Modelling of the circulation, water exchange and water age properties of the Gulf of Bothnia

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Abstract

To estimate the mean circulation, water exchange and water age in the Gulf of Bothnia a ten-year simulation using a three-dimensional numerical model was carried out. The results confirmed the early findings by Witting (1912) and Palmén (1930) that a mean cyclonic circulation takes place both in the Bothnian Sea and in the Bothnian Bay. However, the modelling results showed clearly that there exist meso-scale circulation features including coastal 'jets', not reported in the Witting-Palmén results. The simulated mean currents were also higher than those found earlier, while the persistency of this circulation is typically between 20 and 60%, which is similar to the earlier results. There is a large difference between the various model-based water-exchange estimates: these are strictly dependent on the time-averaging used. Water age proved to reflect properties of the mean circulation system, and the highest water age (of around 7.4 years) was found in the central part of the Bothnian Bay. The water age was found to be rather high also in the entire Gulf of Bothnia, which provides evidence of the rather slow water exchange between the Gulf and the Baltic Sea. This leads to the conclusion that, from the physical point of view, the Gulf of Bothnia is vulnerable to eutrophication.

1. Introduction

The present study is based on the use of a three-dimensional hydrodynamic OAAS model (Andrejev & Sokolov 1989, Andrejev et al. 2002, Myrberg & Andrejev 2003, Andrejev et al. 2004a,b) for the Baltic Sea. It was focused on the Gulf of Bothnia (GOB) for the period 1991–2000 to investigate key physical processes in this semi-enclosed sea-area (Fig. 1). The reasoning behind carrying out this study is that since the Finnish-Swedish Gulf of Bothnia Year 1991 (Perttilä & Ehlin, 1993), not many case studies have been devoted, using numerical modelling tools, to investigating the physics of GOB. Hence, some basic physical processes, like the mean circulation of the GOB, and also the water exchange between this basin and the Baltic Proper, still need further analysis with the currently available high-resolution three-dimensional models. Additionally, only few estimates of the retention time ('water age') of GOB waters are available; such estimates are certainly needed, not only out of theoretical considerations, but also for practical purposes. Our study concentrates on the GOB circulation systems during the above-mentioned period in 1991–2000, but decadal variations are not included in the simulations. Such very long term changes in Baltic Sea physics have been analysed e.g. by Meier & Kauker (2003) and by Meier (2005).

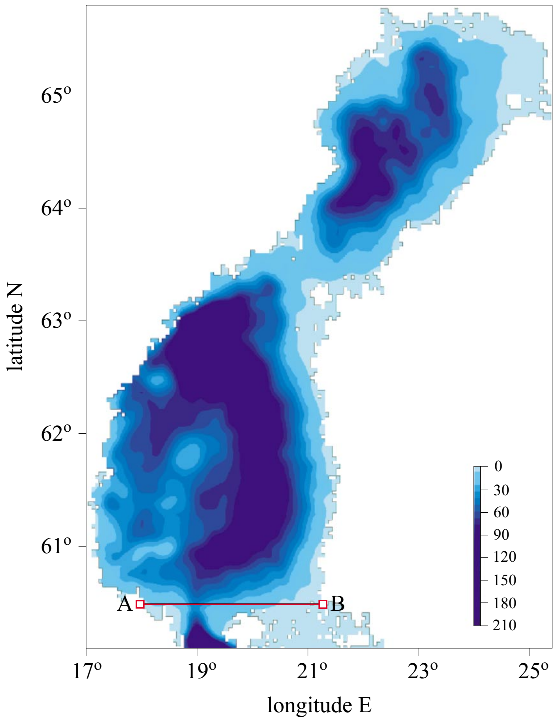

Fig. 1. The bottom topography of the Baltic Sea reproduced from Stigebrandt & Wulff (1987). The transect used in Fig. 8 (page 69) is marked by a red line

The Gulf of Bothnia is the northernmost basin of the Baltic Sea. Connected with the Baltic Sea Proper via the Åland Sea on the Swedish side and via the Archipelago Sea on the Finnish side (see Håkansson et al. 1996), the Gulf of Bothnia is geographically divided into four sub-basins: the Bothnian Sea, the Bothnian Bay, the Åland Sea and the Archipelago Sea (Fig. 1). The Gulf of Bothnia covers 36% of the whole Baltic Sea and has a mean depth of 55 m; the greatest depths are located in the Bothnian Sea (Ulvö Deep 294 m), but the Bothnian Bay is shallower. The Northern Quark between the Bothnian Sea and the Bothnian Bay has a sill depth of 25 m, and the sill between the Bothnian and Åland Seas (max depth 301 m) is 70 m beneath the sea surface. The other connection between the Gulf of Bothnia and the Baltic Sea Proper passes through the Archipelago Sea, which is very shallow with a mean depth of only 19 m. The salinity in the open part of the Bothnian Sea is between 5 and 7 permilles, whereas in the Bothnian Bay salinities of 3–4 permilles are typical; near river mouths the salinity is close to zero. The density (salinity) has a two-layered structure in the Bothnian Sea, with a weak halocline at about 50–70 m; below that, the salinity increases linearly with depth. In the Bothnian Bay the halocline is even weaker, if it exists at all. The bottom waters of the Bothnian Sea are originally surface water masses of the Baltic Proper that advect to the GOB over the sill between these two basins. Wind-mixing and cooling are strongest in autumn and spring, during such periods when the upper layer or even the whole water mass inverts. During the summer, a seasonal thermocline develops with a typical depth of about 15 m. The Gulf of Bothnia receives about 200 km^3 yr^{-1} of fresh water from rivers (the whole Baltic about 445 km^3 yr^{-1}, see Fonselius 1996). The largest rivers are the River Kemijoki (18 km^3 yr^{-1}), the Tornionjoki (17 km^3 yr^{-1}) and he Luleåälv (16 km^3 yr^{-1}).

The long-term mean circulation of the Gulf Bothnia, as in the other main basins of the Baltic, is usually cyclonic. This knowledge is based on early studies by Witting (1910, 1912) and Palmén (1930), even though the circulation is weak and the persistency of the circulation system is not very high everywhere. This traditional concept was later supported by model studies (e.g. Myrberg 1991, Lehmann & Hinrichsen 2000a). The mean circulation, even if it is a statistical artifact not reflecting the true physical circulation, is usable for estimating e.g. the average distribution of pollutants or nutrients from point sources. Also, many practical activities like shipping and coastal constructions need practical information about the mean circulation and its persistency.

The experimental studies by Witting (1912) and Palmén (1930) and later by Sjöberg (ed.) (1992) showed that it is possible to discover the main features of the long-term circulation. However, there are still gaps in our understanding of the variability and structure of the mean GOB circulation pattern because the observational network, based on measurements carried out on light vessels, was coarse. Thus, high-resolution numerical model simulations in the area are needed (e.g. Lehmann & Hinrichsen 2000a,b) for a more detailed view. These modelling results showed that because of the weak baroclinicity in the GOB, the circulation is determined mainly by Ekman dynamics and modified by the Coriolis effect, bottom topography and coastline shape. However, in spring and early summer, wind forcing is weak, and the circulation in the Baltic is thus dominated by baroclinic effects, (Lehmann & Hinrichsen 2000a). However, these effects are not so pronounced in the GOB as, say, in the Gulf of Finland. To give an example of this: in some areas of the GOB (e.g. in Finngrundet) there exists a clear linear relation between wind and current speeds (Palmén 1930). We have focused our attention on the near-surface layers, because of their importance to ecosystem processes, and additionally, because Witting (1912) and Palmén (1930) only dealt with the uppermost layers.

Estimates of the water exchange between the GOB and the Baltic Sea have often been based on Knudsen-type (Knudsen 1900) budget estimations, which are no doubt useful as a first approximation. However, the results depend strongly on the calculation period and the data sets used. Only a few water exchange estimates based on three-dimensional modelling results, which somewhat better reflect the internal dynamics of the GOB, are at present available. We are therefore continuing our investigation of this very important problem here. Further information about GOB internal dynamics can be obtained by introducing an auxiliary variable denoted as 'water age', a concept originally suggested by Bolin & Rodhe (1973). The aim of our present work is to demonstrate how an analysis of this quantity can be used to estimate water residence time in a semi-enclosed basin like the GOB.

The structure of this paper is as follows. In the next section we briefly describe the three-dimensional model we have used here (Myrberg & Andrejev 2003, Andrejev et al. 2004a,b), and we also introduce the model simulations. In the third section we discuss the results with respect to mean circulation, water exchange and water age of the Gulf of Bothnia, and in the last section we summarise the main findings of the study.

2. Material and methods

The numerical model, developed by Andrejev & Sokolov (1989, 1990), is of the time-dependent, free-surface, baroclinic and three-dimensional type. However, in the present case we applied a barotropic variant of the model. In addition, we introduced a number of simplifications: the hydrostatic approximation, an incompressibility condition, a Laplacian closure hypothesis for sub-grid scale turbulent mixing, and the traditional f-plane approximation. Since the reader will find a detailed description of the model in e.g. Myrberg & Andrejev (2003) and Andrejev et al. (2002, 2004a,b), we shall only describe the model in brief.

2.1. Main parameters and assumptions

In order to apply the model, we need to specify a number of quantities (for details, see Andrejev et al. 2004a,b). The horizontal kinematic eddy diffusivity coefficient is set constant at 50 m^2 s^{-1} for the Baltic Sea. The vertical eddy diffusivity coefficient is taken to depend on the local velocity shear (Kochergin 1987). Wind stress is described by the well-known quadratic laws following Niiler & Kraus (1977), and the drag coefficient at the sea-surface was formulated according to Bunker (1976). A quadratic law was used for the bottom friction, where the drag coefficient was prescribed as 0.0026 (Proudman 1953).

2.2. Set-up of the numerical model experiments

A simulation period from January 1, 1991 to December 31, 2000 was investigated using the model, which was adjusted to the initial conditions by running it for the period June 1–December 31, 1990. The open boundary of the large-scale model domain is placed in the Kattegat along latitude 57°35′N. In order to properly prescribe the sea level in the Kattegat, we need to use observations from both ends of the open boundary, namely, one observational point on the Swedish side and one on the Danish side. We used an active free radiation condition (Orlanski 1976, Mutzke 1998) for the Kattegat sea level and the respective sea-level measurements at Göteborg (Sweden) and Fredikshamn (Denmark) at 1 h intervals.

The horizontal resolution for the entire Baltic Sea model is 2 nautical miles in both horizontal directions. The model comprises 40 levels in the vertical with a layer thickness increasing monotonically towards the bottom (5 m intervals down to 152.5 m and below that 10 m intervals). The model run was initiated from a quiescent state.

We used meteorological data for the simulation period with a spatial resolution of 1 degree for the entire Baltic Sea area and with a temporal resolution of 3 hours. Since the wind velocities in the data set represent geostrophic values, they must be extrapolated to the sea-surface. A standard method for this correction is to multiply the wind speed by a factor of 0.6 and deflect the direction 15° counter-clockwise (Bo Gustafsson, personal communication). The mean monthly river discharges for 1970–1990 (Bergström & Carlsson 1994, Sokolov et al. 1997) were used. We took

29 rivers into account for the entire Baltic model. The runoffs of small rivers were added to discharges of the main rivers.

2.3. Calculation of persistency

Witting (1912) and Palmén (1930) defined the persistency R of a current as the ratio between its vector and scalar mean speeds:

$$R = \frac{\sqrt{\left(\frac{1}{N}\sum_n u_n\right)^2 + \left(\frac{1}{N}\sum_n v_n\right)^2}}{\frac{1}{N}\sum_n \sqrt{u_n^2 + v_n^2}} \times 100, \qquad (1)$$

where N is the number of observations (in our case model time steps), $n = 1 \ldots N$, and R is given as a percentage. Here u and v are the velocities along the eastward and northward x- and y-axes respectively. The persistency is essentially a measure of the variability of the current direction, thus it also serves as an indirect measure of the net transport. When the current is unidirectional in time, the persistency is 100%. The more variable the direction, the smaller the persistency (which, furthermore, assumes a value of zero when the net water transport reaches zero).

2.4. Calculation of water age

The concept of water age was originally introduced by Bolin & Rodhe (1973), since when a large number of investigations focusing on this topic have been published. Comprehensive reviews of these studies as well as the theory itself can be found in Delhez et al. (1999) and in Deleersnijder et al. (2001). The general theory of water age (Deleersnijder et al. 2001) regards seawater as a mixture of several constituents: pure water, dissolved salts, pollutants, plankton, etc. Following Delhez et al. (1999), the age of a 'particle' of a seawater constituent is considered to be 'the time that has elapsed since the particle under consideration left the region in which its age is prescribed as being zero'. Deleersnijder et al. (2001) apply the Eulerian age theory, in which advection, diffusion, production and destruction of seawater constituents are properly accounted for, and an equation is established for a concentration-distribution function (i.e. the dimensionless mass fraction at a given time and location), from which the equation for the age concentration can be derived. If we bear in mind that the major constituent of seawater is pure water, which is neither produced nor destroyed, we may then with a high degree of accuracy reduce the problem of seawater age to an advection-diffusion equation governing the evolution of the water-age concentration (Deleersnijder et al. 2001). This approximation was successfully used by e.g. Thiele & Sarmiento (1990), England (1995) and Engqvist (1996) to estimate ventilation timescales in various basins (see also Andrejev et al. 2004b).

Water age is governed by an advection-diffusion equation:

$$\frac{\partial A}{\partial t} + \frac{\partial uA}{\partial x} + \frac{\partial vA}{\partial y} + \frac{\partial wA}{\partial z} = \mu\,\Delta A + \frac{\partial}{\partial z}\left(\vartheta\frac{\partial A}{\partial z}\right) + F_A, \qquad (2)$$

where u, v and w are the velocities in the x-, y- and z-directions (the z-axis is assumed to point downwards) respectively; A is the water-age concentration; μ and ∂ are the horizontal and vertical kinematic eddy diffusivity coefficients respectively; Δ denotes the horizontal Laplacian operator; and F_A is a source term, equal to 1. The water age is thus controlled by the advection through the grid-cell walls and mixing. When this equation is solved numerically, initial as well as boundary conditions must be prescribed. As initial conditions we used $A = 0$ days. We set the same value at the open boundary with the Baltic proper (60°03′N) and at point freshwater sources at the solid boundaries. There, as well as at the free surface of the Gulf, we assumed no-flux conditions to hold.

3. Results

Our analysis of the model results focuses on three separate topics: first, we introduce the results relating to the mean circulation; then, we analyse the water exchange between the Baltic Proper and the Gulf of Bothnia; finally, we discuss the horizontal distribution of the water age.

3.1. Mean circulation and its persistency

The main forcing of the currents in the Gulf of Bothnia is due to wind stress; density-driven currents play a less important role in the overall circulation because of the rather gentle horizontal density gradients there as compared, for example, with the Gulf of Finland or the Danish Straits. The sea-surface slope resulting from the permanent water supply to the Gulf also contributes appreciably to the existing circulation. This is primarily geostrophic in character, since the Gulf of Bothnia is large enough to experience the effects of the earth's rotation (Witting 1912, Palmén 1930). Accordingly, by using those long-term current measurements (5 to 10 years), it is possible to determine the general mean circulation. The old measurements concentrated very much on the surface layer of the sea, and the traditional but idealised view is that the mean surface circulation is cyclonic with an average velocity of a few cm s^{-1}. Cyclonic circulation cells exist both in the Gulf of Bothnia and in the Bothnian Bay, with the Quark being a transitional area between these two basins. The modelled circulation and its persistency can be compared with the classical analyses of Witting and Palmén (which, however, must be regarded as educated guesses based on very sparse observational data sets).

Here, in the first of our articles on GOB physics, we investigate the barotropic aspect of sea dynamics, which plays a key role in GOB. In part, we have taken this approach in order to reduce the computing time needed to carry out simulations for the entire Baltic Sea with a high resolution for the rather long period of 1991–2000. We also omit ice modelling here, because we shall be examining its effect on the general circulation separately in a forthcoming paper.

The ten-year mean circulation in the uppermost layer of the model (0–2.5 m) is mainly Ekman-type drift (Fig. 2). The cyclonic cells are, however, visible in both the Bothnian Sea and in the Bothnian Bay, while the Quark is a transitional zone. In the northernmost Bothnian Bay there is a pronounced cyclonic cell, the appearance of which is linked to the bottom topography. At the open Gulf the currents are typically directed east-south-eastwards, in accordance with the prevailing westerly winds.

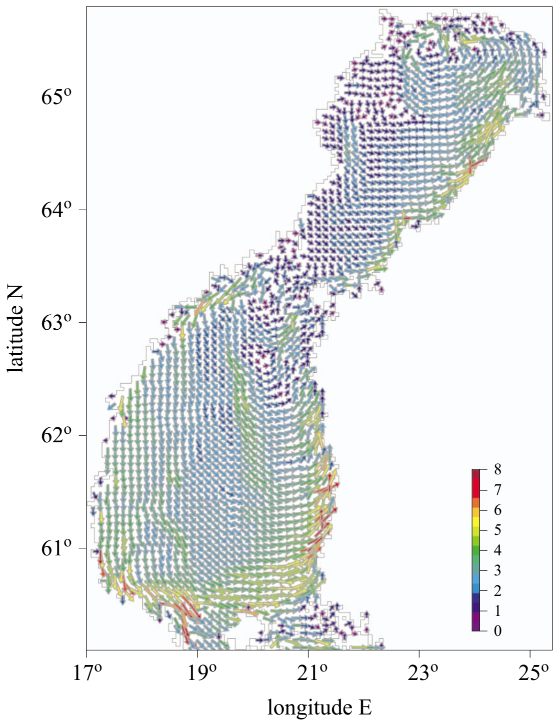

Fig. 2. The simulated mean surface layer circulation [cm s^{-1}] between 0 and 2.5 m during 1991–2000

Coastal currents – 'jets' – are discernible along the Finnish and the Swedish coasts. The current velocities near the coast are about $5 - 7$ cm s^{-1}, while in the open sea values of $2 - 4$ cm s^{-1} are typically obtained.

The sub-surface layer between 2.5 and 7.5 m is the one most easily compared to the Witting-Palmén observations (Fig. 3a), since it is located just below the most wind-affected surface layer but well above the average summer thermocline. The circulation here has the same overall structure as that found in the immediate surface layer but in this lower layer, the cyclonic circulation off the Finnish coasts is even more pronounced as compared with the open sea circulation. However, off the Swedish coast the situation is reversed and, according to the model, the circulation is less intense in the lower layer. Typical velocities in the 2–5–7.5 m layer in the open sea are about 1–2 cm s^{-1}, but nearer the coast they are between 4 and 6 cm s^{-1}. The overall structure of the flow field in the 2.5–7.5 m layer bears a close resemblance to those of Palmén and Witting (Fig. 3b), not only as regards the overall cyclonic circulation in the basins and the transitional Quark area, but also in terms of the quasi-permanent circulation patterns discernible in the Bothnian Bay and Sea. However, owing to the relatively high resolution of our simulation, even more details become apparent in relation to meso-scale eddies. According to Witting and Palmén, the current velocities were smaller than those produced by the model. Those authors stated mean velocities only of 0.5–2 cm s^{-1} and found no obvious coastal 'jets', very probably because of the very coarse observational network available at that time. The model results of Lehmann & Hinrichsen (2000a) reflect (not shown) the cyclonic circulation in the Bothnian Sea in the same way as in our model results and according to the Witting-Palmén results. However, in the Bothnian Bay the results of Lehmann & Hinrichsen (2000a), based on a four-year simulation with a 5 km horizontal resolution, yielded a less pronounced circulation than our results did – this might be because our simulations did not take ice cover into account, and so yielded faster mean currents. Other reasons behind the differences between these model results are the different horizontal resolutions and simulation periods used.

To obtain more information about the current system and its variability, we also investigated the persistency of the circulation. In spite of the rather high similarity between the mean circulation patterns in the two uppermost layers of the model, the corresponding persistencies proved to differ considerably from one another. In the uppermost layer (0–2.5 m), the persistency is highest near the Finnish coasts in general and in the southernmost part of the Bothnian Sea (Fig. 4). In those areas, maximum values of up to 30–40% were obtained, whereas average values in the open sea

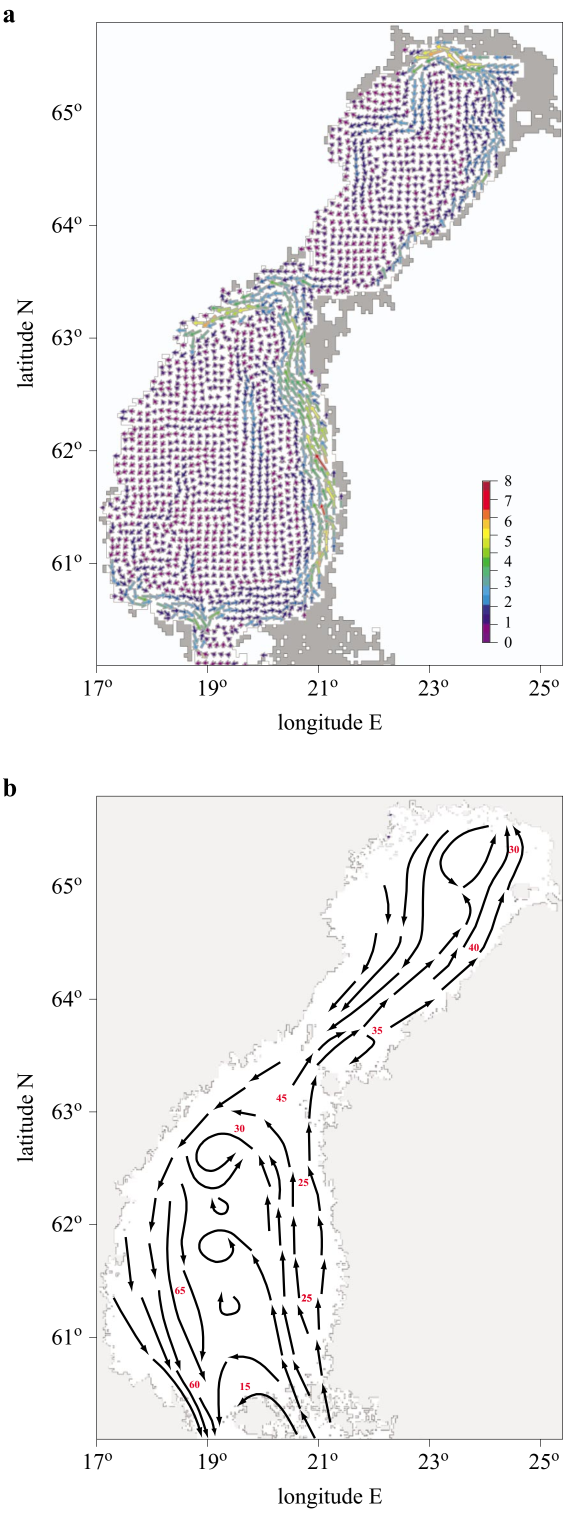

Fig. 3. The simulated mean circulation [cm s^{-1}] in the sub-surface layer between 2.5 and 7.5 m during 1991 –2000 (a). A schematic picture of the corresponding long-term mean circulation and its persistency for the uppermost layer (about 0 –20 m), based on the results from Witting (1936) (b)

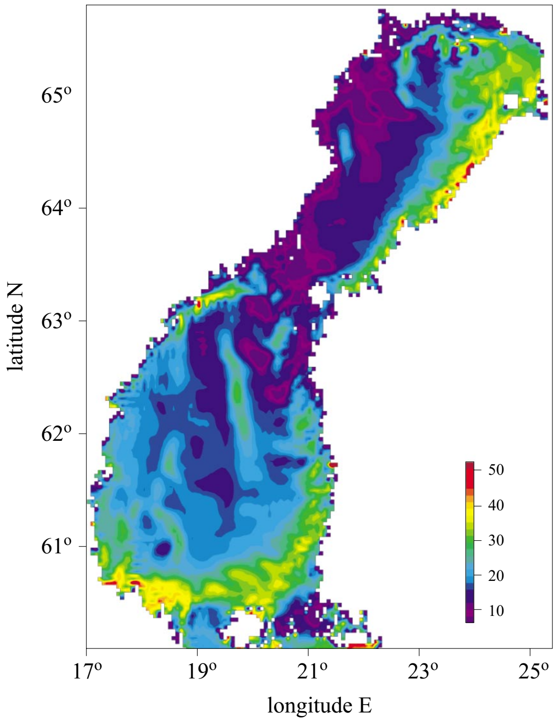

Fig. 4. The simulated mean persistency [%] in the immediate surface layer between 0 and 2.5 m for 1991–2000

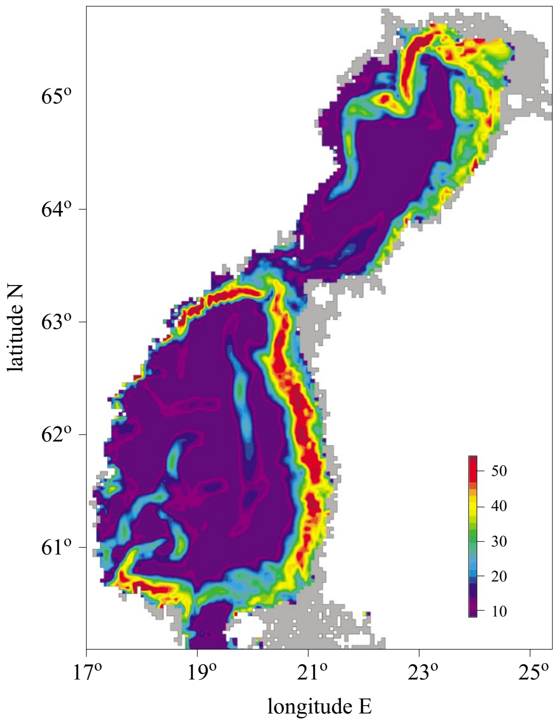

Fig. 5. The simulated mean persistency [%] in the subsurface layer between 2.5 and 7.5 m for 1991–2000

were around 5–25%. The persistency in the layer below 2.5–7.5 m, however, is characterised by maximum values of 30–50% (sometimes even 60%, Fig. 5) near the Finnish coast and in the northernmost Bothnian Sea as well in the central area of the northernmost Bothnian Bay (topographic steering). The stability off the Swedish coast is again somewhat weaker (about 15 –30%) except in the south–western Bothnian Sea, where the outflow has a persistency of 40–50%. In the open sea the persistency is much less than near the coast – only about 5–15%. Comparison of these results with those of Witting-Palmén (Fig. 3b) shows that they also found the persistencies near the coast to be between 25 and 60%. However, they had only a few observations from the open sea at their disposal, so their stability estimates are valid mostly for the coastal area. According to Lehmann & Hinrichsen (2000a), the highest persistencies are also located near the coasts, with values somewhat higher than in our estimates in the Bothnian Sea (40 –70%), In the Bothnian Bay their estimates are similar to our results in the open sea area, but Lehmann & Hinrichsen (2000a) did not find either high persistencies of coastal currents or cyclonic circulation cells. This might be because they analysed the surface currents, which are mostly Ekman-type drift currents.

A special feature concerning the coastal current system was found off the Finnish coast of the Bothnian Sea. The mean current field showed that the near-surface currents (Fig. 6a) were flowing in a north-easterly direction towards the Finnish coast, whereas the mean currents at 20 m depth (Fig. 6b) were flowing north-north-westwards. This downwelling area was also revealed in the statistical study of upwelling/downwelling regions in the Baltic Sea by Myrberg & Andrejev (2003). According to that study, the Finnish side of the Bothnian Sea coast was a downwelling area: even the ten-year average current field shows this feature. There are often large temperature contrasts off the Finnish coast in this area, which Kahru et al. (1995) refer to as ‘the eastern Bothnian Sea Front’.

3.2. Water exchange

Water exchange estimates at the mouth of the GOB have so far been based mostly on budget estimates (Fonselius 1971, Dahlin 1976, Ehlin & Ambjörn 1978); as a first approximation, this yields useful information that is readily comparable with the results of the present three-dimensional model. According to Dahlin (1976), the inflow to the GOB is 1380 km^3 yr^{-1} and the outflow is 1570 km^3 yr^{-1}. On the other hand, Ehlin & Ambjörn (1978) stated much higher figures: 2200 km^3 yr^{-1} (inflow) and 2400 km^3 yr^{-1} (outflow); Fonselius (1971) gave 900 km^3 yr^{-1} (inflow) and 1100 km^3 yr^{-1} (outflow). The broad scatter between these

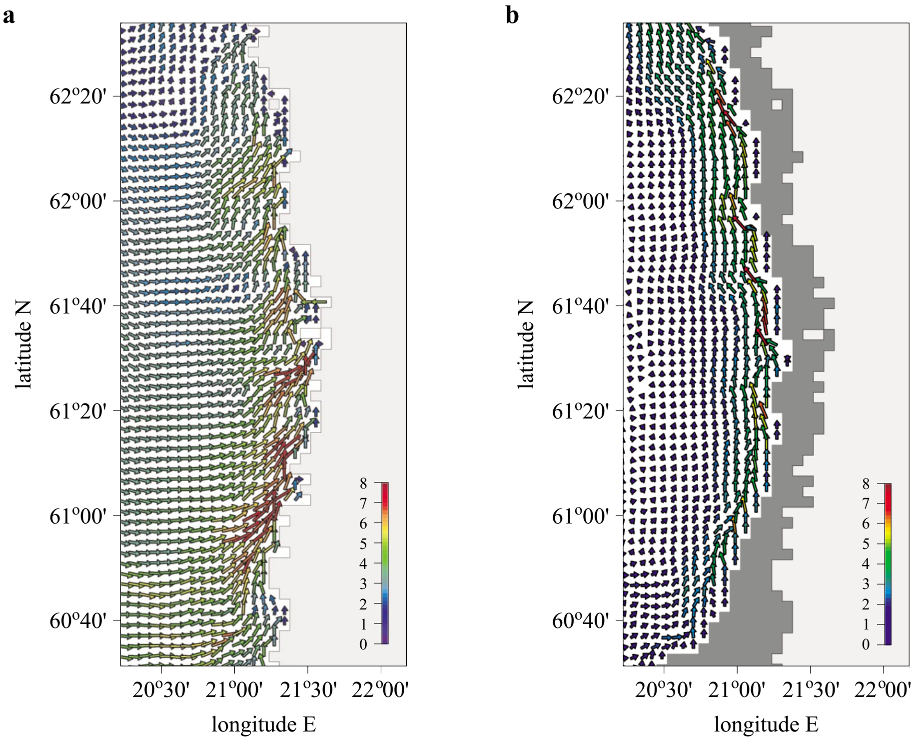

Fig. 6. The simulated currents [cm s^{-1}] for 1991–2000 off the Finnish coast of the Gulf of Bothnia. Near the surface (0–2.5 m) (a), in the layer between 17.5 and 22.5 m (b)

estimates results from different data sets being used with non-constant averaging periods. In spite of this, the differences between outflows and inflows are close to the river runoff to the GOB, which is approximately 180–190 km^3 yr^{-1} (Fonselius 1996). According to the three-dimensional modelling results of Lehmann & Hinrichsen (2000b), the corresponding differences were 199 km^3 yr^{-1} (1986) and 221 km^3 yr^{-1} (in 1993).

So the water balance between the GOB and the Baltic Proper is known approximately, but the exact figures relating to the in- and outflows need further investigation. Using our three-dimensional model, we therefore calculated the water exchange across latitude 60°27′N (the red line in Fig. 1, page 56). In this analysis two different approaches were used. Firstly, the in- and outflows were summed over the transect 60°27′N at each time step during the entire simulation, a procedure which yielded average flows for the whole simulation period. Taking into account all the water masses transgressing the cross-section, these calculations yielded respective average in- and outflows of 3480 and 3648 km^3 yr^{-1}. Secondly, the water exchange across the section was estimated on the basis of the average velocities for the whole simulation period (corresponding to the mean circulation fields). With this method the short-term variability of the circulation will be damped. These estimates yielded an inflow of only 255 km^3 yr^{-1} and an outflow of 424 km^3 yr^{-1}). So, all the previous budget estimates are somewhere in between the upper and lower estimates obtained with the model. According to the model, the respective differences between in- and outflows were 168 km^3 yr^{-1} and 169 km^3 yr^{-1} in the first and second cases, both values being reasonably close to the total river runoff debouching into the Gulf. What is the reason for these big differences? Analysis of the short-term (daily) variability of the currents shows that in the Åland Sea area, at the entrance of the GOB, there are quasi-permanent anticyclonic circulation cells (Fig. 7), with a continuous inflow-outflow system across the section where the water exchange is estimated by the model. So, when estimating the water exchange across the 60°27′N cross-section on the basis of the average velocities for the whole simulation period, this short-term variability is damped and the figures for in- and outflow are much reduced compared with the case when short-term variability of currents was included. So the discrepancy between the budget estimates and our estimates is very large, and we conclude that estimates of the water exchange obtained using standard budget calculations, i.e. based roughly on the in- and outflowing water masses, can hardly ever be used in practice because of the associated uncertainties. The resulting figures thus cannot answer the question of how the inflowing water affects the inner part of the Gulf

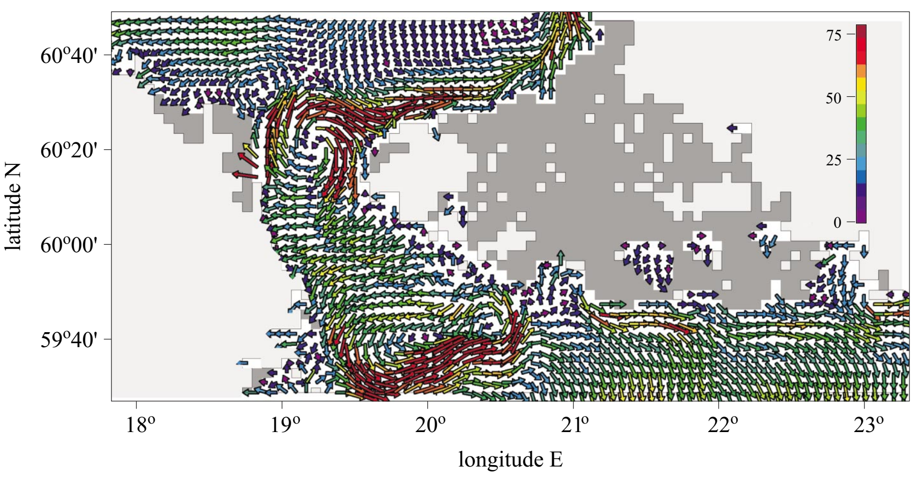

Fig. 7. A simulated snapshot of currents [cm s^{-1}] in November 1999 at the mouth of the GOB representing the layer between 7.5 and 12.5 m

or how far north this water penetrates. Even when using three-dimensional modelling, the results depend strictly on the time-scale of averaging and the location of the cross-section where the in- and outflows are calculated.

At present, the water exchange between the Baltic Proper and the GOB is being investigated through a cross-section (latitude 60°27′N, the red line in Fig. 1) in the southern Gulf of Bothnia. As already shown in the previous sub-section, the outflow near the Swedish coast through the Åland Sea is strong, with mean velocities of up to 5–9 cm s^{-1} in the whole water mass (Fig. 8). Off the Finnish coast there is a weaker inflow in the near-surface layer with velocities mostly between 4 and 6 cm s^{-1}. The central part of the Gulf is dominated by a west-east flow with a mean velocity of a few cm s^{-1}. So the difference in both direction and speed of the mean currents between the coastal and open sea regions is clearly visible.

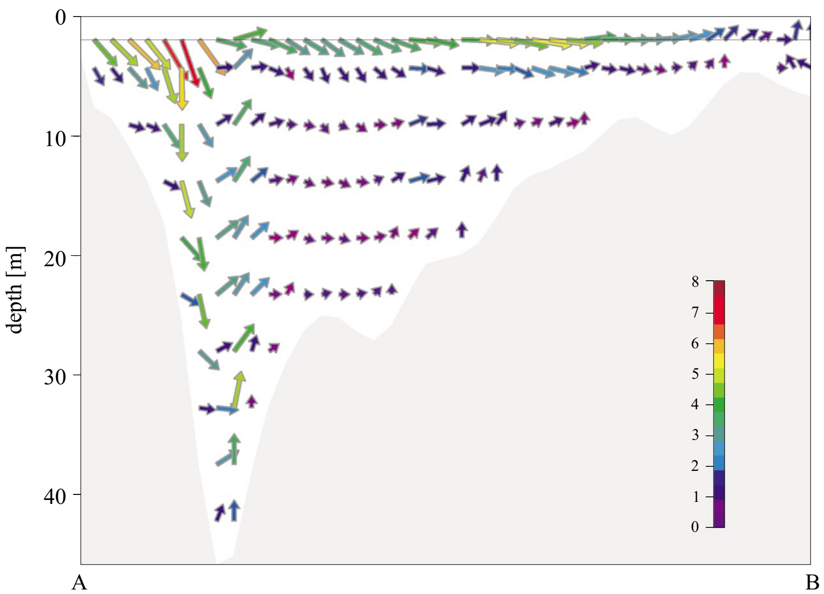

Fig. 8. Simulated means of currents [cm s^{-1}] for 1991–2000 at latitude 60°27′N at the entrance of the GOB (see Fig. 1, page 56). The currents on the left are flowing southwards, those in the middle eastwards and those on the right northwards

3.3. Water age

We can expect the results of the numerical simulations to provide us with useful information about the spatio-temporal variability of water age. It is of considerable interest to examine whether the comparatively clear-cut characteristics of the mean current field such as the inflow-outflow system described above are also reflected in the water age distribution structure, not least since for practical purposes it would be extremely useful to determine a possible upper limit of the water age in the Gulf of Bothnia. In Fig. 9 the water age is shown in a near-surface layer of the model (2.5–7.5 m) at the end of our entire ten-year simulation. The water age distribution shows that the water age in the Bothnian Bay is close to 7 years, and is higher off the Finnish coast (7.4 years) than off the Swedish coast (about 6.5 years). The age is in general somewhat higher in the Bothnian Bay than in the Bothnian Sea, where the age is typically 5 to 6.5 years. This is not surprising, since the circulation in the Bothnian Bay is rather isolated from that in the Bothnian Sea. Lower values of water age are found in the northernmost Bothnian Bay (between 2 and 5 years), owing to the large river inputs there. Also, the water age is lower on the Finnish side of the Bothnian Sea because of the inflow of waters to the north along the Finnish coast as a part of the cyclonic circulation in the area (age typically between 3 and 5 years). So the overall distribution of water age reflects the mean circulation pattern. However, it is important to note that the water age in the entire Gulf of Bothnia is rather high, from which we can infer that the water exchange between the Baltic Proper and the Gulf of Bothnia is really rather slow.

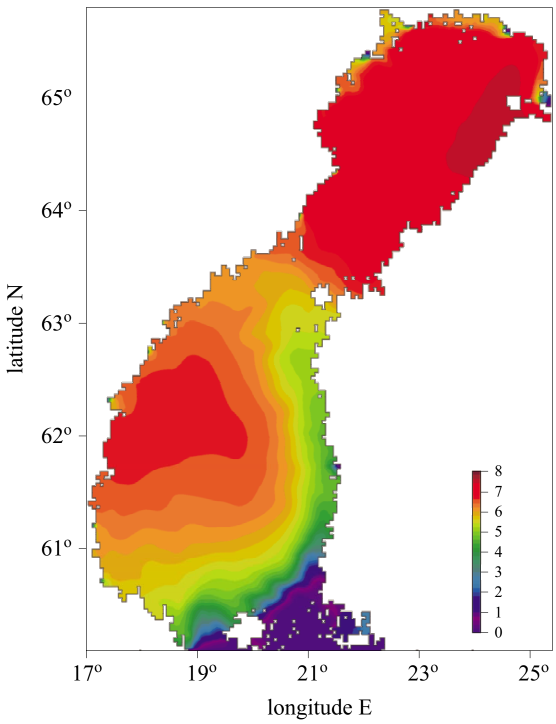

Fig. 9. Water age (in years) in the Gulf of Bothnia, based on the simulation between 1991–2000

The maximum water age in the Gulf of Bothnia is found to be in the middle of the Bothnian Bay with a value of about 7.4 years; this maximum age did not change any more after a further 8 years' model simulation. Those areas with a high water age have a rather steep gradient with the water masses to the north of them in the northernmost part of the Bay, where the rivers bring new water into the basin. The existing gradient is associated with the internal cyclonic circulation of the basins, and the existence of the 'buffer zone' between water masses of rather different ages bears a close resemblance to that which Andrejev et al. (2004b) demonstrated in the easternmost Gulf of Finland.

Meier (2005) calculated water age as the time elapsed since the water particle left the surface. Even if his approach has a different environmental background than ours, it is interesting to compare these results. In the Gulf of Bothnia the maximum water age according to Meier's definition – 4.2 years – is only about half the value that we estimated. According to Meier (2005), the water masses exhibit a steep vertical age gradient as a result of effective vertical mixing and the renewal of the Bothnian Sea deep waters ensuing from advection of surface water from the Baltic Proper (Marmefelt & Omstedt 1993).

4. Discussion

Based on a simulation of the Baltic Sea during 1991–2000, with a special focus on the Gulf of Bothnia, our results support the traditional view of the cyclonic mean circulation of the GOB with a general persistency of the circulation between 20 and 60%, the largest persistencies being close to coasts, as Witting and Palmén already showed a long time ago. Our barotropic model, with its fairly high horizontal resolution, support the idea that the main features of the circulation can be reproduced with a barotropic, wind-induced model. However, the mean current velocities in our simulation were clearly larger than those of Witting-Palmén; moreover, those early results did not describe meso-scale features like the quite pronounced differences in speed and direction between the coastal and open sea currents. This is most probably because those early measurements were based on a very coarse observational network and the measurements were carried out by means of simple 'flow crosses'. Our results have shown that the structure of the mean circulation as well as its persistency are, especially in the Bothnian Sea, close to the results obtained by Lehmann & Hinrichsen (2000a), whose results were also based on barotropic modelling, but for a four-year period.

Water exchange estimates between the Baltic Proper and the Gulf of Bothnia have been traditionally carried out by using a Knudsen-type budget calculus, which does not reflect the internal dynamics of the GOB. However, there is also a broad scatter between the estimates obtained by the three-dimensional model, these latter results showing the estimates depending closely on the time-averaging used. We can also conclude that the budget-type of estimates are somewhere between the upper and lower estimates obtained by the model.

In view of the rather complex problem of evaluating the internal dynamics of the GOB based on water- exchange estimates, the concept of water age was introduced. It turned out that the greatest water ages were obtained in the central part of the Bothnian Bay and that the entire Gulf of Bothnia is characterised by a rather high water age of up to 7.4 years. This means that water exchange between the Baltic Proper and the Gulf of Bothnia is sluggish. The regions associated with the highest water ages are, from the physical point of view, the most vulnerable to the effects of eutrophication, and the ecological state of those areas should be monitored with a high sampling frequency.

In our forthcoming work, we shall be directing our attention towards solving the effects of baroclinicity and ice cover on the long-term mean circulation, water exchange and water age of the Gulf of Bothnia.

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