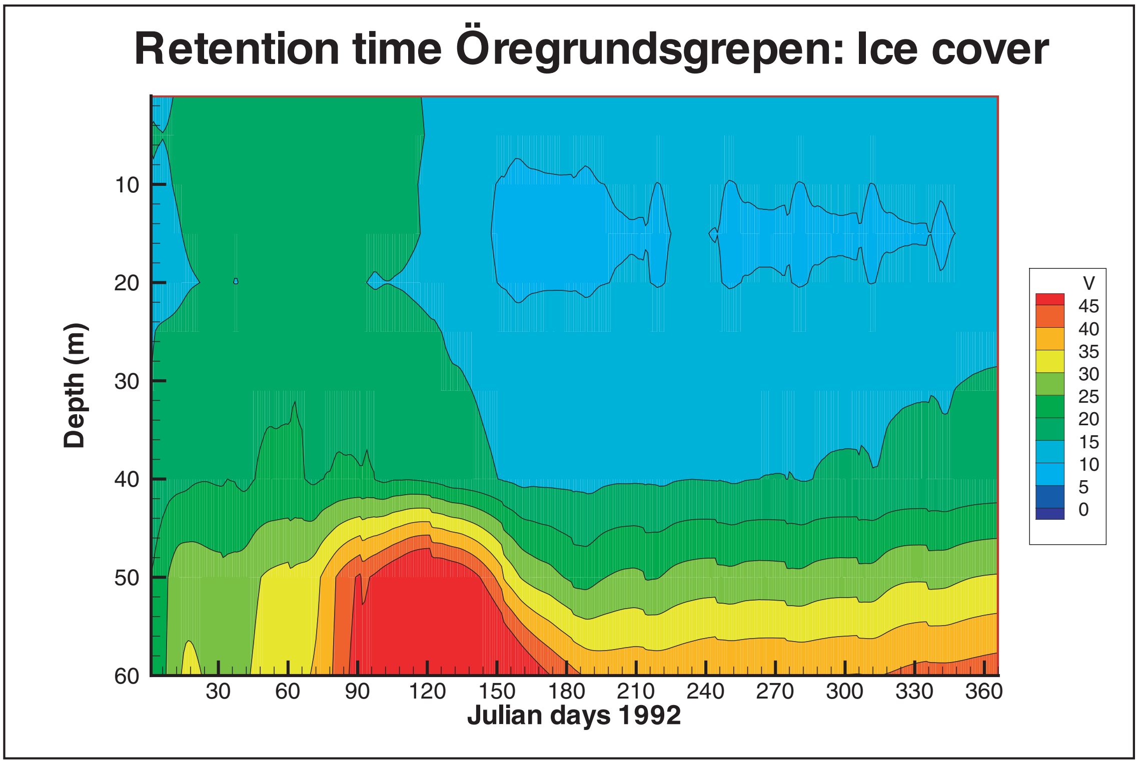

Figure 4-6a. *Contour plot of ÖG area in the* ***permanent ice cover regime****. The small reminiscent circulation is mainly caused by baroclinic effects.*

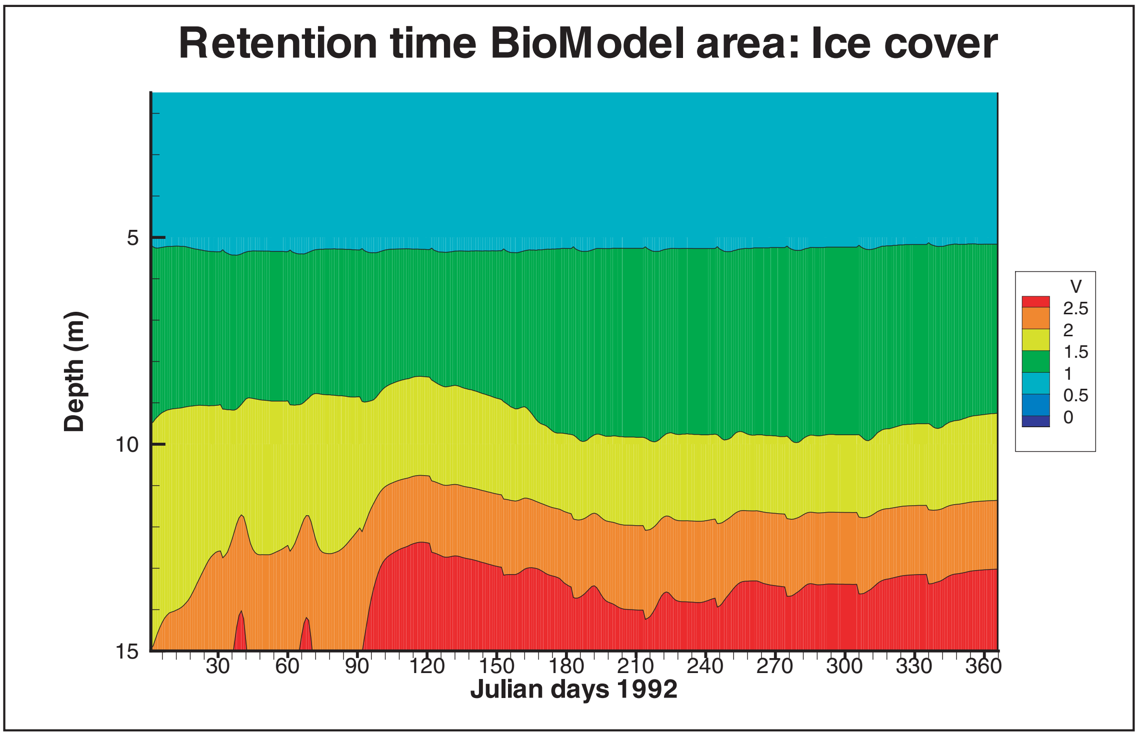

Figure 4-6b. *Contour plot of BM area in the* ***permanent ice cover regime****. The seasonal variations have all but ceased.*

In Figure 4-6b the numeric effect of the lost derivative information at the shift from one month to the next can also be seen. In spite of strictly maintained continuity of the state variables (salinity, temperature, velocity components), the momentary losses of the derivatives are seen at small jumps. The equilibrium is however soon attained so no attempts to make the transitions smoother are required.

4.7 Future land rise regime 4000 AD

The final simulation was run with the nominal parameters but with a Baltic and an ÖG area hypsography that has been modified according to the anticipated shoreline displacement /Påsse, 1997/. In absence of more suitable available data, the future hypsography of the Baltic was reconstructed by first identifying three suitable localities for which the shore line had been estimated for the year 4000 AD. The choice fell on Oskarshamn, Östhammar and Ångermanland. The coordinates of these places were identified in the Baltic grid (Figure 1-1) . Together with the future shore level displacements (3.2 m, 11 m and 17 m respectively), this gives a linear equation system representing the plane in the Baltic model coordinate system that will become an equipotential surface in 2000 years (Figure 3-1). The analogous change for the ÖG area is simpler, since it only amounts to lowering the mean surface sea level 11 m from its present level. An overview of the area in the year 4000 AD is given in Figure 2-2 and the corresponding grid in Figure 3-2. The resulting retention times are presented in Table 4-10, in which the number of layers is now reduced by two due to the 11-m depth reduction.

Table 4-10. The monthly averages of *differential* retention time (days) relative to the nominal run for land rise regime with regard to depth. Two layers have disappeared in the process.

	ÖG Depth (m)										BM Depth (m)			
Month	**1**	**5**	**10**	**15**	**20**	**25**	**31**	**40**	**50**	**60**	**1**	**5**	**10**	**15**
1	1.46	1.10	1.16	1.37	0.62	-0.74	-0.42	1.56			4.176	1.928		
2	2.19	1.70	1.84	2.18	1.12	-0.97	-0.42	2.55			5.956	2.263		
3	2.94	2.22	1.87	2.19	0.71	-1.97	-0.59	3.71			7.551	2.310		
4	2.90	2.12	1.93	2.36	0.62	-2.57	-1.22	4.28			9.272	2.392		
5	3.82	2.74	1.88	2.15	0.60	-1.67	0.78	6.78			10.751	2.530		
6	2.59	1.03	0.29	0.95	-1.28	-4.50	2.06	17.76			12.448	2.506		
7	2.29	0.63	-0.32	-0.52	-3.32	-7.71	-4.40	6.41			13.995	2.437		
8	4.77	3.29	2.25	2.08	-0.29	-4.11	-2.15	3.05			15.507	2.262		
9	5.22	3.58	2.93	2.43	-1.11	-7.24	-6.65	-2.09			17.176	2.374		
10	3.13	1.84	1.75	2.16	0.82	-1.73	-0.65	2.88			18.664	2.162		
11	3.58	2.17	1.85	2.33	1.12	-1.07	0.40	4.54			20.181	2.217		
12	4.29	2.80	2.59	3.01	1.63	-0.43	0.79	4.88			21.537	2.075		
Avg.	**3.27**	**2.10**	**1.67**	**1.89**	**0.10**	**-2.89**	**-1.04**	**4.69**			**13.101**	**2.288**		

The corresponding contour plot in Figure 4-7a gives a more detailed picture of the temporal variation, but in Figure 4-7b the contour legend has fallen far out of scale. Since the exchange of the narrow and elongated entrance to the BM area in the future will mainly be determined by the baroclinc processes, the renewal of the bottom water is considerably faster than for the more voluminous surface layers. In Figure 4-8a one sees

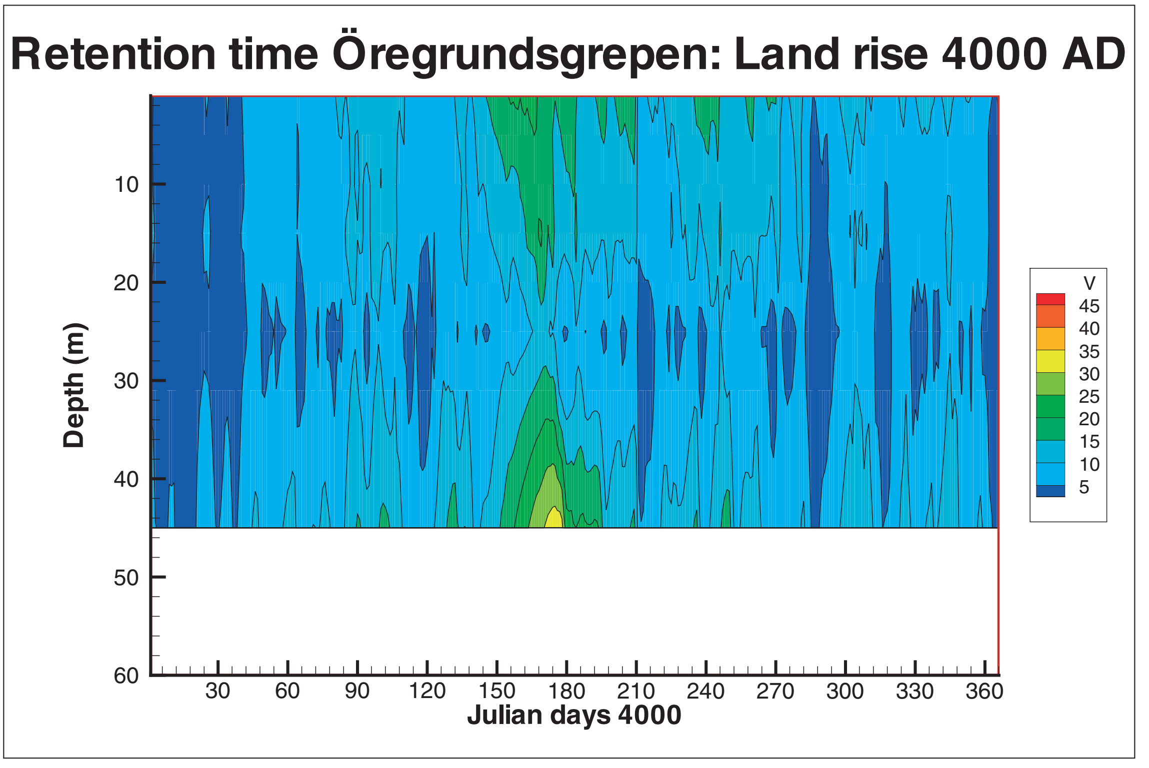

Figure 4-7a. Contour plot of ÖG area in the future ***land rise regime****. A conspicuous vertical symmetry occurs around the intermediary level where a newly formed sill occurs.*

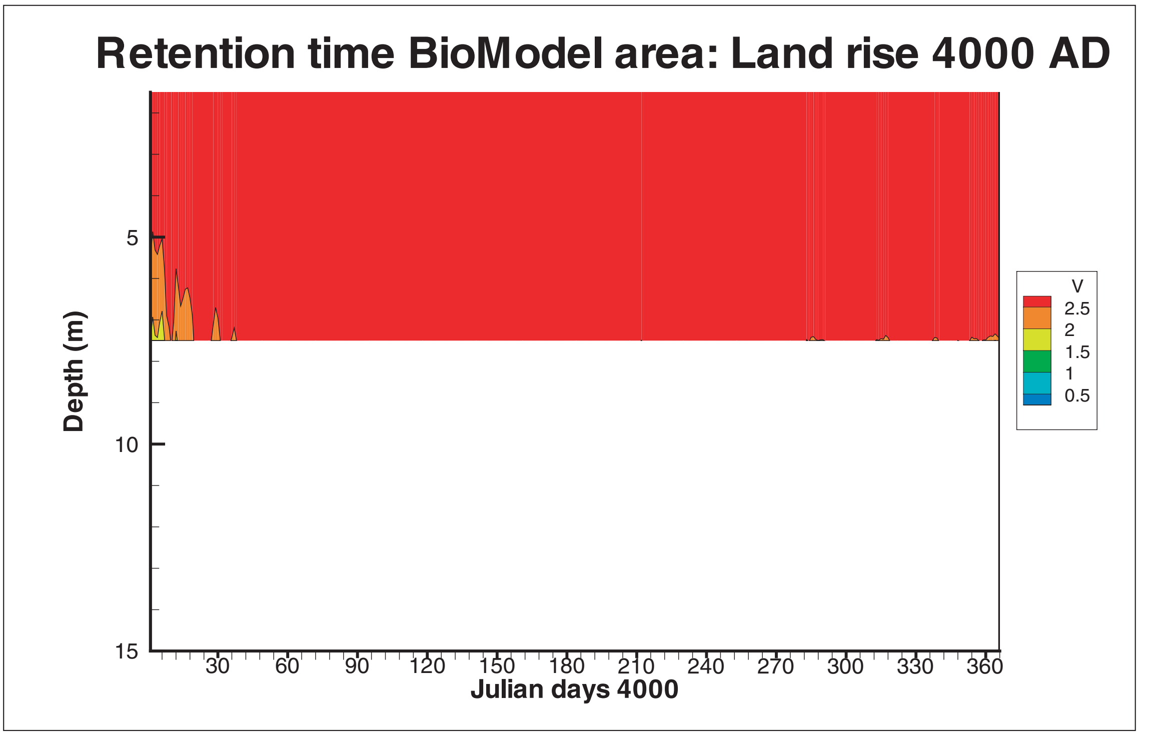

Figure 4-7b. Contour plot of BM area in the future ***land rise regime****. Except for only a small section at the beginning of the simulation, the maximum contour levels are not exceeded.*

that for the ÖG area, the retention time of the bottom layers never attains the levels of their counterparts of the nominal run. As for the BM area the rejuvenation takes place on an intermediary level which is a certain indication that the intermediary circulation is the dominant process. In Figure 4-8b with a ten-fold increase in the range of the vertical axis, it is indicated that the top layer in the model (lower curve in the diagram), attains a quasi-equilibrium just below 3 days. The lower layer (top curve) does not reach steady-state, but continues increasing its retention time for the duration of the simulated year. A slight tendency to level out can possibly be noted, but the yearly averages must be treated accordingly to allow for this. At the very least one could double the annual average value for the BM top layer in Table 4-10, and still have a conservative estimate.

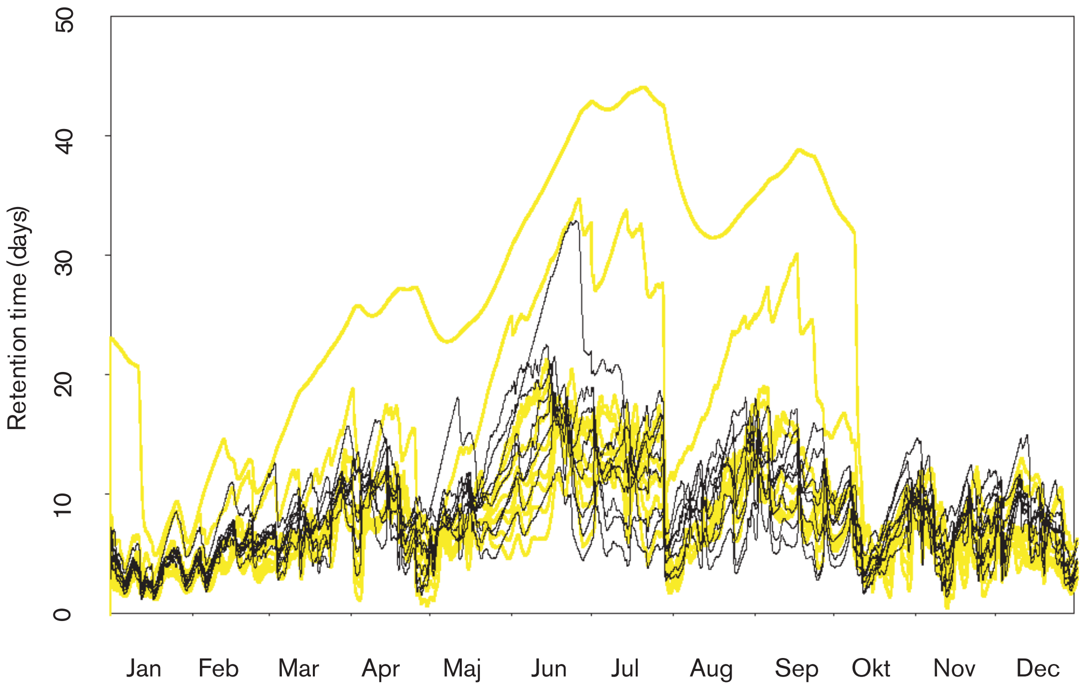

Figure 4-8a. *Retention time for the ten layers of the ÖG area. The colours denote:* ***Land rise regime*** *(black) and for comparison the* ***nominal run*** *(yellow). The deepest two layers (upper two curves) of the nominal run are depicted with broken lines to indicate that these layers will have disappeared in the year 4000 AD.*

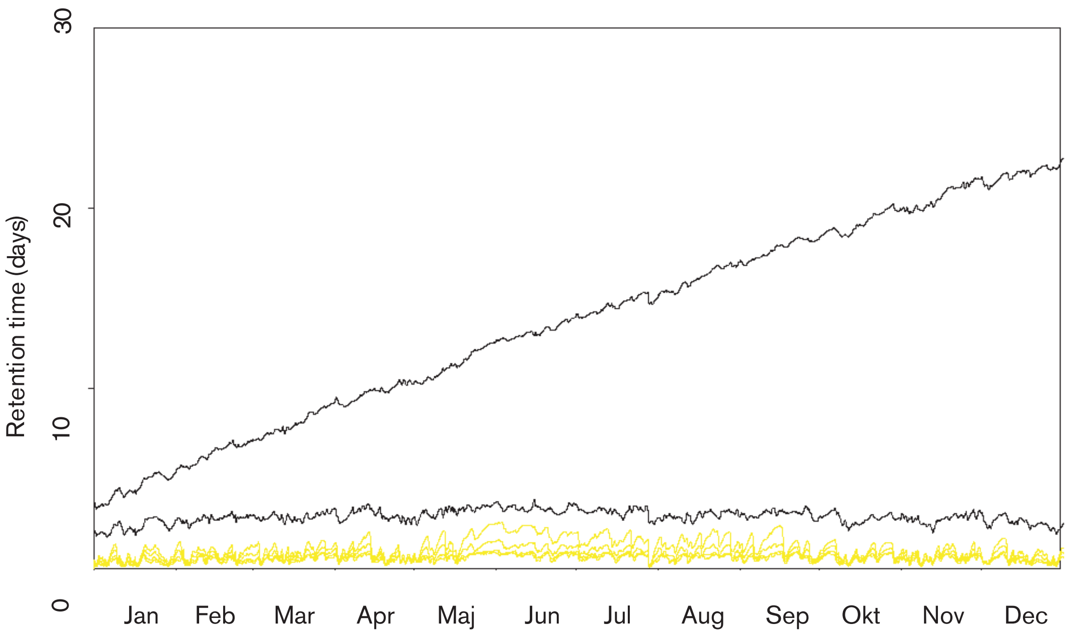

Figure 4-8b. *Retention time for the ten layers of the BM area. The colours denote:* ***Land rise regime*** *(black) and for comparison the* ***nominal run*** *(yellow). The lower curve corresponds to the bottom layer. The top curve that corresponds to the bottom layer has evidently not attained a steady-state during the simulated year but indicates a tendency to level off.*

5 Discussion

5.1 Overview of the simulations

An overview of the different simulations is presented in Table 5-1, in which the yearly averages are juxtaposed and their relative importance is also computed in order to facilitate comparison. Even though the imposed forcing changes concerning the atmospheric temperature, the freshwater flow and the salinity variation are to be considered substantial, their effect on the turnover time is generally mild, of the order of a few percent. With the possible exception of the case when the salinity range was lowered, their general influence on the circulation can be readily explained by invoking standard coastal oceanographic theory.

5.2 Comments on the regime-type simulations

The wind forcing expresses itself by raising the retention time an order of magnitude even when the reduction is merely 10%. The wind action may be subdivided into three categories. The first is the influence by the remote large-scale wind field over the Baltic, which enters the ÖG-model solely through the border forcing. The second and third wind actions are the friction drag on the surface layers and the contribution to the vertical mixing which is proportional to the wind speed cubed. This means that the applied 10% reduction results in an approximately 30% reduction in wind mixing intensity. If time had allowed, it could have been possible to investigate the difference between the local and remote wind influence by running simulations where reduced local and intact remote winds were combined.

The land rise regime was aimed at anticipating the hypsography that will arise in the year 4000 AD. With the same forcing set-up as for the nominal run, one would expect, at least for the BM area, a considerable increase of the retention time. This increase would occur because the section area available for ventilation is reduced at the same time as the degrees of freedom for the water movement is reduced. In the 2000 YAP future it will consist of mainly one appendix-like bay arm that opens in the north direction. Any other unanticipated surprises could be handled by a spin-up period of more than one year in order to achieve a steady-state prior to the year cycle simulation.

For the entire ÖG area one would also have guessed that an increase of the retention time would result, which reassuringly is the result of the simulation, except for two layers next to the bottom that have become the main route for bottom water renewal. The entire set of corresponding layers of the nominal run with which the comparison is made were above this level, explaining the marked dip in the relative retention time in Table 5-1 for both the 25-m and the 31-m (midpoint) layers.

All ten of these simulations have been run with identical time steps and internal parameters, e.g. those that determine the heat exchange, the turbulent mixing properties, etc. Of course, no sensitivity analysis is complete without such an analysis. To achieve this for simulations spanning a complete year cycle is, however, as great a computational undertaking as the present analysis and consequently the prospect for accomplishing this must be dampened.

Table 5-1. Absolute and relative deviation compared to the nominal run for the ÖG and the BM areas. Positive changes have been marked with in bold type. For the BM area the volume averages have also been computed. The only value that is knowingly misrepresentative of a quasi steady-state equilibrium is the top layer of the BM area for the land rise case.

	ÖG depth (m)										BM depth (m)				
	1	5	10	15	20	25	31	40	50	60	1	5	10	15	Vol. Avg.
Abs. deviation (days)															
Temp Low	**0.08**	**0.09**	**0.12**	**0.17**	**0.20**	**0.30**	**0.31**	**0.28**	**0.15**	-0.17	**0.002**	**0.002**	**0.007**	**0.009**	**0.004**
Temp High	-0.07	-0.09	-0.12	-0.16	-0.18	-0.22	-0.21	-0.16	-0.06	**0.51**	0.000	0.000	-0.002	-0.003	-0.001
Qf Low	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.10**	**0.10**	**0.10**	**0.18**	**0.16**	**0.000**	-0.001	**0.001**	**0.002**	0.000
Qf High	-0.07	-0.07	-0.09	-0.11	-0.12	-0.17	-0.18	-0.17	-0.36	-0.35	-0.009	-0.010	-0.013	-0.016	-0.011
Salt Low	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.02	-0.01	0.000	0.000	0.000	0.000	0.000
Salt High	-0.46	-0.51	-0.60	-0.65	-0.63	-0.84	-0.98	-1.17	-3.76	-3.28	**0.003**	**0.001**	-0.011	-0.041	-0.006
Wind 10%	**1.47**	**1.51**	**1.48**	**1.44**	**1.46**	**1.62**	**1.49**	**1.23**	**3.28**	**3.70**	**0.037**	**0.046**	**0.075**	**0.120**	**0.059**
Ice cover regime	**5.82**	**5.89**	**5.22**	**5.03**	**4.64**	**6.07**	**7.71**	**9.83**	**16.77**	**18.84**	**0.273**	**0.380**	**0.790**	**1.651**	**0.596**
Land rise regime	**3.27**	**2.10**	**1.67**	**1.89**	**0.10**	-2.89	-1.04	**4.69**	–	–	**13.1**	**2.29**	–	–	**9.47**
Rel. deviation (%):															
Temp Low	**1**	**1**	**2**	**2**	**3**	**4**	**4**	**4**	**1**	-1	**0.3**	**0.3**	**0.8**	**0.8**	**0.6**
Temp High	-1	-1	-2	-2	-2	-3	-3	-2	0	**2**	0.0	0.0	-0.3	-0.2	-0.1
Qf Low	0	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	-0.1	-0.1	**0.1**	**0.2**	0.0
Qf High	-1	-1	-1	-2	-2	-2	-2	-2	-2	-2	-1.7	-1.6	-1.6	-1.4	-1.6
Salt Low	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
Salt High	-6	-7	-8	-9	-9	-10	-12	-17	-25	-14	**0.7**	**0.2**	-1.3	-3.5	-0.8
Wind 10%	**20**	**20**	**21**	**21**	**20**	**20**	**19**	**18**	**22**	**16**	**7.3**	**7.8**	**9.3**	**10.3**	**8.6**
Ice cover regime	**77**	**78**	**73**	**72**	**65**	**73**	**98**	**144**	**112**	**81**	**53.5**	**65.1**	**98.6**	**141.6**	**86.9**
Land rise regime	**43**	**28**	**23**	**27**	**1**	-35	-13	**69**	–	–	**2566**	**392**	–	–	**1836**

6 Conclusions

A series of whole-year simulations has been successfully performed. The major result is a quantitative appreciation of the sensitivity of the water turnover with regard to the physical forcing factors. With one possible exception (the case with reduced salinity range at the border) the results are consistent with coastal oceanographic principles.

For the BM area which comes in first focus, the ranking order of impact on the retention time is the following (the yearly average influence on the retention time is given within parentheses) :

1. Decreasing the local freshwater discharge 50% (0.01%)
2. Increasing the atmospheric temperature 2.5 °C (-0.1%)
3. Reducing the atmospheric temperature 2.5 °C (0.6%)
4. Increasing the salinity variation range 100% (-0.8%)
5. Increasing the local freshwater discharge 100% (-1.6%)
6. Decreasing the wind (local and large-scale) 10% (8.6%)

The case with the decreased border salinity variation is exempted from this list, simply because it produced only insignificant change. The corresponding ranking list for the entire ÖG area is mainly the same.

In addition to these simulations, two whole-year studies of regimes with more than one alteration of the forcing factors have been performed. The first was aimed at mimicking the resulting water circulation if a radical climatic change occurred that produced a permanent ice cover. In this case both the lowering of the atmospheric temperature and the reduction of wind speed act together to considerably increase the retention times. It does not seem possible to deduce from these simulations whether there would occur a synergistic effect between those two factors, i.e. that the combined alteration produces a greater influence than the sum of these two factors applied one at the time.

For the future land rise regime in the year 4000 AD, the increase of retention times, in particular for the BM area, is even more accentuated. It seems that for the progressively more and more shallow embayments, the phase immediately prior to being totally disconnected from contact with the coastal water, the baroclinic component becomes the dominating mode of exchange. This is most likely due to a two-fold causation: one is the intermediary circulation, the other the estuarine circulation. This latter mode becomes relatively more important as the buoyancy flux per unit area increases. The yearly average retention time is presently estimated to increase at least 36 times, making a generous allowance for the fact that steady-state conditions were not attained during the simulated full year period.

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8 References

Andersson J, Riggare P, Skagius K, 1998a. Project SAFE – Update of the SFR-1 safety assessment Phase 1. SKB R-98-43, Swedish Nuclear Fuel and Waste Management.

Andersson J, Riggare P, Skagius K, 1998b. Project SAFE – Update of the SFR-1 safety assessment Phase 1 Appendices. SKB R-98-44, Swedish Nuclear Fuel and Waste Management.

Andrejev O, Sokolov A, 1989. Numerical modelling of the water dynamics and passive pollutant transport in the Neva inlet. Meteorologia i Hydrologia, 12, 78–85, (in Russian).

Andrejev O, Sokolov A, 1990. 3D baroclinic hydrodynamic model and its applications to Skagerrak circulation modelling. 17th Conf. of the Baltic Oceanographers, Proc., 38–46, 23, 280–287.

Andrejev O, Sokolov A, 1997. The data assimilation system for data analysis in the Baltic Sea. System Ecology contributions No. 3. 66 pp.

Bolin B, Rodhe H, 1973. A note on the concepts of age distribution and transit term in natural reservoirs. Tellus, 25, 58–62.

Brunberg A K, Blomqvist P, 1999. Characteristics and ontogeny of oligotrophic hardwater lakes in the Forsmark area, central Sweden. SKB R-99-68, Swedish Nuclear Fuel and Waste Management.

Brunberg A K, Blomqvist P, 2000. Post-glacial, land rise-induced formation and development of lakes in the Forsmark area, central Sweden. SKB TR-00-02, Swedish Nuclear Fuel and Waste Management.

Brydsten L, 1999a. Shore level displacement in Öregrundsgrepen. SKB TR-99-16, Swedish Nuclear Fuel and Waste Management.

Brydsten L, 1999b. Change in coastal sedimentation conditions due to positive shore displacement in Öregrundsgrepen. SKB-TR-99-37, Swedish Nuclear Fuel and Waste Management.

Engqvist A, 1996. Long-term nutrient budgets in the eutrophication of Himmerfjärden estuary. Estuarine, Coastal & Shelf Science, 42, 483–507.

Engqvist A, 1999. Estimated retention times for a selection of coupled coastal embayments on the Swedish west, east and north coasts. Naturvårdsverket (Swedish EPA) report 4910. 22 pp.

Engqvist A, Andrejev O, 1999. Water exchange in Öregrundsgrepen – A baroclinic 3D-model study. SKB TR-99-11, Swedish Nuclear Fuel and Waste Management.

Gustafsson B, 1999. Time-dependent modelling of the Baltic entrance area. Part 1: Quantification of circulation and residence times in the Kattegat and the straits of the Baltic sill. Estuaries (under revision).

Jerling L, Schüldt R, Isaeus M, Lanneck J, in manus. The vegetation in the SFR-region: Yesterday-Today-Tomorrow.

Kautsky H, Plantman P, Borgiel M, 1999. Quantitative distribution of aquatic plant and animal communites in the Forsmark area. SKB R-99-69, Swedish Nuclear Fuel and Waste Management.

Kumblad L, 1999. A carbon budget for the aquatic ecosystem above SFR in Öregrundsgrepen. SKB R-99-40, Swedish Nuclear Fuel and Waste Management.

Kumblad L, in manus. Dynamic Carbon-14 Flow Models for the Aquatic Ecosystem Surrounding SFR, Öregrundsgrepen.

Mattson J, 1996. Analysis of the exchange of salt between the Baltic and the Kattegat through the Öresund using a three-layer model. J. Geophys. Res. 101:C7, 16571–16584.

Morén L, Påsse T, 1999. A Scandinavian climate scenario for the Weichsel and the next 150 000 years. SKB TR-99-XX in press, Swedish Nuclear Fuel and Waste Management.

Omstedt A, 1998. Freezing estuaries and semi-enclosed basins. Physics of ice-covered seas, **2**, 483–516.

Omstedt A, 1999. Forecasting ice on lakes, estuaries and shelf seas. In: J S Wettlaufer, J G Dash and N Untersteiner (Eds.) Ice physics and the natural environment, NATO ASI Ser., Vol. I 56. Springer-Verlag, Berlin. pp. 185–207.

Påsse T, 1997. A mathematical model of the past, present and future shore level displacement in Fennoscandia. SKB TR-97-28, Swedish Nuclear Fuel and Waste Management.

SKB, 1999. Deep repository for spent fuel SR 97 – Post closure safety. SKB TR-99-06, Swedish Nuclear Fuel and Waste Management.

Söderkvist J, 1997. Water exchange in a shallow bay. Dept. of Oceanography, Göteborg University. ISSN 1400–3821. 24 pp.

Stigebrandt A, 1990. On the response of the horizontal mean vertical density distribution in a fjord to low-frequency density fluctuations in the coastal water. Tellus, 42A, 605–614.

Stigebrandt A, Aure J, 1990. De ytre drivkrefternas betydning for vannutskiftningen i fjorderne fra Skagerrak til Finnmark. Rapport FO 9003, Havforskningsinstituttet, Nordnes (N). 24 pp.

Vedin H, 1995. Lufttemperatur. In: B Raab & H Vedin (Eds.) Sveriges Nationalatlas (in Swedish) Bra Böcker. Höganäs. p. 49.

Westman P, Gustafsson B, Wastegård S, Omstedt A, Schoning K, 1999. Salinity change in the Baltic Sea during the last 8500 years: Evidence, causes and models. SKB-TR-99-38, Swedish Nuclear Fuel and Waste Management.