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Mean circulation and water exchange in the Gulf of Finland — a study based on three-dimensional modelling

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A three-dimensional baroclinic prognostic model has been applied to study the mean circulation and its persistency as well as the water exchange in the Gulf of Finland. A five-year simulation for 1987–1992 was carried out using a nested grid approach, where a high-resolution sub-model of the Gulf of Finland was forced at the open boundary by a larger-scale Baltic Sea model. Realistic meteorological forcing for the period under study was used. The overall results of the investigation showed that the mean circulation pattern was complex with numerous meso-scale eddies, although a cyclonic mean circulation generally is discernible. The mean surface circulation of the Gulf was found to take place in the form of a strong outflow adjacent to the Finnish coast compensated for by an inflow at the Estonian coast, a circulation which is highly dependent on depth. The outflow on the northern side of the Gulf proved to be a distinct feature with a persistency ranging between 50% and 80%. The water exchange between the Gulf and the Baltic Proper appears to be stronger than previously estimated. It was found that ordinary budget estimates of water exchange (based on calculating the amount of in- and out-flowing water) do not give much relevant information concerning the Baltic Sea Proper–Gulf water exchange since these straightforward estimates do not reflect the internal dynamics of the Gulf of Finland.

Introduction

The Baltic Sea (Fig. 1) is one of the largest brackish water areas in the world. It has a very limited water exchange with the open ocean via the narrow and shallow Danish Sounds, and is characterised by a significant fresh-water surplus due to voluminous river runoffs. This leads to a two-layer salinity stratification which plays an important role for the physical processes e.g. by preventing vertical mixing of the water body. The currents are mainly caused by the wind stress, even though thermohaline effects cannot be disregarded. The sea-surface slope resulting from the permanent water supply due to river runoff contributes appreciably to the existing circulation pattern. The bottom topography plays a role modifying the physical processes and, in spite of the comparatively small size of the Baltic Sea, its various sub-basins are characterised by quite different dynamics. The present study is focused on the Gulf of Finland, a sub-basin located in

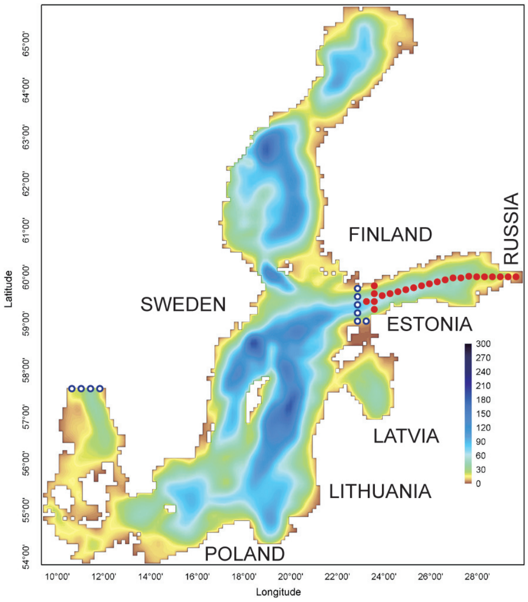

Fig. 1. The bottom topography of the Baltic Sea reproduced from Stigebrandt and Wulff (1987) with relevant geographical positions of the open boundaries (white dots) and sections used in the analyses of the model results in the Gulf of Finland (red dots).

the north-eastern extremity of the Baltic (Fig. 1). This Gulf is an elongated estuary with a mean depth of 37 m (maximum depth 123 m), in which physical processes ranging over scales from small vortices to the overall circulation take place. The western end of the Gulf is a direct continuation of the Baltic Sea Proper, whereas the eastern end receives the largest single fresh water inflow to the Baltic Sea; the Neva river. This leads to a strong east–west salinity gradient. The stratification is furthermore highly variable in both space and time, where the large seasonal variability of the incoming solar radiation plays a considerable role (Alenius *et al*. 1998).

Even if the mean circulation is a statistical artifact, which does not reflect a true physical situation, it can be used to estimate e.g. the average distribution of pollutants or nutrients released from point sources. Practical activities, like shipping and coastal construction, also need information concerning the circulation and its persistency. Contemporary ideas about the mean circulation of the Gulf are to a large extent based on general knowledge of the pattern of wind forcing, the fresh water input and, last but not least, classical studies which, although based on sparse sets of observational data, comprised perceptive dynamical insights. The mean circulation of the Gulf has hitherto not been investigated in any greater detail, neither on the basis of extensive field measurements nor using highly resolving three-dimensional hydrodynamic models. The most comprehensive investigations of the mean circulation, carried out by Witting (1912), Palmén (1930) and Hela (1952) using light-vessel observations of currents, show that a cyclonic circulation takes place in the Gulf. Using modern measurement tehniques, Sarkkula (1991) as well as Michailov and Chernyshova (1997) have given further credence to the idea of a cyclonic circulation and these investigators have found that the outflow at the Finnish coast is relatively strong. This outflow and the surface-layer inflow near the Estonian coast is also found in the scheme of annual mean currents presented by Sjöberg (1992). Recently published papers (Lehmann and Hinrichsen 2000, Lehmann *et al.* 2002) present results of comprehensive investigations of the mean circulation of the Baltic Sea obtained by using a three-dimensional hydrodynamic model with a horizontal resolution of 5 kilometres. The following conclusions found in the course of the abovementioned investigations are of importance for the present study:

1. The mean circulation of the entire Baltic Sea can be regarded as a system of cyclonic circulation cells comprising the sub-basins of the Baltic.
2. Some patterns of the averaged velocity in surface (0–24 m) layer show a very high stability of the outflowing current near the Finnish coast.
3. The most persistent features of the mean circulation are correlated with the bathymetry due to interaction between topography and buoyancy.

There are still gaps in our understanding of the variability and structure of the mean circulation pattern of the Gulf of Finland. The overall character of the average current field and the persistency of the flow are, however, known; e.g. Lehmann *et al.* (2002) reproduced the cyclonic general circulation of the Gulf using a numerical model. These features are studied here in detail using a three-dimensional hydrodynamic model with a high horizontal resolution capable of doing justice to the meso-scale circulation of the Gulf (cf. Fennel *et al*. 1991, Alenius *et al*. 2003).

Some estimates of the water exchange between the Gulf and the Baltic Sea Proper have been published (e.g. Witting 1910), but these are somewhat inaccurate due to a lack of observations. Only few estimates of the time-scale for the renewal of the Gulf waters have been made (Witting 1912, Aitsam and Astok 1972), and thus this question will be further examined in the course of the present investigation. It will be shown in the section "Water exchange" that usual budget estimates of water exchange by calculating the amount of inflowing and outflowing water (Knudsen 1900) do not provide much relevant information concerning the water exchange between the Gulf and the Baltic Sea Proper. This is because such simple estimates do not reflect the internal dynamics of the Gulf and furthermore the results tend to depend strongly on the calculation method employed.

We shall here use a three-dimensional, baroclinic hydrodynamic model (Andrejev and Sokolov 1989, Sokolov *et al*. 1997, Andrejev *et al*. 2000, Andrejev *et al*. 2002, Myrberg and Andrejev 2003; *see* also Appendix) to examine the circulation characteristics of the Gulf of Finland. The model simulations of the mean circulation are focused on a five-year period, following ideas of Palmén (1930). Our calculations are carried out for the period from 1987 to 1992, which was chosen since the entire water mass of the Gulf is expected to be renewed in 3–5 years (*see* e.g. Witting 1910, Astok and Mälkki 1988). These years furthermore did not include any major inflows of saline water to the Baltic Sea, and thus no exceptional changes of the stratification were to be expected.

In the next section we describe the implementation of the model as well as the data sets and forcing functions which have been employed for the numerical experiments. The methods used for the analysis of the circulation and its persistency, as well as the corresponding water exchange, are also dealt with. In section 3 the modelling results are discussed in some detail, whereafter the study is concluded by a summary and a review of some practical consequences of the investigation to possibly be kept in mind when taking environmental action.

Model implementation

The numerical model, developed by Andrejev and Sokolov (1989, 1990), is of the time-dependent, free-surface, baroclinic, and three-dimensional variety. Simplifications in the form of the hydrostatic approximation, an incompressibility condition, a Laplacian closure hypothesis for sub-grid scale turbulent mixing, and the traditional *f*-plane approximation are made. It is furthermore assumed that density variations only manifest themselves in the buoyancy terms; elsewhere the density is taken to be constant. The governing equations and the numerical methods employed are summarised in an appendix.

Main parameters and assumptions

In order to apply the model, it is necessary to specify a number of quantities. The horizontal kinematic eddy diffusivity coefficient μ is prescribed to be constant at 50 m^2 s^{-1} for the Baltic Sea Proper and 30 m^2 s^{-1} for the Gulf of Finland. The vertical eddy diffusivity coefficient ϑ is taken to be dependent on the local velocity shear and buoyancy forces (Kochergin 1987):

$$\vartheta = (0.5h)^2 \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2 - \frac{g}{\rho_0}\frac{\partial \rho}{\partial z}}, \quad (1)$$

where u and v are the velocity components along the eastward- and northward-directed x- and y-axes, respectively. The z-axis is taken to point downwards, ρ is the density, ρ_0 is a reference density and the gravitational acceleration is denoted by g. Equation 1 is based on a reduced equation for the turbulent kinetic energy (TKE) and the parameter h stands for a turbulent length scale. In our calculation it was assumed to be 2.5 m, which is equal to the thickness of the uppermost layer in the model.

Following Niiler and Kraus (1977), the wind stress components take the form

$$\tau_x = \rho_a C_d W_x \left|\overline{W}\right|,$$
$$\tau_y = \rho_a C_d W_y \left|\overline{W}\right|,$$

where W is the wind velocity and ρ_a is the density of air. In accordance with Bunker (1977), the drag coefficient C_d at the sea-surface was formulated as

$$C_d = 0.0012(0.066|W| + 0.63). \quad (2)$$

A quadratic law was used for the bottom friction, where the drag coefficient C_b was prescribed as 0.0026 (Proudman 1953).

The heat transfer and radiation balance at the air-sea interface is, following Lane and Prandle (1996), taken to be

$$F_T = Q_s + k(T_a - T_s), \quad (3)$$

where Q_s is the effective mean solar radiation (approximated by a sinusoidal function of the time of year and latitude), T_a is the air temperature, T_s is the sea-surface temperature and k is an exchange coefficient. The latter quantity is calculated by using an empirical expression based on the temperature and the square of the wind speed, and also taking into account conduction as well as evaporation. For salinity the corresponding flux F_s is to a lowest-order approximation prescribed as zero, because the difference between precipitation and evaporation is not known accurately due to a lack of observations. F_s is usually estimated to be slightly positive in the Gulf, but there are large discrepancies between the published estimates (e.g. Ehlin 1981, HELCOM 1986, Omstedt *et al*. 1997).

The winters during the period of interest were rather mild. In accordance with information from the Finnish Ice Service (A. Seinä pers. comm.) and following standard international classification of ice-conditions, three of these winters were extremely mild, one was mild and only the winter of 1988 showed average conditions. Hence the Gulf of Finland was mostly free of ice, which permits us to assume that a simple parameterisation can be used to describe ice formation and melting. Even though no ice-drift mechanism is modelled, the effects of sea ice are taken into account since for water temperatures below –0.2 °C, the wind stress is decreased by a factor of 10, and at 0.0 °C the heat flux through the ice ceases as long as cooling conditions prevail. The reason for not reducing the wind stress to zero is that "wind-stau" effects manifest themselves in the form of a tilting of the ice-covered surface.

Vertical convection has to be parameterised since the model uses the hydrostatic approximation. The following heuristic algorithm is used: first a check is made of whether the water in a grid cell is stable relative to the water of the underlying cell. If not, the water of the unstable grid cell (or some part of it, cf. Sokolov *et al.* 1997) is moved into the lower cell and the same volume of water from the lower cell is displaced upwards and mixed with the upper-cell water. This procedure of water replacement proceeds cell by cell, until the sinking volume finds itself in stable conditions and the water column is well-mixed in the vertical direction.

Set-up of the numerical model experiments

The modelling is based on a nested grid system, where the large-scale Baltic model is run using a coarse grid and its output (sea-level, temperature and salinity) is used as open-boundary data for the local highly-resolving version of the model which is applied to the Gulf of Finland. As outlined in the appendix, at the open boundary the data from the large-scale model are interpolated in space and time to the fine-resolution grid for each model level.

A five-year period from 1 August 1987 to 31 August 1992 was investigated using the model. A spin-up time, sufficient to remove irregularities of the initial sea-temperature and salinity fields (the calculation started from zero initial velocity and sea-level) and to adjust the model conditions to external forces, was determined to be 1 month for the Baltic Sea (Andrejev *et al.* 2000). In this case spin-up period was 1 July–31 July 1987. The open boundary of the large-scale model domain is placed in the Kattegatt along latitude 57°35´N. During the simulation period (1987–1992) there were no significant inflows from the North Sea into the Baltic. On the other hand, in order to prescribe the sea level properly in the Kattegat, it is necessary to use observations at both ends of the open boundary, viz. one observational point from the Swedish side and one from the Danish side. Our experience shows that the zero level can differ between observational points. To avoid this problem and furthermore keeping in mind that the present study is devoted to the mean circulation, we have used a passive free radiation condition (Orlanski 1976, Mutzke 1998) for the Kattegat sea level. For temperature and salinity a nudging procedure is carried out for the entire Baltic model. A comparison with observations presented here indicates that the coarse-resolution model yields reasonably good open boundary conditions for the Gulf of Finland model. The latter model domain has two open boundaries, where the western one coincides with longitude 22°32´E and the southern one with latitude 59°05´N. Both models have the same vertical resolution, and in the Baltic Proper the horizontal resolution is taken to be 5 nautical miles (Stigebrandt and Wulff 1987), whereas in the Gulf of Finland it is prescribed as 1 nautical mile. For the bottom topography we used the standard bathymetry provided by Seifert and Kayser (1995). The large-scale Baltic model comprises 18 levels in the vertical with a monotonically increasing layer thickness towards the bottom. The depths of the layer interfaces are: 0 m, 2.5 m, 7.5 m, 12.5 m, 17.5 m, 22.5 m, 27.5 m, 35.0 m, 45.0 m, 55.0 m, 65.0 m, 75.0 m, 85.0 m, 95.0 m, 105.0 m, 137.5 m, 162.5 m, 187.5 m and the bottom. The limited-area model does not include the three last layers defined here, since the Gulf is more shallow than the Baltic Proper.

The initial temperature and salinity fields for both the Baltic Sea and Gulf of Finland model versions were assembled using a data assimilation system due to Sokolov *et al*. (1997), which in turn is coupled to a Baltic environmental database (Wulff and Rahm 1991) and to the three-dimensional model employed here. To construct the initial fields for August 1987 (the first month of the numerical experiment), temperature and salinity data for all months of July from 1980 to 1992 were averaged. The reason for this somewhat artificial choice is the insufficient amount of true data available for July 1987. These composite fields can thus be regarded as climatic fields valid for the period (during which no significant salt water intrusion took place to the Baltic Sea). The model run was initiated from a quiescent state.

A simple data assimilation procedure was carried out for the coarse-resolution Baltic Sea model. Each July, throughout the experiment, the salinity and temperature fields were slightly corrected using a procedure (Stauffeur and Bao 1993) based on a nudging term

$$N = k_a(C_i - C_m) \quad (4)$$

where k_a is a nudging coefficient which was prescribed here as 2.0×10^6, C_i is an initial temperature or salinity in a grid point and C_m is the simulated temperature or salinity at the same point. It means that at each time step (2 hours) model variables were corrected for about 1.5% of the difference between model and assimilated values. We only used the nudging for the coarse-resolution Baltic model, since the aim solely is to generate open boundary conditions for the high-resolution model of the Gulf of Finland.

We have used SMHI (Swedish Meteorological and Hydrological Institute) meteorological data for 1987–1992 with a spatial resolution of 1° for the entire Baltic Sea area and 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 (Bumke *et al*. 1998). The monthly mean values of river discharges for 1970–1990 (Bergström and Carlsson 1994, Sokolov *et al*. 1997) were used. We took into account 29 rivers for the entire Baltic model and 5 rivers (Neva, Narva, Kymi, Keila and Luga) for the Gulf of Finland model. The runoffs from small rivers were added to discharges of the main rivers. In the Gulf of Finland the main river is the Neva; its discharge is about 4 times greater than the runoff from that next in capacity, *viz*. the Kymi river. However, the Neva discharge is primarily controlled by the height difference between Lake Ladoga and the Gulf of Finland and it does not have any significant branches. As a result, the annual variations of its discharge are not large. The order of magnitude of these variations during our experimental period was

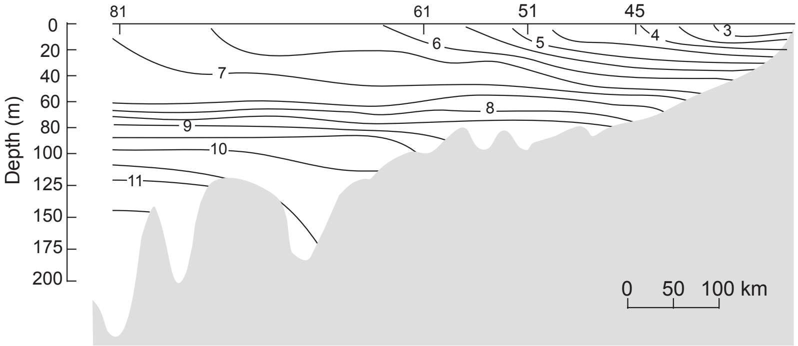

Fig. 2. Typical salinity section along the Gulf of Finland and northern Baltic Sea in summer. Isohalines are shown as continuous lines. The numbered locations are: 45 = Suursaari, 51 = off Helsinki, 61 = off Hanko and 81 = east of Gotland (redrawn from Jurva 1951).

not more than 10% of the monthly discharge. Since our work is focused on the mean circulation in the Gulf of Finland, we assume that these variations influence the circulation only to a very limited extent.

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:

$$R = \frac{\sqrt{\left(\frac{1}{N}\sum_n u_n\right)^2 + \left(\frac{1}{N}\sum_n v_n\right)^2}}{\frac{1}{N}\sum_n \sqrt{u_n^2 + v_n^2}} \times 100, \quad (5)$$

where N is the number of observations (in our case model time steps), $n = 1\ldots N$ and R is given as a percentage. The persistency is essentially a measure of the variability of the current direction and thus 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 is, the smaller the persistency (which furthermore assumes the value of zero when the net water transport reaches zero).

The results of the numerical simulations

Our main interest as regards the modelling results is focused on the analysis of the water masses of the Gulf and on the corresponding mean circulation pattern and water exchange. An overall description of the Gulf hydrography is given as a background, whereafter some comparisons between model results and observations are made in order to examine the model's capacity of reproducing the dominant hydrographic features of the Gulf.

The overall hydrographic conditions

The hydrographic conditions of the Gulf of Finland can be described using e.g. a salinity section (Jurva 1951, Alenius *et al.* 1998) along the axis of the Gulf and the northern Baltic Sea (Fig. 2) which, based on long-term observations, shows that the hydrography of the Gulf typically is estuarine and characterised by large horizontal and vertical variations. The entire Gulf serves as a transition zone from fresh water towards the more saline water masses of the Baltic Proper. This also holds true for the deep waters, since no sill separates the Gulf from the Baltic Proper, and thus no isolated water masses are found in the Gulf. The isohalines are inclined towards greater depths in the east, and at the entrance of the Gulf the salinity increases from around 6 psu at the surface to around 9 psu near the bottom. The vertical gradients are pronounced due to the river-water input as well the saline inflow from the Baltic Proper.

In order to determine the ability of the model to reproduce the overall hydrographical features, we took the high-resolution model results at the end of the five-year run (on 21 August 1992) and compared them with CTD observations carried out on board r/v *Aranda* mainly from 19 until 22 August 1992. This comparison shows that the surface temperature field is reproduced rather well (Fig. 3). On 21 August 1992, the surface

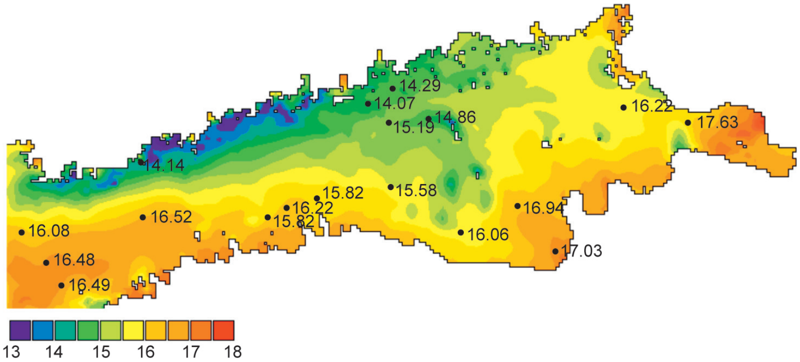

Fig. 3. Simulated surface layer temperature (°C) between 0 and 2.5 m on 21 August 1992. Temperature observations are marked with black dot and the corresponding value.

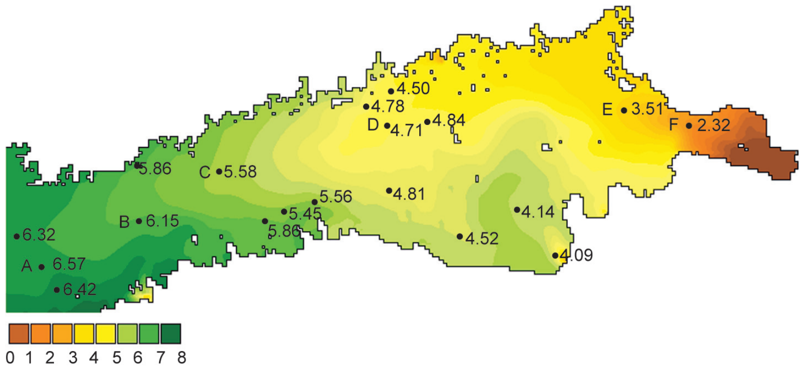

Fig. 4. Simulated surface layer salinity (psu) between 0 and 2.5 m on 21 August 1992.

temperature varied between 13 and 18 °C, with the highest values found in the east and in the west. At the northern coast, signs of a recent upwelling event are visible. The predicted surface temperatures were compared with the corresponding CTD measurements and it was concluded that the model reproduces the surface temperature with an accuracy of around 0.5 °C. The only measurement in the eastern part of the Gulf shows a noticeable difference, about 2 °C, as compared with our calculations. This is not very surprising since the measurement took place on 18 August, three days before the date for which the calculated results were obtained and the sea-surface temperature at this shallow point is strongly time-dependent. A calculated temperature distribution in the west–east direction indicates that the stratification is strong with a pronounced thermocline at a depth ranging from 12 to 21 m, where, however, the water masses in the shallow coastal areas are well-mixed. The isotherms are quasi-horizontal, and at the bottom the predicted temperature is more-or-less homogeneous with a mean value of around 4 °C, i.e. slightly higher than that observed on average (e.g. Haapala and Alenius 1994).

The observed surface salinity (Fig. 4) is reproduced by the model with an accuracy of around 0.5 psu. The surface salinity varies from around 0 psu in the Neva Bight to about 6.8 psu on the Hanko–Osmussaar line at the mouth of the Gulf. The water mass in the northern part of the Gulf is fresher than that found along the southern coast, with surface salinities at the Estonian coast 0.5–1.5 psu higher than on the Finnish side due to the fresh water inputs from the rivers Neva and Kymi. The distribution of surface salinity thus directly supports the assumption of the Gulf being characterised by a cyclonic circulation. Figure 5 shows a salinity cross-section through points marked by letters from A to F in Fig. 4. The near-bottom salinities are lower than the climatological averages (Fig. 2), but in good agreement with observations made around 21 August 1992. The penetration of Baltic water into the Gulf is furthermore clearly discernible.

For the model runs, the open boundary sea-levels were obtained from the coarse-resolution

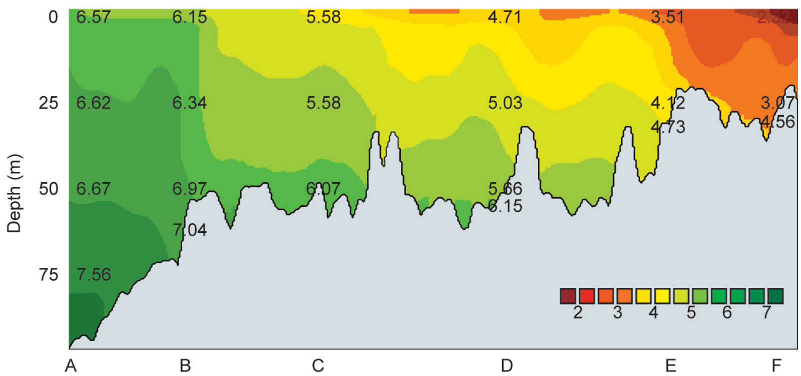

Fig. 5. The simulated west–east salinity-section in the Gulf of Finland on 21 August 1992. The location of the section is shown by letters from A to F in Fig. 4. The scale of the corresponding colours is shown below.

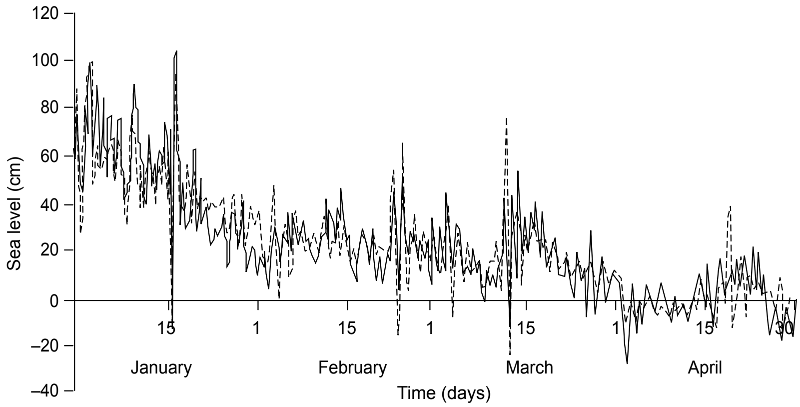

Fig. 6. Time-evolution (days) of the sea-level height (cm) at the Helsinki station during 1 January–30 April 1992. The observed sea-levels are marked with a solid line, the model results with a dashed line.

model of the Baltic Sea. A convincing example of predicted and observed sea-levels from Helsinki during the period 1 January–30 April 1992 is shown in Fig. 6, and it has furthermore been ascertained that the model is capable of reproducing the main features of the sea-level variability in the Gulf of Finland during the entire five-year period. No major phase differences were observed between the model results and the measurements. The maxima and minima of the sea-level are in general well reproduced by the model, and it was found that the errors in these predictions primarily arose from the inaccuracies of the prescribed atmospheric forcing.

Mean circulation and persistency

Although the main forcing of the currents in the Gulf of Finland, as in the whole Baltic, is due to wind stress, density-driven currents also play an important role for the overall circulation via the pronounced horizontal density gradients caused by variations of salinity and temperature. The sea-surface slope that results from the permanent water supply to the eastern part of the Gulf also contributes appreciably to the existing circulation. This is primarily geostrophic in character since the Gulf is large enough to experience the effects of the earth's rotation (Witting 1912, Palmén 1930, Hela 1946). A traditional, but idealised, view is that the mean surface circulation is cyclonic with an average velocity of a few cm s^{-1}. The modelled circulation and its persistency can be compared with the classical analyses due to Witting and Palmén (which, however, must be regarded as educated guesses based on very sparse observational data sets).

The circulation in the uppermost layer of the model (0–2.5 m) is mainly wind-driven. The mean currents near the coasts are deflected to the right from the mean wind, which is directed along the axis of the Gulf (Fig. 7). The resulting inflow is most intense on the Estonian side, and adjacent to the northern coast the outflow from the Gulf shows a meandering structure. The

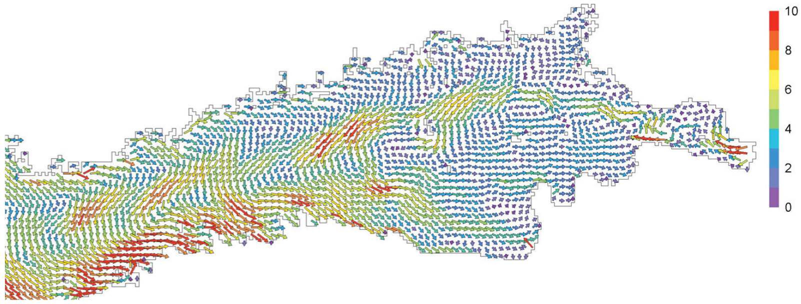

Fig. 7. The simulated mean surface layer circulation (cm s^{-1}) between 0 and 2.5 m from 31 August 1987 to 31 August 1992. Each second grid point is drawn due to practical reasons.

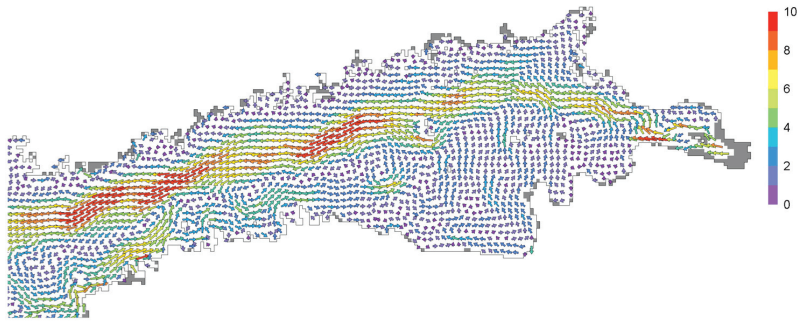

Fig. 8. The simulated mean circulation (cm s^{-1}) in the sub-surface layer between 2.5 and 7.5 m from 31 August 1987 to 31 August 1992. Each second grid point is drawn due to practical reasons.

circulation in the eastern part of the central Gulf is mainly characterised by small-scale eddies, although the Neva runoff becomes visible as a strong westward-directed flow in the easternmost Gulf. The sub-surface layer between 2.5 and 7.5 m is the one most easily compared to the Witting-Palmén observations, 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 the outflow is more intense, while the coastal currents are weaker (Fig. 8). This comparatively stable outflow has also been discussed by e.g. Sarkkula (1991), Michailov and Chernyshova (1997), and reproduced in a numerical model by Lehmann *et al*. (2002). In the western part of the Gulf meso-scale cyclonic circulation patterns with characteristic size of about 60 km, not visible in the surface layer, occur. As will be discussed in next sub-section, these vortices play an important role for the water exchange between the Gulf and the Baltic Proper. Typical current velocities in the uppermost layers range between 5 and 10 cm s^{-1}, where the largest speeds are associated with the in- and out-flow patterns. The predicted mean speeds agree well with measurements reported by Sarkkula (1991) as well as Michailov and Chernyshova (1997).

To obtain more information about the current system and its variability, the persistency of the circulation has also been investigated. Despite the similarities 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 (Fig. 9) is highest in coastal areas with values up to 50%, whereas the values near the central axis of the Gulf only are around 15%–20%. However, as seen from Fig. 10, the persistency in the layer below (2.5–7.5 m) is characterised by maximal values of 50%–60% just north of the central axis of the Gulf, while adjacent to the Estonian coast it is only around 15% (with the exception of the south-western coastal region, where values of around 45%–55% are found). In both of these uppermost layers, the highest persistencies are found near the mouth of the Neva river with values of 90%–100%. The discrepancy elsewhere has dynamical causes, since in the surface layer wind-drift is of great importance (as reflected by the high persistencies in the coastal zone), while the motion in the layer below is dominated by

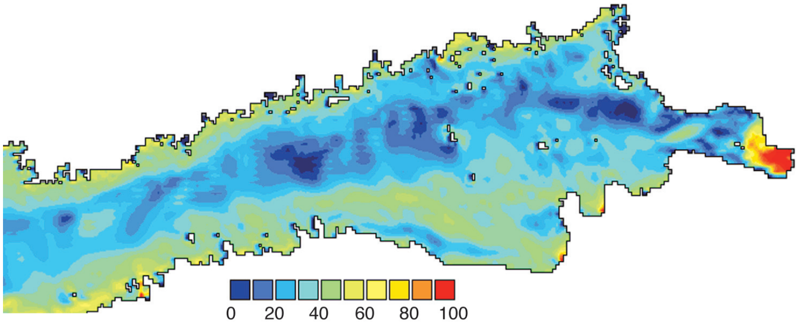

Fig. 9. The simulated five-year mean persistency (%) in the immediate surface layer between 0 and 2.5 m.

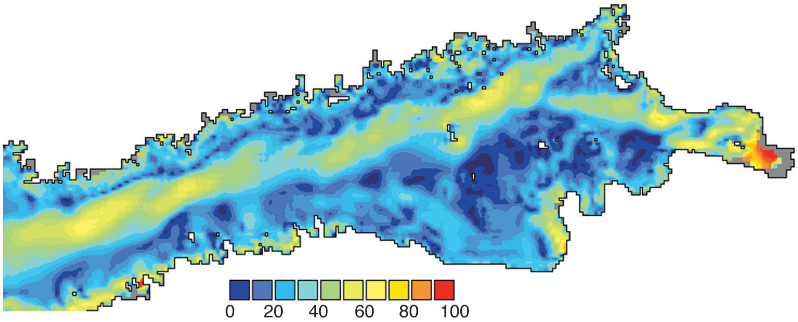

Fig. 10. The simulated five-year mean persistency (%) in the sub-surface layer between 2.5 and 7.5 m.

the large-scale circulation system. This general cyclonic circulation is also reflected in the salinity patterns (cf. Fig. 4), since the lowest values of salinity were found near the northern coast where the fresh water from the Neva river flows out, whereas systematically higher salinities are observed adjacent to the Estonian coast where Baltic waters enter the Gulf.

The current system found below these surface layers is more or less homogeneous down to a depth of 45 m. The outflow on the northern side of the Gulf proved to be a distinct feature with a persistency ranging between 50% and 80%. The inflow adjacent to the Estonian coast is visible at all depths, with a persistency ranging between 50% and 80%, and thus a strong cyclonic circulation takes place down to around 45 m. At deeper levels the effects of bottom topography become evident in the form of small-scale vortices. Here it may finally also be noted that there are regions in the eastern part of the central Gulf with persistencies over 50% through the entire water column, indicating the presence of quasi-stationary areas where a smaller-scale internal circulation dominates. To visualize the velocity field in the most representative layer (2.5–7.5 m) more clearly, a current scheme corresponding to the solutions shown in Fig. 8 was constructed (Fig. 11). A comparison of this scheme with the Gulf of Finland bottom topography (Fig. 1) indicates that, as discussed already in the introduction, the mean circulation is closely correlated to the topography. All significant eddies are of the cyclonic type and located south of the outflowing waters above pronounced bathymetric depressions. These meso-scale vortices extend to the bottom and their persistency in the lower layers (from the layer 12.5–17.5 m to the bottom) ranges between 35% and 60%.

Water exchange

The water exchange between the Gulf of Finland and the Baltic Proper has hitherto not been studied very extensively. Estimates of the annual water exchange have been presented in some early studies, e.g. by Witting (1910) who calculated in- and outflows of 480 and 600 km^3 a^{-1}, respectively. These values correspond to mean flows of approximately 1 cm s^{-1}, which appears to be an underestimate when compared not only to the present modelling results, but also to recent observations by Sarkkula (1991) as well

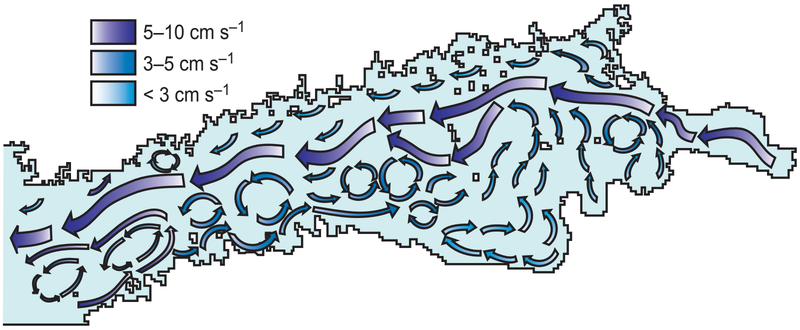

Fig. 11. The current scheme in the sub-surface layer between 2.5 and 7.5 m.

as Michailov and Chernyshova (1997). A discrepancy of this magnitude is, however, not surprising since Witting's calculations were based on simple budget estimates using the classical Knudsen formula (Knudsen 1900). The input of river water to the Gulf is around 115 km^3 a^{-1} (Bergström and Carlsson 1994), and thus the difference between in- and outflows is expected to be roughly 110 to 120 km^3 a^{-1}. Using a three-dimensional model, Lehmann and Hinrichsen (2000) obtained differences of 148 km^3 a^{-1} and 103 km^3 a^{-1} from simulations for the years 1988 and 1994, respectively.

The mean circulation pattern, as shown in Figs. 7 and 8, indicates the presence of a meso-scale cyclonic circulation system located at the entrance of the Gulf. Hence water masses may "visit" the Gulf for a brief period without affecting the general hydrography of the central and eastern parts. The water-exchange estimates are furthermore dependent on the methods employed for the analysis of the model results. Two different approaches were pursued in the present study. *Pro primo*, the in- and out-flows were summed over the transect between Hanko and Osmussaar at each time step during the five-year simulation, a procedure which yielded average flows for the period 1987–1992. These calculations, taking into account all water masses transgressing the section, yielded average in- and out-flows of 3154 and 3273 km^3 a^{-1}, respectively. *Pro secundo*, the water exchange across the section was estimated on the basis of the average velocities for the five-year period of simulation (corresponding to the mean circulation fields). Using this method the short-term variability of the circulation will be damped out, whereas the quasi-stationary cyclonic meso-scale circulation pattern at the western end of the Gulf is still taken into account. These estimates yielded an inflow of 1417 km^3 a^{-1} and an outflow of 1532 km^3 a^{-1}. The difference between in- and out-flows was 119 km^3 a^{-1} and 115 km^3 a^{-1} for the first and second cases, both values reasonably close to the total river runoff debouching into the Gulf. Summarising these results, we conclude that estimates of the water exchange obtained using standard budget calculations, viz. roughly based on the in- and out-flowing water masses, can hardly ever be used in practise because of the associated uncertainties. The resulting numbers thus cannot answer the question of how the inflowing water affects the inner part of the Gulf or how far this water penetrates to the east.

At the open boundary of the Gulf (cf. in Fig. 1) the five-year means of normal velocities (Fig. 12) indicate that the inflow adjacent to the Estonian coast takes place over the entire water column, with the most intense flow occurring near the surface. Typical velocities of the inflowing water are between 1 and 4 cm s^{-1}, but near the surface values ranging from 7 to 10 cm s^{-1} are found. On the Finnish side, a comparatively intense transport into the Gulf takes place in the near-surface layer, with velocities up to 8 cm s^{-1}. However, the northern side of the Gulf is primarily dominated by an outflow taking place offshore the coast (but north of the central axis of the Gulf) where the mean velocity can reach a magnitude of 8 cm s^{-1}. This outflow takes place from around 10 m depth down to 40–50 m. The inflow-outflow system at the mouth of the Gulf appears to be a permanent fixture of the circulation, since a previously conducted numerical experiment of one-year duration revealed the same general velocity structure (Andrejev *et al.*

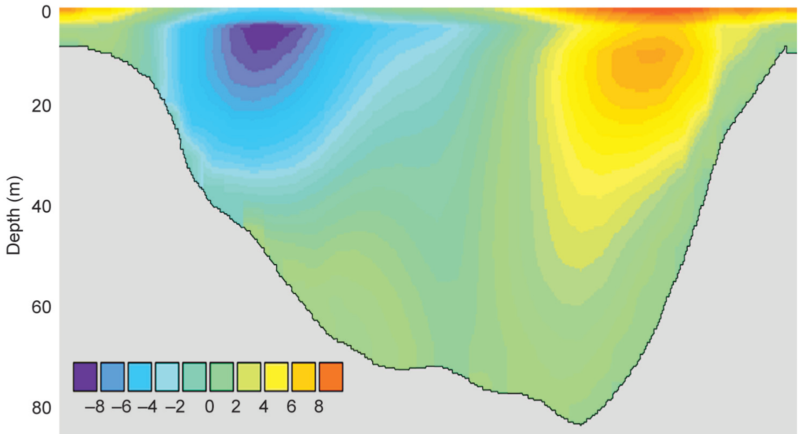

Fig. 12. Simulated five-year means of inflow (positive) and outflow (negative) in cm s^{-1} at the entrance to the Gulf (Hanko–Osmussaar line; *see* Fig. 1).

2000). A similar current structure at the mouth of the Gulf was recently modelled by Meier (1999).

Summary and conclusions

The overall results of the investigation showed that the mean circulation pattern in the Gulf of Finland was complex with numerous meso-scale eddies, although a cyclonic mean circulation generally is discernible. It should be noted that in order to resolve the small-scale eddies, a resolution of one nautical mile was necessary in the model, this due to the small baroclinic Rossby radius typical for the Gulf (cf. Fennel *et al*. 1991, Alenius *et al*. 2003).

The surface-layer flow pattern is characterised mainly by an Ekman-type drift, resulting in an inflow near the coasts and a compensating outflow in the open Gulf, where the persistency of the currents is highest in the coastal zones. However, for the sub-surface layers, the outflow slightly north of the central axis of the Gulf (about 30 km offshore from the Finnish coast) becomes stronger and shows a high persistency. We can thus conclude that the external loading from the St. Petersburg area is not the only factor which affects the Finnish coastal areas. The high nutrient concentrations in the Finnish coastal waters are also partly due to local point sources. According to the model results this outflow weakens considerably near the bottom, whereas the inflow adjacent to the Estonian coast is visible at all depths with a high degree of persistency. An internal circulation is seen in the eastern part of the central Gulf as a system of meso-scale vortices. In the easternmost part of the Gulf, the Neva Bight is characterised by strong and persistent north to north-westerly currents caused by the voluminous runoff from the Neva.

It was found that ordinary budget estimates of the water exchange, based on calculating the amount of in- and out-flowing water, did not enhance our understanding of the water exchange between the Gulf and the Baltic Sea Proper. The reason is that these estimates do not reflect the internal dynamics of the Gulf of Finland. Our estimates of the net in- and out-flows based on three-dimensional modelling were found to be larger than those previously established. These modelled results correspond to mean in- and outflows of 2.5–5 cm s^{-1}, a magnitude which is realistic. The water exchange at the mouth of the Gulf was studied in detail, and it was found that near the Estonian coast the inflow takes place in a deep layer, whereas on the Finnish side it occurs in a near-surface layer. The outflow takes place somewhat north of the central axis of the Gulf from near the surface down to a depth of 45–50 metres. The velocities in the entrance area range from 2–3 cm s^{-1} up to 7–8 cm s^{-1}. It has been judged that the general structure of the inflow-outflow system is rather stable, this since the same main features were found after a one- as well as a five-year simulation.

The discrepancy between our different water-exchange estimates is partly due to the fact that we are dealing with water parcels inherently constituting a part of the cyclonic circulation system at the mouth of the Gulf. These never move far away from the border and thus play no significant role in the overall dynamics of the Gulf. The resulting estimates of the water exchange also strongly depend on the averaging procedure applied to the current velocities. In other words, previous estimates have not properly taken into account the internal dynamics of the Gulf. A possible way of resolving this problem would be to investigate the "age" as well as spatial distribution of the water in the Gulf.

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Appendix

In the model the governing equations are:

$$\frac{\partial u}{\partial t}+\frac{\partial uu}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}=-fv-\frac{1}{\rho_0}\frac{\partial p}{\partial x}+\mu\Delta u+\frac{\partial}{\partial z}\left(\vartheta\frac{\partial u}{\partial z}\right), \tag{A1}$$

$$\frac{\partial v}{\partial t}+\frac{\partial vu}{\partial x}+\frac{\partial vv}{\partial y}+\frac{\partial vw}{\partial z}=-fu-\frac{1}{\rho_0}\frac{\partial p}{\partial y}+\mu\Delta v+\frac{\partial}{\partial z}\left(\vartheta\frac{\partial v}{\partial z}\right). \tag{A2}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0, \tag{A3}$$

$$\rho=\rho(T,S), \tag{A4}$$

$$\frac{\partial \rho}{\partial z}=\rho g, \tag{A5}$$

$$\frac{\partial A}{\partial t}+\frac{\partial uA}{\partial x}+\frac{\partial vA}{\partial y}+\frac{\partial wA}{\partial z}=\mu_{\mathrm{A}}\Delta A+\frac{\partial}{\partial z}\left(\vartheta_{\mathrm{A}}\frac{\partial A}{\partial z}\right)+F_{\mathrm{A}}. \tag{A6}$$

Equations A1 and A2 describe the momentum balances for the velocities u and v in the x and y directions respectively, where x increases eastwards and y increases northwards. The velocity along the downward-directed z-axis is denoted by w, pressure by p, and ρ_0 is a reference density. Equation A3 is the volume conservation equation, where the small compressibility of water is neglected (hereby introducing a negligible mass conservation error). The equation of state A4, thus, also reflects the absence of depth dependence (Millero and Kremling 1976).

Equation A5 takes into account the vertical density variations, which are not reflected in Eqs. A1 and A2. This is often referred to as the Boussinesqian hydrostatic approximation. The gravitational acceleration is g and in Eq. A6 A denotes the concentration of the modelled scalar properties that transgress the model boundaries or have sources/sinks (denoted F_A), within the model domain. These scalars are salinity S and heat $\rho C_p T$ (where C_p is the specific heat of water and T is the temperature).

The kinematic eddy diffusivity coefficients in the horizontal and vertical directions are μ and ϑ, respectively, the Coriolis parameter is f, and the horizontal Laplacian operator is denoted by Δ. External forces, such as wind stress and bottom friction, enter as boundary conditions. For the sea-surface $z = -\varsigma(x, y, t)$ these are:

$$\vartheta \frac{\partial u}{\partial z} = \frac{-\tau_x}{\rho_0}, \tag{A7}$$

$$\vartheta \frac{\partial v}{\partial z} = \frac{-\tau_y}{\rho_0}, \tag{A8}$$

$$\vartheta_T \frac{\partial T}{\partial z} = -q_T, \tag{A9}$$

$$\vartheta_S \frac{\partial u}{\partial z} = -q_S, \tag{A10}$$

$$p = p_a \tag{A11}$$

$$w = \frac{\partial \varsigma}{\partial t} + u \frac{\partial \varsigma}{\partial x} + v \frac{\partial \varsigma}{\partial y}, \tag{A12}$$

Here p_a is the air pressure, ς is the elevation of the free surface and H is the water depth, whereas q_T and q_S are the heat and salt fluxes.

The kinematic boundary condition A12 signifies that a fluid particle at the surface remains there regardless of possible advective motion of the underlying layers.

At the sea-bed $z = H(x,y)$ the boundary conditions are:

$$u = v = w = 0, \tag{A13}$$

$$\vartheta_T \frac{\partial T}{\partial z} = \vartheta_S \frac{\partial S}{\partial z} = 0. \tag{A14}$$

The bottom stress is taken into account in the form of a quadratic law (Blumberg and Mellor 1987). The solid vertical walls are taken to be of the no-slip type. Neither these nor the seabed are permeable for the scalar properties, excepting the locations where rivers discharge. At these points the salinity is prescribed as zero, and the river water is taken to adapt instantaneously to the ambient temperature. For the entire Baltic model a passive radiation condition for the surface elevation (Mutzke 1998, Orlanski 1976), combined with a sponge-layer approach for other variables, is used. For the Gulf model the combination of an active radiation condition with a sponge-layer approach is used for all variables. A sponge layer is defined as the zone adjacent to an open boundary where the lateral diffusivity coefficient increases linearly towards the open boundary. In our calculations the width of this zone was taken to be 9 grid cells; the increment of the lateral diffusivity coefficient was prescribed as 10 and 5 m^2 s^{-1} for the coarse and fine model, respectively.

Numerical scheme

Since a comprehensive description of the numerical scheme has been given by Andrejev and Sokolov (1989, 1990) and Sokolov *et al.* (1997) only a brief outline of its main features is provided here. The governing equations are used in flux form, this to ensure that a number of integral constraints (Blumberg and Mellor 1987) are maintained. The finite-difference approximations are constructed by integrating the model equations over the C-grid cell volume (Mesinger and Arakawa 1976). The time step was split up, as suggested by Liu and Leendertse (1978), and thus the u-equations are solved at time steps $n - 1/2 \sim n + 1/2$, the v-equations are solved at time steps $n \sim n + 1$, and all other equations are solved at every half time step. All vertical derivatives as well as the bottom friction were treated implicitly. The mode-splitting technique (Simons 1974) was employed, where the two-dimensional equation for the volume transport (viz. the external mode) was obtained by vertical summation of the finite-difference approximations of the three-dimensional momentum equations. Before the three-dimensional finite-difference equations corresponding to the internal mode can be resolved, the sea-surface elevation must be calculated from the volume transport equation and from the vertically integrated equation of continuity. The frictional stress at the bottom enters semi-implicitly into both modes and is based on a bottom-layer velocity, which is calculated using an iterative procedure. The two- and three-dimensional momentum equations are thus solved repeatedly until the absolute value of the maximum difference between the bottom velocities for subsequent iterations becomes smaller than an *a priori* prescribed minute positive number. This adjustment process permits the use of an alternating-direction implicit method for solving the volume transport equation (Liu and Leendertse 1978, Andrejev and Sokolov 1989), and furthermore allows the use of the same time step (in the present study 30 min.) for the two- as well as three-dimensional elements of the model. The Gaussian elimination method makes it possible to solve these equations quite easily.