Helsinki University of Technology

Systems Analysis Laboratory Research Reports E9, September 2001

COMPARISON OF HYDRODYNAMICAL MODELS OF THE GULF OF FINLAND IN 1995 – A CASE STUDY

Arto Inkala **Kai Myrberg**

TEKNILLINEN KORKEAKOULU
TEKNISKA HÖGSKOLAN
HELSINKI UNIVERSITY OF TECHNOLOGY
TECHNISCHE UNIVERSITÄT HELSINKI
UNIVERSITE DE TECHNOLOGIE D'HELSINKI

Distribution:
Systems Analysis Laboratory
Helsinki University of Technology
P.O. Box 1100
FIN-02015 HUT, FINLAND
Tel. +358-9-451 3056
Fax. +358-9-451 3096
systems.analysis@hut.fi

This report is downloadable at

www.e-reports.sal.hut.fi/pdf/E9.pdf

Series E – Elecronic Reports
www.e-reports.sal.hut.fi

ISBN 951-22-5663-0
ISSN 1456-5218

Title: Comparison of hydrodynamical models of the Gulf of Finland in 1995 -a case study

Author: Arto Inkala
Environmental Impact Assessment Center of Finland (EIA ltd.)
Tekniikantie 21 B, 02150 Espoo, FINLAND
arto.inkala@iki.fi

Kai Myrberg
Finnish Institute of Marine Research
PL 33, 00930 Helsinki, FINLAND
kai.myrberg@fimr.fi

Date: September, 2001

Status: Systems Analysis Laboratory Research Reports E9 September 2001

Abstract: Three-dimensional hydrodynamic models of the Gulf of Finland, namely FINNFLOW and FinEst, have been compared with observations of salinity, temperature water levels and currents in 1995. The FINNFLOW model had a vertical co-ordinate system with fixed levels whereas in the FinEst model a modified sigma co-ordinate system was used. The model results were also compared with each other. Both models were able to reproduce the main spatial east-west gradient of salinity, the temporal variability of temperatures in the uppermost layers and the height variations of water levels. Problems were caused by the inaccuracies of the open boundary conditions. The verification of the models with current measurements gave less satisfactory results mainly due to the too coarse horizontal resolution of the models. The accuracy of the near-bottom salinity and temperature suffered from inaccuracies in the open boundary condition and related problems in defining the stratification conditions in the Gulf. The FINNFLOW model described better up- and downwellings, while the stratification conditions were more accurately described by the FinEst model. These differences are probably best explained by the different co-ordinate systems in the models.

Keywords: modelling, salinity, temperature, sea level, currents, FINNFLOW, FinEst, Baltic Sea, Gulf of Finland (24° - 31° E, 59° - 61° N)

1. Introduction

The Baltic Sea is one of the largest brackish water areas in the world. In spite of its relatively small size, different sub-basins have different physical processes (stratifications and river effects). The main topic of this article is the comparison of two most commonly used hydrodynamic models in Finland. The comparison was made by modelling physical processes of the Gulf Finland. The Gulf of Finland is an elongated estuarine sea with a mean depth of 37 m, where physical processes from small-scale vortices up to a large-scale circulation exist. It is a complicated hydrographic region, having saline water input from the Baltic Sea Proper in the west and a large fresh water input from the rivers (approx. 25 % of the total fresh water to the Baltic Sea), mainly in the east. Due to the pronounced baroclinicity of the Gulf, the currents are not only driven by the wind, but the thermohaline circulation plays an important role too.

Due to the relatively small scale of the gulf (length 400 km, width 48-135 km) its complex physics can be studied quite accurately in space and time by carrying out measurements. Therefore, the gulf is a relatively good “marine laboratory”. Two three-dimensional models, namely FinEst (FinEst=Finnish-Estonian; Tamsalu, 1998, Myrberg, 1998) and FINNFLOW (Simons, 1980, Koponen et al. 1992), are used. The simulations are carried out using both models on the year 1995. The hydrodynamic models are verified against measurements of salinity, temperature, water level height and currents. The model results are compared also with each other to find out the differences between the models. The comparisons are made so that the external forcing wind and river flows, initial and boundary conditions were same in both the models during the simulation period. The modelled domain is the Gulf of Finland area, even if the authors fully admit the problems related to the uncertainty of the open boundary conditions. However, more important is that the external parameters in the models are the same.
The background of our model comparison is a practical one. Some years ago there was a national project in Finland concerning the ecological response of the Gulf of Finland to reduction of nutrient loading (Kiirikki et al. 2000). Two hydrodynamic-ecological models, namely the FINNFLOW and FinEst-models were used in these long-term simulations. It came out that there is a need to compare the results of the hydrodynamic models in order to be sure that there are no major differences between the results. Different processes are included in the usual application of each model. These differences are kept in the models, because the aim was not to compare the numerical method but the practical results of the models. A good idea in the near future is to test out models with more well-known 3D-models.

The results of the hydrodynamic modelling are important input information for ecosystem modelling, in which of the hydrodynamic parameters; salinity and temperature have variations which play the most important role in ecosystems. An accurately simulated salinity field is to some extent a proof that the transport of passive biochemical tracers can also be simulated correctly. Biological processes are often functions of sea temperature, which has to be predicted accurately by the hydrodynamic model. For these reasons, the model studies here and the verification of the model results concentrate on investigating salinity and temperature variations and structures but the model results are also verified against current and water level measurements.

The variety in numerical techniques, differences in parameterising sub-grid scale processes, different co-ordinate systems in vertical etc. lead to the fact that the results of the various 3D models are not the same. Here, we try to emphasise what reasons are to be found behind the differences in the results of the models. Both the models are also verified with measurements, but it should be stressed that due to the relatively low number of observations, which is usually the case in marine research, we should be careful in judging which model gives the most accurate results.

The structure of the paper is the following. In the first chapter, the physics of the Gulf of Finland are shortly described. The main characteristic numbers are given and the main hydrography of the gulf is described. The models used in the simulations are described in chapter 2. The next chapter is devoted to introducing the data sets used in the simulations, the main forcing factors, initial and boundary conditions as well as the simulation period. In the fourth chapter, the simulated model results as well as the comparison with measurements are described. Myrberg (1998) has carried out some preliminary calculations of horizontal salinity and temperature fields in 1995 using the FinEst model. The last chapter is focused on a summary of the results. The conclusions of the models’ ability to describe the physics of the gulf are discussed. Some guidelines for future work are outlined.

2. The Gulf of Finland

The Gulf of Finland (Fig.1) is an elongated basin in the north-eastern Baltic Sea. The gulf has no sill to the Baltic Sea Proper. The line between the Hanko peninsula and the island of Osmussaar is often treated as the western boundary of the gulf. The length of the gulf so defined is about 400 km and its width varies between 48 and 135 km. The surface area of the gulf is 29 571 km^2. The mean depth is 37 m, the maximum depth being 123 m (in the Baltic Sea 459 m), while the total volume is 1103 km^3, which is 5 % of the volume of the whole Baltic Sea. The northern coastal area is shallow and it has plenty of small island unlike the deep southern region of the gulf. The drainage area of 420 990 km^2 is 20 % of the total drainage area of the Baltic Sea (see Falkenmark and Mikulski, 1975).

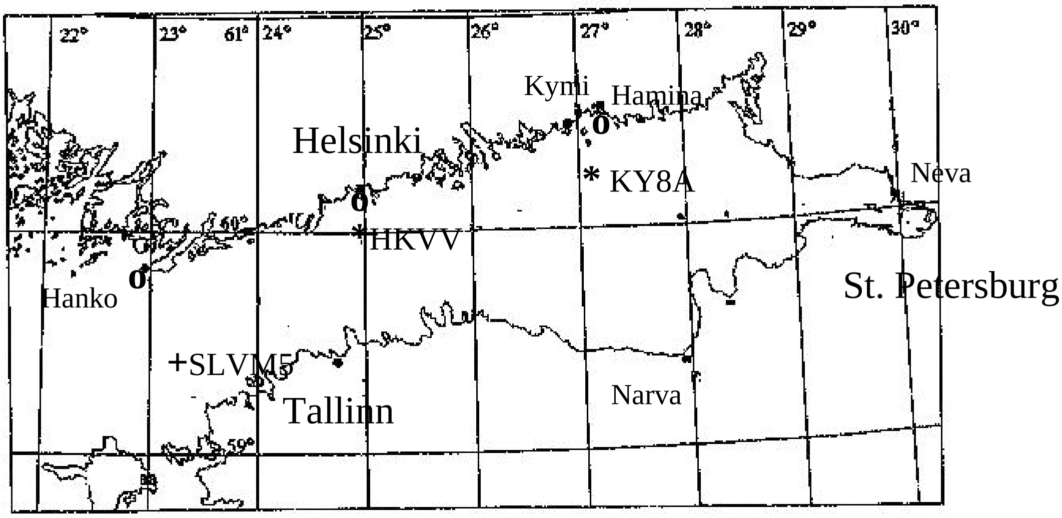


Fig.1. Relevant geographic locations in the Gulf of Finland (from Alenius et al. 1998). + = current mearurement station (slvm5), * = salinity and temperature measurement stations (hkvv and ky8a) and o = waterlevel measurement stations (Hanko, Helsinki and Hamina).

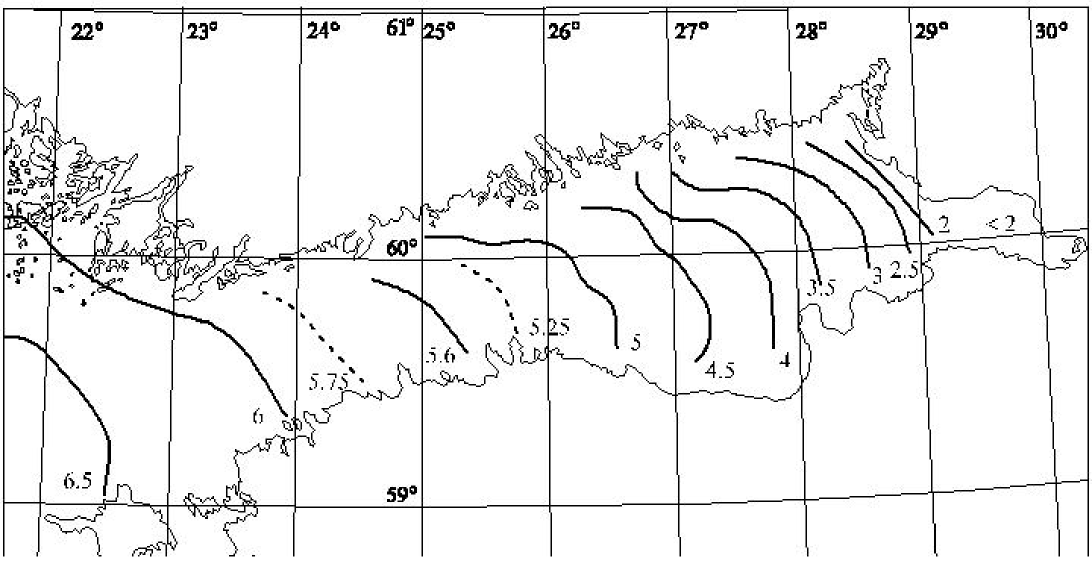


Fig.2. The average surface salinity in PSU in the Gulf of Finland (redrawn from Jurva 1951).

The eastern end of the gulf receives the largest single fresh water input to the whole Baltic Sea, namely the River Neva with a mean input of about 2700 m^3/s. This leads to a rather strong continuous east-west salinity gradient in the gulf (Fig. 2). The stratification conditions are very variable in space and time due to the above-mentioned reasons and because of the large seasonal variations in incoming solar radiation (Fig. 3). The density-driven circulation is an important factor in modifying currents in the gulf in addition to the wind forcing and the forcing introduced by the surface slope. The hydrographic features are strongly modified by the variable and complex bottom topography as well. The physical oceanography of the gulf is described in detail by Alenius et al. (1998).

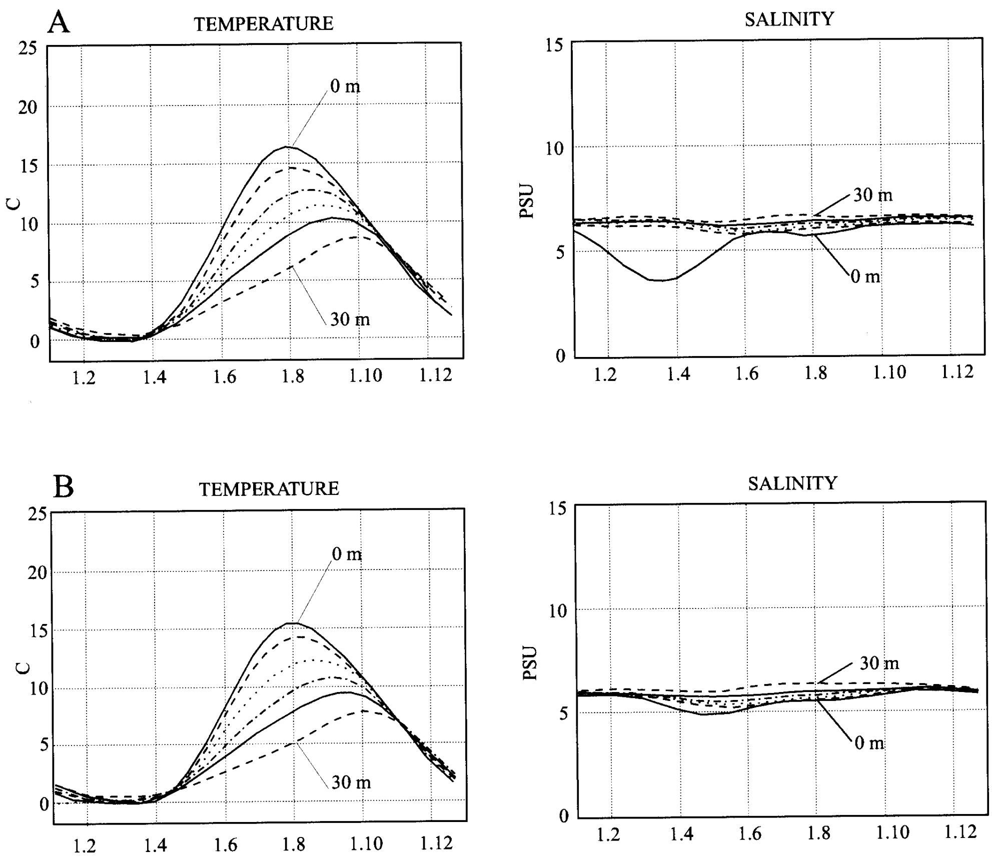


Fig.3. (A) The annual course of temperature (left) and salinity (right) at Tvärminne (near Hanko), based on observations in 1960-1991. (B) The same, but for Harmaja (near Helsinki) from Haapala and Alenius 1994.

3. The Models

The two hydrodynamic models used here are the FINNFLOW model (Koponen et al. 1992) and the FinEst model (Tamsalu, 1998, Myrberg, 1998). These two models are most widely used in the applications in Finland. The processes described in the models are those most usually simulated in the applications of each model, however they are not same between the models. Several assumptions are introduced in both models.

·The equation of entropy transfer is replaced by the equation of heat conduction in a fluid.
·Molecular processes are completely disregarded.
·The effect of the curvature of the earth is disregarded.
·The horizontal components of the rotation vector of the earth are disregarded.
·Boussinesq approximation
·Hydrostatic assumption

At the surface boundary both models calculate sensible heat, the latent heat of evaporation and the long wave radiative fluxes. The incoming short- and long wave fluxes are taken from the meteorological model. The turbulent flux of momentum depends squarely on wind velocity. The bottom friction depends squarely on flow velocity.

3.1 The FINNFLOW Model

The FINNFLOW model is developed in the Technical Researh Center of Finland in the early 1980's. It has been applied in the most environmental consulting cases in Finland.

The model used is a 3-dimensional baroclinic multilayer model (Simons, 1980, Virtanen et al, 1986, Koponen et al, 1992). The model area is divided into constant vertical layers as in the z-level models. Horizontally, the model area is subdivided into rectangles. The grid system is E according Arakawa's classification, which means that u- and v-components are calculated in the center of the grid cell and the pressure, concentrations and w-components in the corners of the grid points. u- and v-components are calculated to diagonal directions.

Control volume approach is used in numerical solution. The division of the calculation of the 3D currents is made by integrated 2D external mode (surface heights, depth integrated currents) and to 1D internal mode (layer velocity differences). Fractional steps are used (different time steps for different physical processes). Forward-backward Euler method is used in external mode with trapezoidal approximation for Coriolis term and forward Euler in other modules. The first order explicit upwind method is used for advection of concentration (and momentum). The density of the water is calculated linearly from salinity and squarely from temperature.

Eddy viscosity approximation of turbulence is used with constant coefficients vertically 15 $cm^2 s^{-1}$ (in spite of layers over 20 m depth (thermocline), where viscosity was 0.01 $cm^2 s^{-1}$) and horizontally 100 $cm^2 s^{-1}$. The advection of momentum has only minor effects on flows, when the flow velocities are small and horizontal resolution coarse. It was not calculated in the model. The shortest timestep used was 130 s.

3.2 The FinEst Model

The hydrodynamic-ecosystem model FinEst has been developed in the 1990´s in co-operation between Finland and Estonia (Tamsalu, 1998). Both two-dimensional and three-dimensional versions of the model have been developed. The model has been applied in many studies both in the Baltic Sea and in the Mediterranean. The Baltic Sea research has concentrated on the Gulf of Finland (Tamsalu, 1995, Myrberg, 1997) and on ecosystem studies (Tamsalu and Ennet, 1995, Ennet et al., 1999). The physical and biological model simulations of the Gulf of Finland, the Gulf of Riga, the Baltic Proper and the Mediterranean are described by Tamsalu (1998). A detailed description of the derivation of the model equations as well as their numerical solution is given by Tamsalu (1998).

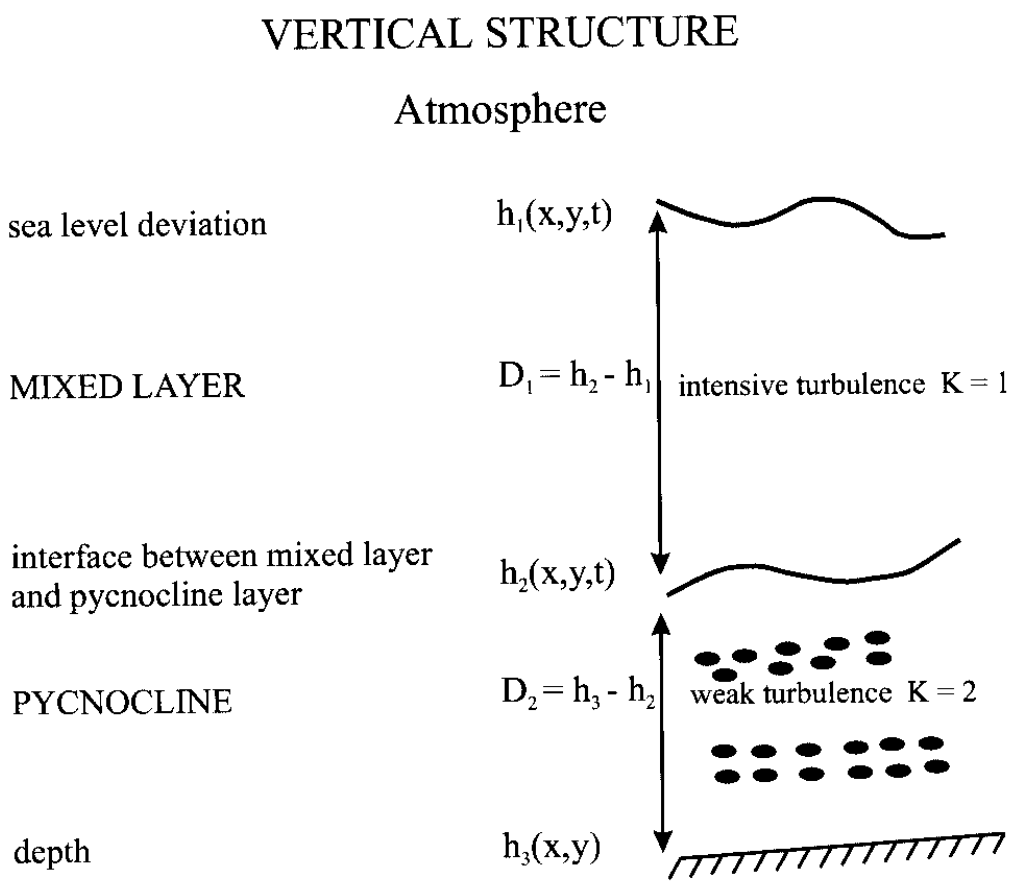


Fig.4. The vertical structure of the three-dimensional FinEst-model.

The vertical structure of the three-dimensional version of the FinEst model is based on a modified sigma-co-ordinate system (Fig.4), in which the model is vertically divided into two layers. In the upper layer, the turbulence is continuous. The thickness of the upper mixed layer is a prognostic variable. Below that layer, there is a stratified layer with intermittent turbulence. The model consists of eight levels in the well-mixed layer and eight levels in the stratified layer. All variables have a three-dimensional structure at all levels, except salinity and temperature, which are vertically integrated in the upper mixed layer.

The so-called split-up method (Marchuk, 1975) is used to solve the marine system equations. The numerical scheme used in the model was devised by Mesinger (1981). The scheme is a consistent and convergent second-order numerical solution. Implicit methods have been used (for details, see Tamsalu, 1998). In the half grid-step positions, the variables have been calculated using interpolation. The density of the water is calculated by UNESCO (1976) formula.

Turbulence is parameterised using the coefficients of eddy diffusivity; the coefficient of vertical turbulence is dependent on the Richardson number. The advection of momentum is included to the model. The time step used is 10 minutes. No case specific parameter values was used in the application.

4. Material and Methods

Background

Simulations by the FINNFLOW and the FinEst models concentrated on the Gulf of Finland in the year 1995. In the following, the main model simulations are introduced and the corresponding data sets used for model input are listed. The verification material is briefly described as well.

<u>The Modelled Area</u>

In this study, the same depth grid was used for both models. The horizontal resolution of the models was 5 minutes in longitude and 2.5 minutes in latitude, which means about 4.5*4.5 kilometres. The co-ordinates of the lower left corner of the model grid are 58°57.5'N, 22°25'E and the upper right corner is located at 60°32.5'N, 30°00'E.

<u>External Forcing for the Model</u>

The meteorological data for wind speed and direction and for the atmospheric temperature were taken from the HIRLAM model (Gustafsson, 1991). The fields used for wind speed, direction, and atmospheric temperatures were 6 h forecasts from the 10 m level. Air temperature used is from 2 m height. Every 6 hours the atmospheric data for humidity was taken from the observations of weather station of Kalbådagrund (59°58'N, 25°37'E; height of observations: about 31 m). Since the total cloudiness is not observed at Kalbådagrund, the 6 h values of cloudiness were taken from the observations of the Isosaari weather station (60°07'N, 25°03'E). An areal interpolation was carried out in order to place the HIRLAM data on the grid of the sea model. The humidity and cloudiness data was not available from the HIRLAM model.

In the simulations, the mean monthly river runoffs for the Rivers Neva, Kymijoki, Narva and Luga were taken into account for 1995, and the runoffs of small rivers were added to these. The sea level observations (hourly means) from Hanko (59°50'N, 23°00'E) on the Finnish side were used as input too.

<u>Verification Data</u>

The verification data used in simulations consists of the following parts: temperature and salinity measurements, CTD data, water level data, and Aanderaa-current measurement data.

In 1995, the data exists in the period between May 29 and June 9 (77 CTD casts, see R/V Aranda Cruise Report 9a-b, 1995) and in the period between August 28 and September 8 (96 CTD casts, see R/V Aranda Cruise Report 16a-b, 1995). The data from the May-June cruise have been used in determining the models' initial conditions. The data from the August-September cruise is used in model verifications. The CTD data has been further transformed into files in which temperature and salinity are given at 1 m depth intervals. This data is the basis for the model verifications in this study. The surface temperature and salinity have been given the values at a depth of 5 m, and the bottom salinity and temperature are the corresponding values at the lowest depth (about 5 meters form sea bed) at which measurements were carried out.

The time evolution of temperature and salinity have been recorded at numerous coastal stations during April 1- October 1, 1995. The highest temporal resolution of the measurements was at stations (HKVV 60°05'N, 25°08'E and KY8a 60°23'N, 27°39'E). These measurements are used in model verifications of the time evolution of salinity and temperature although the results from other stations are also used as background material in the analyses. At these stations, all the measurements from the surface to 5 m depth are used as representative values for the upper mixed layer, whereas the measurements from 20 m to bottom are expected to represent the near-bottom conditions.

The water level data has been used both for model verification and for data input purposes. The water level observations (1 hour interval) at Helsinki (60°09'N, 24°55'E) and Hamina (60°34'N, 27°10'E) have been used to verify the corresponding model results.

The current measurements used here are based on point measurements (Aanderaa-measurements) at the western gulf at the mouth area of the gulf. The currents are measured at 10 minute intervals. Currents were measured at several points, but this study focuses on two points (SLVM2 at 59 °36'N, 23°16'E and SLVM5 at 59°24'N, 23°20'N) at the depth of 8 meters.

Boundary and Initial Conditions

The boundary conditions for salinity and temperature were determined from the CTD observations (surface and bottom salinity and temperature) in the transition area between the Baltic Proper and the gulf. In 1995, special measurements were carried out at longitude 22° 30' E during R/V Aranda's Gulf of Finland cruises to fulfil the need for boundary conditions. The boundary conditions at the western liquid boundary were determined as follows. The first measurements were carried out in May-June. During this two-week period several transects were taken at the location of the model's open boundary. These measurements were extrapolated on to the grid points along the western boundary. These were the best boundary conditions available and this set was used as initial conditions at the boundary in April, even if the measurements were carried out only later. However the most important thing is that we have relevant information about the salinity close to the bottom and that the salinity stratification is right. The May-June temperature was not used in the beginning of the simulation in April, because the sea is then well-mixed in terms of temperature. The other measurement campaign was carried out in August-September. Boundary condition for salinity and temperature was formed again from the corresponding data set and the new boundary conditions, representing stratified summer conditions, were used from July-August to the end of the simulation.

The water elevation in the boundary was taken from the measurements from Hanko station. Models calculate the water exchange over boundary from these measurements. The average flow velocity is used in all boundary grid points.

The CTD measurements from the May to June cruise were used to determine the initial conditions for salinity and temperature. The set of measurement stations is similar to the set used in result chapter (figs. 9-11).

5. Model Results

The model results studied here are the following: temporal variability of salinity and temperature in surface and in the bottom, spatial variability of temperature and salinity in surface and in the bottom, water level height variability and variability of currents in the upper layer. Results of both the models are compared with measurements as well as with each other.

Some statistical approaches have been used in analyses of the model results. It should be remembered that the statistical analyses are based on a very limited number of observations. Thus, the results give just an overall view of the models' accuracy. The summary of the results from the measurement points is given in the table 1.

Table 1. The summary of the average and maximum errors and the correlations between model simulations and the measurements from different measurement points.

			FINNFLOW			FinEst		
position	Variable	depth	Ave. error	Max. error	R2	Ave. error	Max. error	R2
HKVV	Salinity	0-5 m	0.15	0.55	0.86	0.25	0.80	0.37
KY8A	Salinity	0-5 m	0.3	0.53	0.93	0.18	0.39	0.94
HKVV	Temp.	0-5 m	1.1	3.1	0.97	1.6	6.6	0.91
KY8A	Temp.	0-5 m	0.6	1.6	0.99	0.9	3.1	0.97
HKVV	Salinity	bottom	0.07	0.12	0.95	0.18	0.35	0.47
HKVV	Temp.	bottom	1.0	2.9	0.47	0.8	1.6	0.88

5.1 Temporal Variability of Salinity and Temperature

Upper Layer

There was a decreasing trend in the salinity from April to the beginning of July at station HKVV (60° 05' N, 25° 08' E). The measured values of salinity decreased by about 0.5 PSU. After that, the salinity increased rapidly by about 1 PSU. That was caused most probably by upwelling, which is typical near Hanko and Porkkala Peninsulas when strong westerly and south-westerly winds blow for several days (see e.g. Haapala, 1994, Alenius et al. 1998). Such events become visible in the wind pattern of Kalbådagrund in July-August (for example, on July 4-9, July 18-21, July 22-25, August 22-28.). During the late part of the summer, the salinity was nearly constant due to the pronounced stratification. In September, the dominating easterly winds brought fresher water from east to the area studied. At station KY8A, which is located in the eastern part of the central gulf, the measured salinity increases quite linearly from about 3 PSU in the spring to about 4.5 PSU in October. This kind of behaviour is typical in the gulf, where the highest river runoffs take place in spring. A local minimum of salinity (about 3.3 PSU) is observed in September, as well as at the station HKVV, due to the same reasoning.

The FINNFLOW model was able to simulate well the time evolution of salinity (measurements between 0 and 5 m) measured at the station HKVV (Fig.5a). The statistical comparisons were made between average of measured values between 0-5 m and simulated values. The average error between measurements and model results was less than 0.15 PSU and the maximum difference 0.55 PSU. The correlation was 0.86. At station, KY8A (Fig.5b) the dynamical behaviour of salinity differs from HKVV measurements. The average error was about 0.3 PSU and maximum error 0.53 PSU. However, the correlation was a high 0.93, which means that the dynamical behaviour was very similar in the model and the measurements.

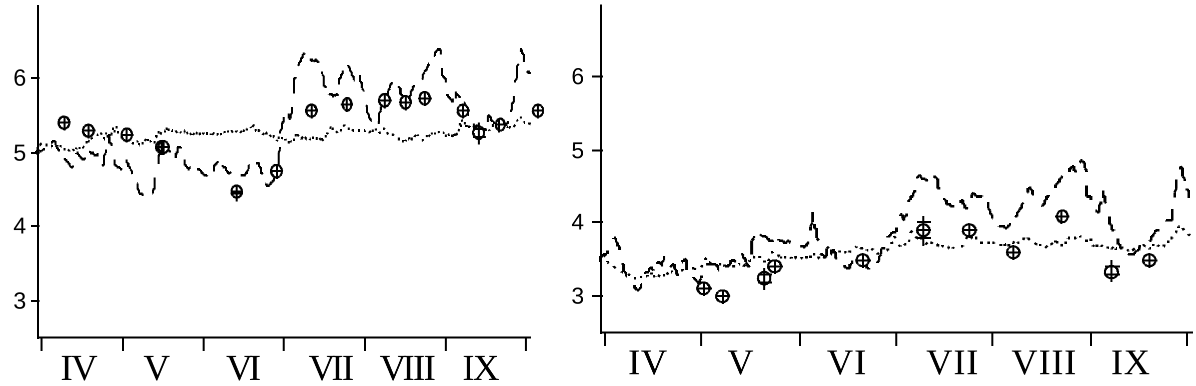


Fig. 5a,b Surface salinity at HKVV (left), KY8A (right) during 1.4.-1.10.1995 by FINNFLOW (dashed line) and by FinEst (dotted line). The plus symbol is measurement, circle is average of simultaneous measurements.

The role played by the fixed values for salinity at the western boundary of the model is seen. Hence, in the FinEst model the variability of the salinity is clearly less than shown by the measurements and by the FINNFLOW model. The model results differ from measurements at both stations HKVV (Fig.5a) and KY8A (Fig.5b) in the early summer by about 0-0.5 PSU, occasionally near 1 PSU. Consequently, the difficulties in describing the evolution of the mixed layer thickness are also reflected in the salinity simulations. In July-August, when the stratification is pronounced, the surface salinity can be simulated with errors of 0-0.0.3 PSU. The relatively high accuracy of these results is partly due to the measurements at the western boundary available. At station KY8A the salinity drops of more than 0.5 PSU in the beginning of September (see above) are not described satisfactorily by the model. Errors up to 0.39 PSU take place at station KY8A, whereas the average errors were about 0.2 PSU in both stations. The correlations were 0.37 at HKVV and 0.94 at KY8A.

The overall variability of the surface temperature was typical with maximum temperatures of about 15-18 degrees in early August. However, the temperature increase was not linear after the beginning of the summer (May-June) due to the upwellings which make simulation more difficult. There was also a clear vertical temperature gradient in the beginning of June. The temperature at the surface was about 15 °C, but at the 5 m depth only 8 °C (station HKVV, Fig.6.). The high gradient is due to the fact that the thermocline is under strong development. The used models were unable to describe these kind of small scale variations, because of the coarse vertical resolution. In addition, the temperatures produced by models are mean values in the 0-5 m layer. Thus, the models underestimate the surface temperature by about 1-3 degrees. One additional reason for these errors in simulations in the spring is explained by the inaccuracies in the atmospheric forcing. The atmospheric planetary boundary layers are very stable in this situation; a very warm air mass advects over the cold sea (air temperature in Kalbådagrund between 20-25 degrees). In this situation the HIRLAM-produced atmospheric temperature (2 m height) is strongly underestimated compared with measurements (see

Myrberg, 1998). This directly influences the surface temperature simulations.

The overall structure of the time evolution of the surface temperature was simulated well by the FINNFLOW model except in late May and early June. The upwelling situations are quite well simulated, but in some cases, the model-produced temperature does not rise after the upwelling as much as according to the measurements. The median difference between simulated and measured temperatures were 0.7 degrees at the station HKVV (Fig.6a) and 0.6 degrees at the station KY8a (Fig,6b). The maximum error was 3.1 degrees at HKVV and 1.6 degrees at KY8a. The correlation was 0.98-0.99 at both stations.

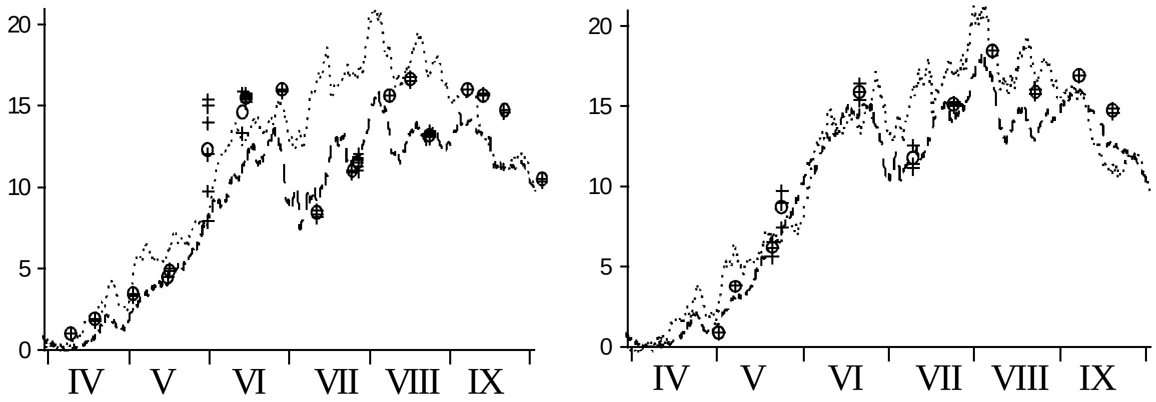


Fig.6a,b Surface temperature at HKVV (left), KY8A (right) during 1.4.-1.10.1995 by FINNFLOW (dashed line) and by FinEst (dotted line). The plus symbol is measurement, circle is average of simultaneous measurements.

The overall structure of the time evolution of temperature in the upper mixed layer was simulated fairly well by the FinEst model at both stations HKVV (Fig.6a) and KY8A (Fig.6b). The error in the model simulations is usually between 0-2 degrees except in May and early June (see above) The FinEst model overestimates the surface temperature in July and August especially at the station HKVV (up to about 6 degrees) due to the inadequate description of upwelling. At the station KY8A, the overestimation is about 1-3 degrees. The correlations were 0.91 at HKVV and 0.97 at KY8A.

Bottom Layer

The simulations in the near-bottom layer are problematic in regional models, because salinity and temperature at the open boundary are very variable but unfortunately badly known due to lack of observations. However, the station HKVV is far from the open boundary and there are not so pronounced gradients of salinity and temperature as near the mouth of the gulf (see section 4.2). The inaccuracies in the averaged depths, used in the grid, also lead to the conclusion that the comparison with measurements was reasonable only at the station HKVV.

Due to the differences of the vertical description of the models, the analyses of the bottom layer can not be exactly the same. In the FINNFLOW model simulated values were compared with the average measurements below 20 meter depth. Due to the low resolution, the depth in the model's grid point was less than at the station in reality. In the FinEst model, the model result represents the condition near the bottom, so the model results are compared with the observations closest to the bottom (depth 45-48 m).

The average difference between measurements and the FINNFLOW model results was 0.07 PSU and maximum difference 0.12 PSU at the HKVV station (Fig. 7). The correlation was 0.95, so the ability of the model to reproduce the salinities in the bottom layer was high. The simulation of the bottom salinity at the station HKVV gave satisfactory results with the FinEst model (Fig.7). The errors in the simulation were less than 0.2 PSU. This result is partly explained by the fact that the salinity was quite constant through the simulation period. However, the correlation was only 0.47.

The modelled bottom temperatures are higher than the measured ones because of higher mixing in the FINNFLOW model. At station HKVV (Fig. 8), average error was 1.0 degrees and the maximum error 2.9 degrees. The correlation was 0.95. The bottom temperature at the station HKVV was fairly well simulated in the FinEst model (Fig. 8). The correlation was 0.88. Due to the different grid definition, the simulation results of FINNFLOW should compare to the circles and the FinEst ones to the * symbol.

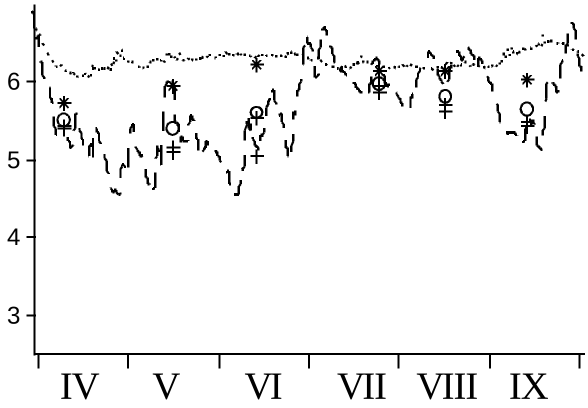


Fig. 7 Bottom salinity at HKVV during 1.4.-1.10.1995 by FINNFLOW (dashed line) and by FinEst (dotted line). The plus symbol is measurement, circle is average of simultaneous measurements and asterisk deepest measurement.

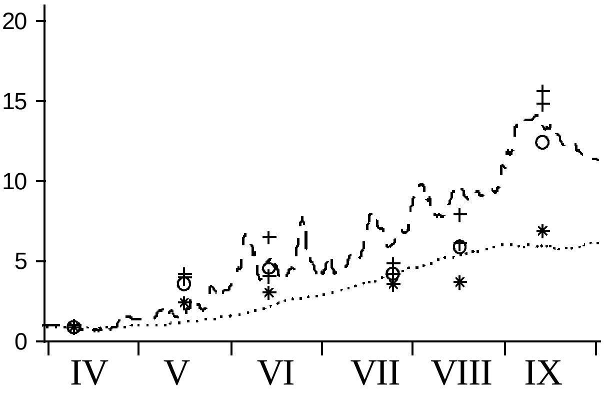


Fig. 8 Bottom temperature at HKVV during 1.4.-1.10.1995 by FINNFLOW (dashed line) and by FinEst (dotted line). The plus symbol is measurement, circle is average of simultaneous measurements and asterisk deepest measurement.

5.2 Spatial Variability of Salinity and Temperature

Surface Layer

The surface salinity varies in the gulf from about 5.5-6.5 PSU in the western part to about 0-2 PSU in the eastern gulf. Relating to the melting of ice cover and the increased springtime Neva runoff, the salinity decreases from winter to midsummer. This was the case in 1995, too. In late summer, the surface salinity somewhat increases.

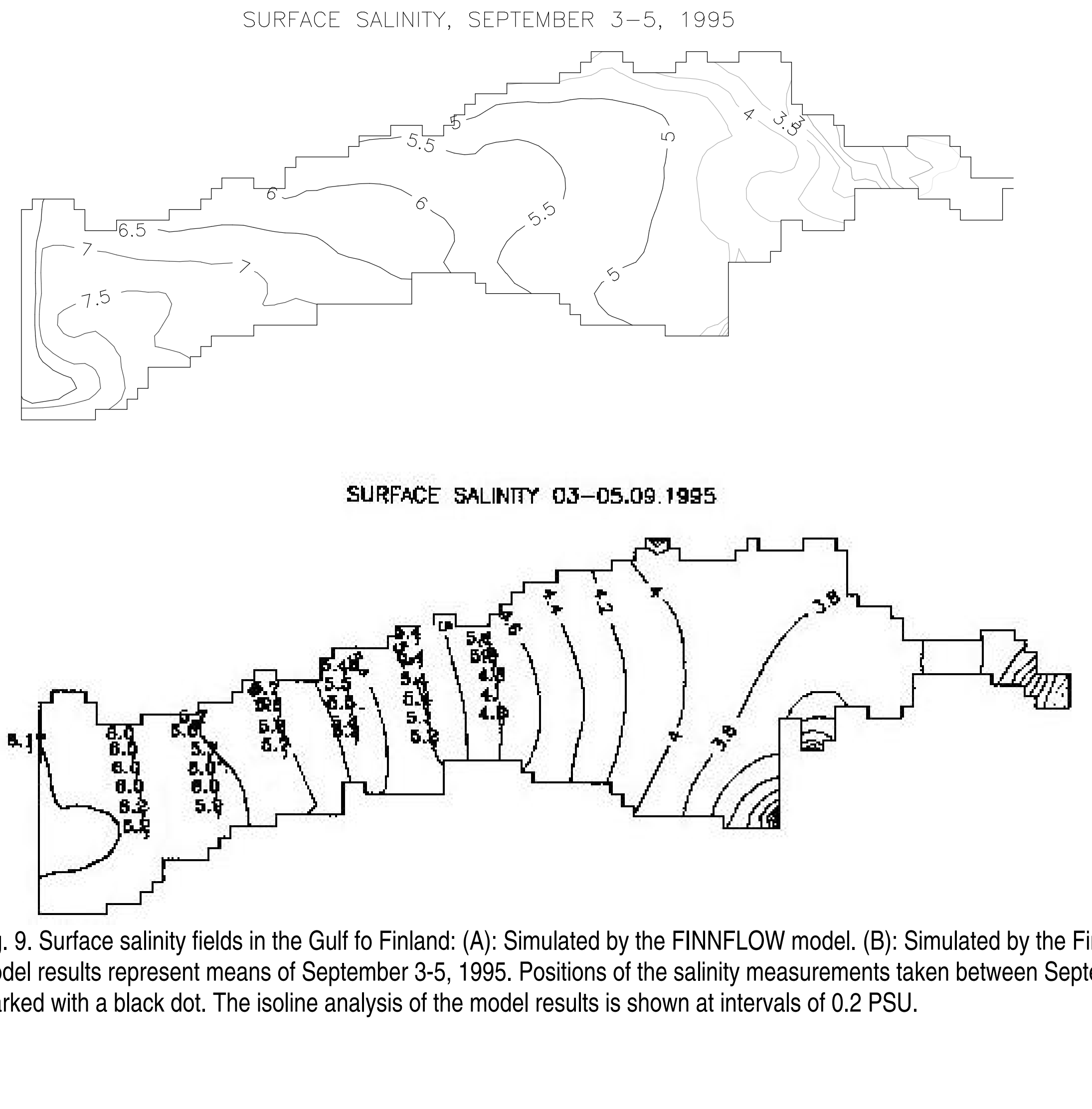


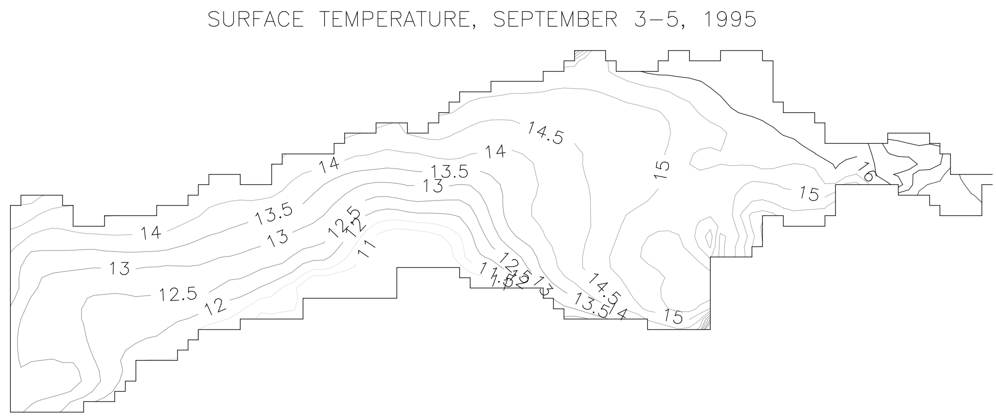
Fig. 9. Surface salinity fields in the Gulf fo Finland: (A): Simulated by the FINNFLOW model. (B): Simulated by the FinEst model.The model results represent means of September 3-5, 1995. Positions of the salinity measurements taken between September 3-5 are marked with a black dot. The isoline analysis of the model results is shown at intervals of 0.2 PSU.

The most intense measurements of the horizontal distribution of salinity and temperature were carried out between August 28 and September 8. Here we discuss how the models can reproduce the observed horizontal distribution firstly of salinity and then that of temperature.

The average spatial distribution from September 3 to 5 simulated by the FINNFLOW model as well as all measurements made during that time are presented in Figure 9a. The simulated surface salinity decreases from the western 7 PSU to 0 near river Neva. The model generates an artificial upwelling in the south-west part of the Gulf of Finland due to the inaccurate description of boarder conditions. Apart from that, the east-west gradient was simulated well. The difference between measurements and simulation was from 0-2 PSU in the western part of the Gulf and approximately half of that in the central part.

The overall horizontal salinity structure given by the FinEst model is generally well in accordance with measurements. The effects of the fresh water input from the main rivers (Neva, Kymijoki, Luga, and Narva) become also visible. The surface salinity is modelled quite accurate, the errors being usually about 0-0.3 PSU compared with measurements (Fig. 9b). The errors are somewhat larger in July, when no new measurements were available at the model's open boundary, being up to 0.5 PSU. So, the statistical errors in percentages in July, August and September are 4.2%, 3.6% and 3.4%. (for details see Myrberg, 1998). No systematic errors were found. The errors have some spatial variability, too. The model results are the most accurate near the open boundary in west, which is supported by measurements (in late August-early September). The errors increase eastward because the surface salinity gradients increase also eastwards and because that area is far from the open boundary where measurements are available. Some possible reasons for the errors in the salinity patterns are the inaccuracies in the HIRLAM-wind fields (see discussion).

The errors in salinity simulations can be estimated also in the following way: the mean salinity change in the gulf is about 1 PSU per 60 kilometres (length 400 km, salinity from 0 to 6.5 PSU). During the stratified season, the error in the salinity simulations varies around 3% at best, when measurements at the open boundary are available. If the average surface salinity in the gulf is about 4.5 PSU, it means that the model's error on spatial scale is between 5 to 10 kilometres, while the model's horizontal resolution has same magnitude 4.5 km.



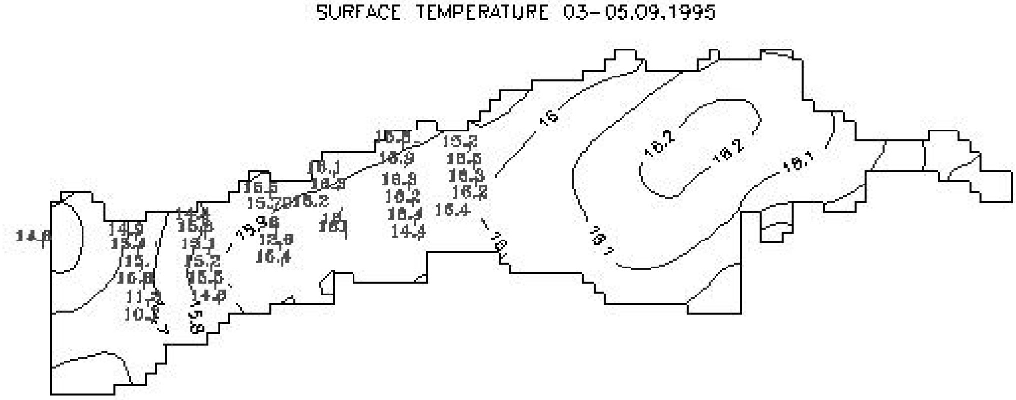


Fig. 10. Surface temperature fields in the Gulf fo Finland: (A): Simulated by the FINNFLOW model. (B): Simulated by the FinEst model.The model results represent means of September 3-5, 1995. Positions of the temperature measurements taken between September 3-5 are marked with a black dot. The isoline analysis of the model results is shown at intervals of 0.2 degrees.

The horizontal structure of the surface temperature has a pronounced variability and thus the simulations of the temperature fields give less satisfactory results than the salinity ones. The local upwellings cause inhomogenities in the temperature field, too. The surface temperature varied during the intense measurement period (August 28-September 8, 1995) usually between 14-16.5°C, but due to local upwellings temperatures as low as 9-10 °C were observed.

There was clear upwelling in the Estonian coast of Gulf of Finland during September 3-5. The surface temperatures were about 4 degrees lower in the south both in the simulated field by the FINNFLOW model as well as according to the measurements (in one horizontal cross section). However, too strong mixing through the thermocline in the model causes lower surface temperatures. The average error was about 2 degrees and there was not much difference between western and central part of the Gulf (Fig. 10a).

The horizontal structure of the surface temperature has a pronounced variability and thus the simulations of the temperature fields according to the FinEst model give less satisfactory results than the salinity simulations. The mean errors of temperature simulations in July, August and September are 14.5%, 9.1%, and 10% respectively. If the average surface temperature is about 15 degrees, the error in model results is of the order of 1-2 degrees, which is a fairly good result. There was usually no remarkable difference in the errors in the function of space. However, the model did not describe the local upwellings well enough. In such situations, errors up to 5 degrees were observed (Fig. 10b).

<u>Bottom Layer</u>

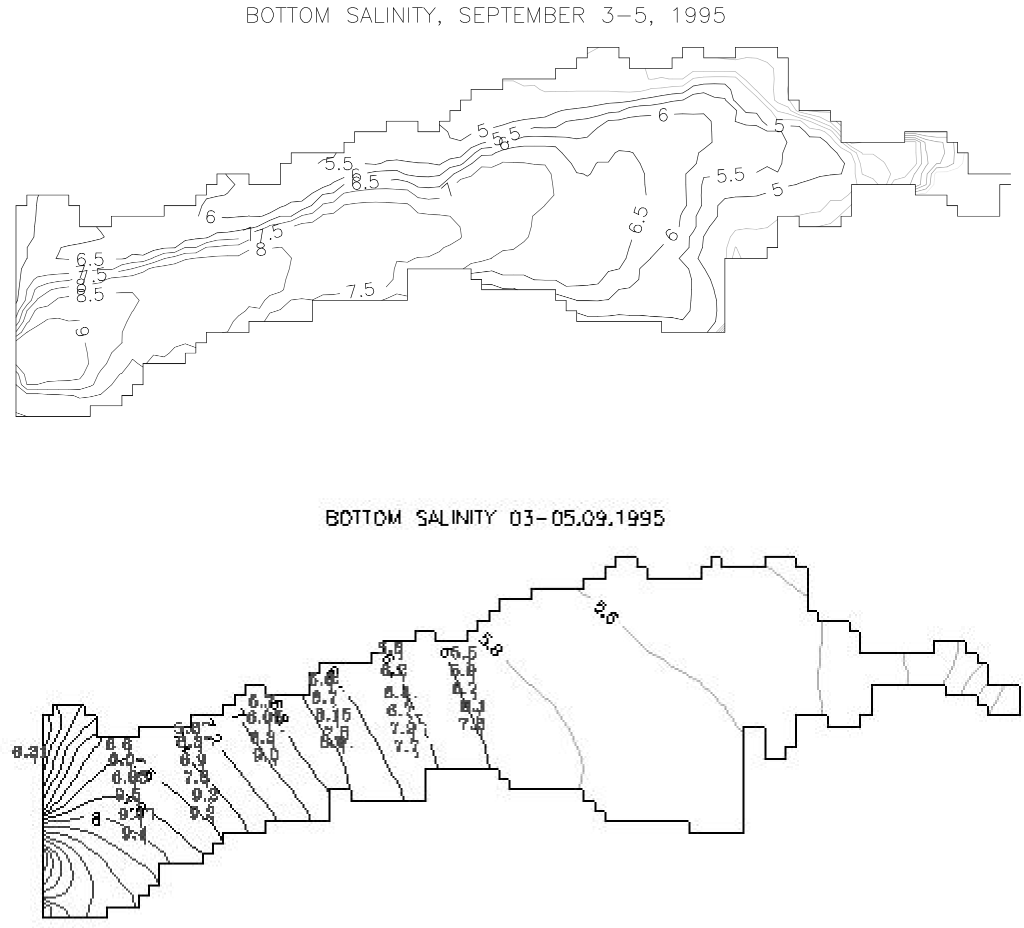


Fig. 11. Bottom salinity fields in the Gulf fo Finland: (A): Simulated by the FINNFLOW model. (B): Simulated by the FinEst model. The model results represent means of September 3-5, 1995. Positions of the salinity measurements taken between September 3-5 are marked with a black dot. The isoline analysis of the model results is shown at intervals of 0.2 PSU.

The horizontal variability of the near-bottom salinity is difficult to simulate in regional models with inadequate open boundary conditions, because the penetration of the saline water in the near-bottom layer is a rapid process in which saline water penetrates to the gulf at the south-western part, where the deepest parts exist (see, Tamsalu and Myrberg, 1995). There are often formed frontal zones of salinity in the area (see e.g. Alenius et al. 1998). The resolution of the models is too coarse to simulate this phenomenon accurately.

The artificial boundary at western Gulf of Finland increases vertical mixing in the model so the differences between measurements were, on average, 0.5-1.0 PSU in the western part of Gulf according to the FINNFLOW model (Fig. 11a). The modelled gradient to the east was the same as in the measurements. Errors were clearly lower (median about 0.3 PSU) than in the surface. However, the simulated salinities were slightly lower than the measured ones in the bottom layers at the same time as the simulated surface values were too high, which indicates that vertical mixing is too effective in the model.

The errors in the horizontal structure of the bottom salinity simulated by the FinEst model are usually about 0.5-1.5 PSU. It becomes clearly visible that the model cannot reproduce accurately the intrusion of saline water from the Baltic Sea Proper (Fig. 11b).

The errors in the simulation of the near-bottom temperatures are closely connected to the problems with the simulations of bottom salinity and thus the problems with estimations of overall stratification conditions. As a consequence, the exchange between surface and bottom layer is not accurate and reflects in the bottom temperatures. Usually the stratification is too weak and the bottom modelled temperatures become higher than the observed ones.

The modelled bottom temperatures according the FINNFLOW model were clearly higher than the measured ones, especially near the artificial boundary in the western Gulf. The boundary causes up- and downwelling phenomena which mix waters in the western part. The effects can be seen clearly as far as in the middle of the Gulf, where the measurements end. The errors were from 2 to 7 degrees.

The near-bottom temperature is underestimated according to the FinEst model in the western gulf by about 0-2 degrees and overestimated in the central gulf about 1-3 degrees; occasionally the errors can be larger, if the stratification conditions in the model are very inaccurate.

5.3 Water Level Height and Surface Currents

<u>Water Level Height</u>

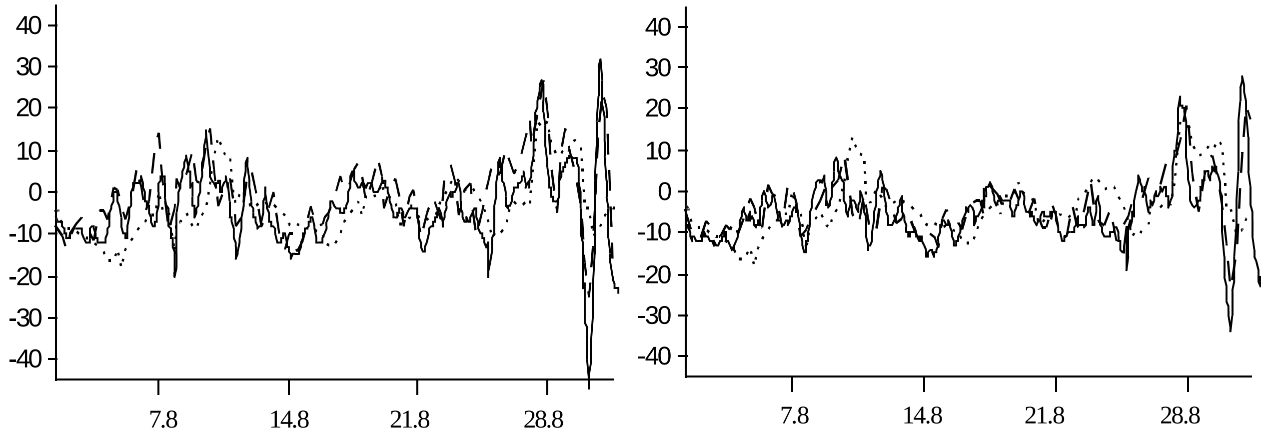


Fig 12. Water level height simulations Helsinki (left) and Hamina (right) during 1.8.-30.8.1995 by the FINNFLOW (dashed line), by the FinEst model (dotted line) and by measurements (continuous line).

The water level height simulations in Helsinki and Hamina were quite successful in both the FINNFLOW and the FinEst models (Fig. 12), which can be expected because the water level variability is mostly a barotropic process. The models are capable of reproducing the main features of the water level variability. There seem to be no major differences between model results and measurements. The timing of the water level maximum is quite well reproduced by the models even if the highest observed water levels are sometimes underestimated by the models. The correlation coefficient between model results and measurements is about 0.9 in both models. However, the correlation coefficient between the Hanko measurements (boundary) condition and Helsinki/Hamina is about 0.95. Thus the dynamic of water level strongly correlates to the boundary conditions and the models did not give more information about this fact. The errors in the simulations can be expected to be related to the inaccuracies of the wind field as well as to the fact that the water level at the open boundary was only available in Hanko.

There is clear 12.4 hour cycle in the spectra of measured water level in Hanko and Hamina. This frequency disappeares in the Fourier transformation series of the data of Helsinki (middle station), which might indicate that this station is in the middle of the seiche wave. These cycles are not found in the spectra of modelled timeseries. There are also same frequencies between 24-28 hours, which might be due to the basin oscillation of the whole Baltic Sea. Models are not able to produce these frequencies, because they use water levels in Hanko as a boundary value.

Currents in the Upper Layer

The comparison between the current measurements and the corresponding model results did not give very promising results (Fig 13). This is due to the fact that the inertial Rossby radius of deformation is in the Gulf of Finland between 1.3 and 2.5 kilometres (Fennel et al. 1991), and this scale cannot be described by the model with a horizontal resolution of about 4.5*4.5 kilometres. The measurement station is unfortunately located quite near to the open boundary of the model, too.

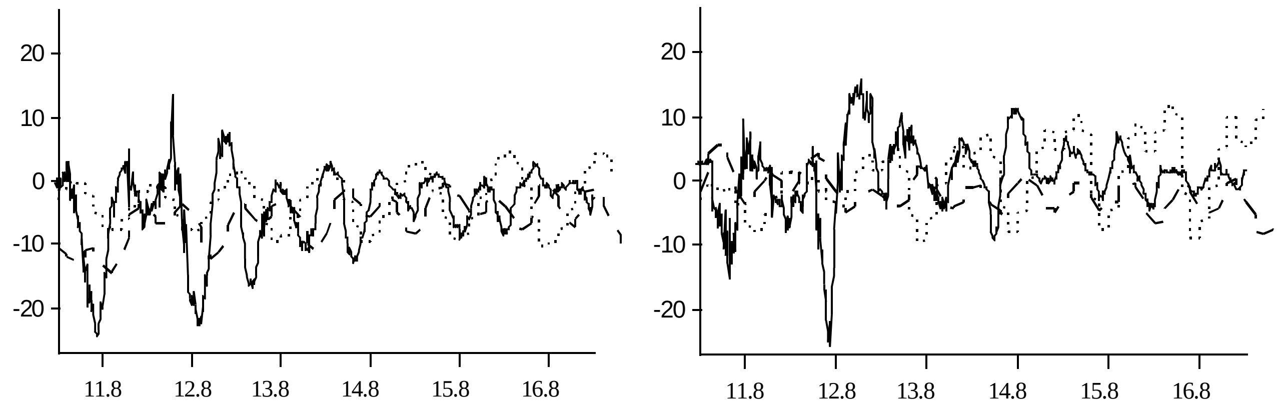


Fig. 13. Simulation of currents (x-direction left, y-direction right) during 11.8.-16.8.1995 by the FINNFLOW (dashed line), by the FinEst model (dotted line) and by measurement (continuous line).

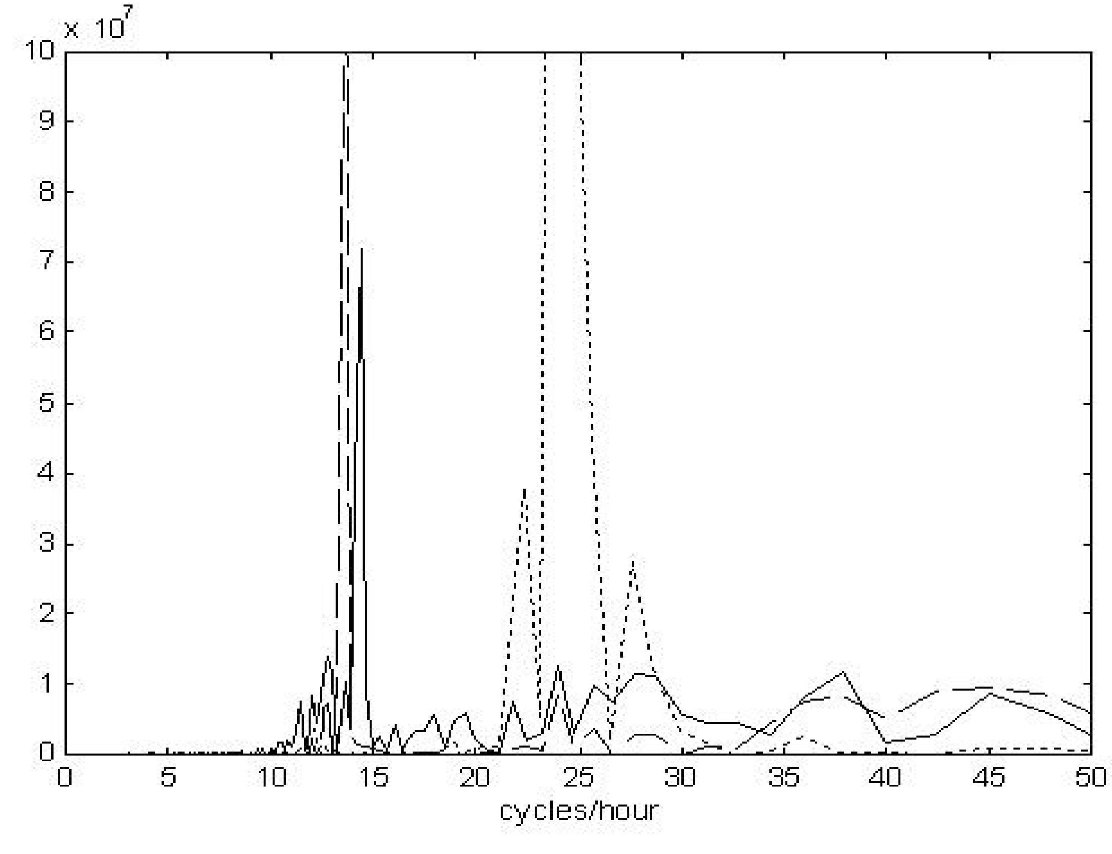


Fig.14. Fourier analysis of measured currents (continuous line) and simulated by the FINNFLOW (dashed line), by the FinEst model (dotted line).

The Fourier transformation was made to the time series. The main frequency in the measurement was 14.4 hours. The inertial period is approximately 13.9 hours at this station (lat. 59.39). The main peak simulated by the FINNFLOW model was very close to this theoretical value (Fig.14).

According to the results of the FinEst model, the role of the inertial oscillation is clearly underestimated and the main energy according to the model results is concentrated on the diurnal time scale. According to Pohlmann (1997), a reason can be found why the three-dimensional model does not describe the inertial oscillations like a one-dimensional model. Namely, one-dimensional model describes local processes while three-dimensional models additionally treat the horizontal viscosity and the advection of momentum. Both processes generate a damping of momentum in the system; the former process is physically meaningful, whereas the latter is caused by the numerical scheme but it is principally taken into account when the horizontal viscosity coefficient is determined. Thus, in one-dimensional models, the inertial oscillations are overestimated because of the lack of horizontal viscosity which in the three-dimensional models as well in reality induces a damping of these oscillations.

6. Discussion and Conclusions

The temporal variability of temperature was simulated well by the models. The FINNFLOW model also reproduced the main upwelling periods with decreasing temperatures as well as the corresponding changes in surface salinity. The pronounced east-west gradient of salinity was fairly well simulated by the models. The FinEst model gave more accurate surface salinity and temperature distributions on the average, whereas the results of the FINNFLOW model were better in bottom distributions.

One possible explanation is that the sigma co-ordinate system in the FinEst-model is a rather complicated and there may be difficulties to keep the right layer structure near the bottom. The FINNFLOW-model has a constant structure of layers, which favours the simulations near the bottom. On the other hand, better described vertical structure is in the FinEst-model. In the FINNFLOW model constant turbulent coefficients for upper and lower layers were used, while in the FinEst model, the vertical turbulence is dependent on Richardson-number. The different parameterisations certainly partly explain the reasons why the stratification conditions are different in the models.

There are other reasons which cause inaccuracies in the simulations of the surface temperature. One main reason is that the atmospheric model HIRLAM had a horizontal resolution only of 55*55 kilometres. So, the description of the temperature pattern over the narrow gulf is not accurate enough**.** There are drawbacks in the description of sea-land temperature differences as well as in estimations of the daily temperature cycles (for details see e.g. Myrberg, 1997).

The accuracy of the near-bottom salinity and temperature suffered from inaccuracies in the open boundary conditions and related problems in defining the stratification conditions in the Gulf. It should be stressed that there are considerably high gradients at the open boundary area in the near-bottom layer. That makes the role of inaccurate boundary conditions more problematic than in the surface layer, where high gradients are not usually observed so often.

The verifications of the models with temporary currents gave unsatisfactory results mainly due to a too horizontal resolution of the models. The internal Rossby radius in the gulf is about 1-3 km, and thus the models cannot describe the small scale eddies and flow patterns. The available measurements were also near the boundary, which cause problems.

It can be argued how the salinity and temperature simulations can be rather successful, when the verification of model results with currents failed. There are several reasons to that. Firstly, the seasonal evolution of sea-surface temperature is strongly dependent on the seasonal cycle of the incoming solar radiation. Even 1D-models can give reasonable good estimates of the surface temperature without any information of circulation systems (Tyrväinen 1978). However, really accurate estimations of salinity and temperature simulations need good information of currents. Because of the good results of salinity and temperature and due to the good mutual agreement of our mean current fields with our basic knowledge the current system, we think that the models can in general reproduce the main features of the current field even if our verification of the model results with current temporary measurements was less successful. This is most probable due to reason that we compared a point measurement of currents with our simulated currents, which represent an average of a 4.5*4.5 km grid box. So, there are small-scale fluctuations in the current fields, which cannot be resolved by the present resolution of the models. The simulated and measured current have also clear cycles. If the phase of the modelled current differs from the measured one the correlation can be even negative, while the mean current is calculated correctly. No better current field measurements were available and on the other hand we wanted to show as objective as possible also the weaknesses of our present models.

The main explanation for the dynamics of water level is the boundary condition. Models were able to transmit these dynamics to the other measurement points but did not give any additional information.

It can be finally concluded that both models gave results with similar accuracy, even if some differences arose, as stated before. However, the main reasons for some unsuccessful results is most probably due to inaccuracies in forcing functions and horizontal resolution as discussed below.

The authors have find the comparison very useful for both sides. Comparing one model which an other model and with measurements allows us to realize the state-of-the art of own models –with its weak and strong points. The comparison shows us clearly, where the major drawbacks of our models are and which elements in the model needs most development work. The authors conclude that this kind of model comparisons are very useful; not only to the authors, but to the scientific community interested in modelling.

The following future developing lines can be given:

· At the present state the models are still quite much as a level of research models. It leads to the fact that the user of model must have relatively much experience and expertise while using the models. One of the goals of our modelling is to develop operational models and thus more testing of models is needed as well as development of user-friendly interfaces and version for different computer systems.
· The present resolution of the sea model should also be refined, following which such features as the upwelling, the dynamics of small-scale vortices and coast-open sea interaction can be modelled. The accuracy of the model in simulating physical processes like these is also of importance for the ecological model, which needs an accurate physical input.
·The regional models showed limitations in their use, because of the continuous need for boundary conditions. These conditions can be provided in the future if zoom modelling is used, in which the high-resolution limited area model gets its boundary conditions from a large-scale model.
·Accurate initial conditions should be formed for the models using all relevant climatological data of wind stress, currents, stratification, river runoffs etc. After creating these initial conditions, model run of several years should be carried out to investigate the models' stability and the role of the accuracy of initial conditions.
· Even the atmospheric forcing from the meteorological model showed some drawbacks. The forecast wind speeds are usually too low, and both the horizontal temperature fields and the diurnal variations of temperature are not accurate enough. However, these factors are important in sea modelling.
·The comparisons of different models should be continued. The models should also be supported in the future by higher resolution data to investigate the meso-scale physics, which is still quite unknown today. Measurements, modelling and up-to-date knowledge of the sea area studied must interact closely. The comparison should be continued for several years to test the effect of errors in the initial conditions. The several years' simulations give also information about the models' ability to produce, keep and mix the stratification.

References:

Aitsam, A., Astok, V., 1972. The box and dispersion models of the Gulf of Finland. National Board of Waters. Tiedotus. Report, 28: 1-12.

Alenius, P., Myrberg, K., Nekrasov, A., 1998. Physical oceanography of the Gulf of Finland: a review. Boreal Environment Research, vol .3, No 2, pp. 97-125

Astok, V., Mälkki, P., 1988. Laht maailmakaardil. Eesti Loodus, 9: 554-558.

Ehlin, U., 1981. Hydrology of the Baltic Sea. In: The Baltic Sea, Aarno Voipio (ed.), pp. 123-134, Elsevier Oceanography Series, Amsterdam, 418 pp.

Ennet, P., Kinnunen, K. and Tamsalu, R., 1989: Ecosystem model FINEST, Valgus Tallinn, 89 p.

Ennet, P., Kuosa, H., Tamsalu, R., 1999. The influence of the upwelling and entrainment to the algal bloom in the Baltic Sea. Journal of Marine Systems (in press).

Falkenmark, M., Mikulski, Z., 1975. The Baltic Sea - a semi-enclosed sea, as seen by the hydrologist. Nordic Hydrology, 6: 115-136.

Fennel, W., Seifert, T., Kayser, B., 1991. Rossby radii and phase speeds in the Baltic Sea. Cont. Shelf Res., 11 (1): 23-36.

Gustafsson, N., 1991. Numerical methods in atmospheric models. ECMWF proceedings, 9-13 September, 1991, 2: 115-145.

Haapala, J., 1994. Upwelling and its influence on nutrient concentration in the coastal area of the Hanko Peninsula, entrance of the Gulf of Finland. Estuarine, Coastal and Shelf Science, 38 (5): 507-521.

Haapala, J., Alenius, P., 1994. Temperature and salinity statistics for the northern Baltic Sea 1961-1990. Finnish Mar. Res., 262: 51-121.

Hela, I., 1946. Coriolis-voiman vaikutuksesta Suomenlahden hydrografisiin oloihin. Terra, 58(2): 52-59 (in Finnish).

HELCOM, 1986. Water balance of the Baltic Sea. Baltic Sea Environment Proceedings, 16, Helsinki, Finland.

Jurva, R., 1951. Meret. In: Suomen maantieteen käsikirja, 121-144. Suomen maantieteellinen seura, Helsinki.

Koponen J., Alasaarela E., Lehtinen K., Sarkkula J., Simbierowicz P., Vepsä H., Virtanen M., 1992. Modelling the dynamics of a large sea area, Publications of water and environment research institute no. 7, Helsinki, 91 pp.

Mesinger, F., 1981. Horizontal advection schemes of a staggered grid -a enstrophy and energy conserving model. Mon. Wea. Rew., 109: 467-478.

Kiirikki M., Westerholm L., Sarkkula J. 2000, (In: Finnish with English summary)Suomenlahden levähaittojen vähentämismahdollisuudet. Suomen ympäristökeskuksen monistesarja. No 416, 36 pp, Helsinki

Launiainen, J. and Vihma, T. 1990. Derivation of the turbulent surface fluxes -an iterative flux-profile method allowing arbitrary observing heights. Environmental Software, 5: 113-124.

Launiainen, J. and Cheng, B. 1995: A simple non-iterative algorithm for calculating turbulent bulk fluxes in diabatic conditions over water, snow and ice and ground surface. Report series in geophysics, No. 33, University of Helsinki, Department of Geophysics, 15 pp.

Marchuk G. 1975. Numerical methods in weather prediction. Academic Press, New York, 277 pp.

Mikulski, Z., 1970. Inflow of river water to the Baltic Sea in period 1951-60. Nordic Hydrology, 4: 216-227.

Miropolski, Y. 1981. Dynamics of internal gravity waves in the ocean, Moscow, 300 pp. (in Russian).

Myrberg, K., 1997. Sensitivity tests of a two-layer hydrodynamic model in the Gulf of Finland with different atmospheric forcings. Geophysica 33, No.2: 69-98.

Myrberg, K., 1998. Analysing and modelling the physical processes of the Gulf fo Finland in the Baltic Sea. Monographs of the Boreal Environment Research, No. 10, 5o pp+ 5 articles.

Mälkki, P. and Tamsalu, R. 1985. Physical features of the Baltic Sea. Finnish Mar. Res., 252: 110 pp.

Omstedt, A., Meuller, L., Nyberg, L., 1997. Interannual, seasonal and regional variations of precipitation and evaporation over the Baltic Sea. Ambio, 26, No. 8: 484-492.

Palmén, E., 1930. Untersuchungen über die Strömungen in den Finnland umgebenden Meeren. Commenationes Physico-Mathematicae, 12, Societas Scientarium Fennica.

Pohlmann, T., 1997. Estimating the influence of advection during FLEX' 76 by means of a three-dimensional shelf sea circulation model. Dt. Hydrogr. Z., 49, No.2/3: 215-226.

R/V Aranda Cruise Report, 1995, No. 9 a-b, Finnish Institute of Marine Research, Helsinki.

R/V Aranda Cruise Report, 1995, No. 16 a-b, Finnish Institute of Marine Research, Helsinki.

Simons, T.J., 1980. Circulation models of lakes and inland seas. Can. Bull. Fish. Aquat. Sci., 203, 145 pp.

Tamsalu, R., Myrberg, K., 1995. Ecosystem modelling in the Gulf of Finland. I. General features and the hydrodynamic prognostic model FINEST. Estuarine, Coastal and Shelf Science, 41: 249-273.

Tamsalu, R., Ennet, P., 1995. Ecosystem modelling in the Gulf of Finland. Part 2. The aquatic ecosystem model FINEST. Estuarine, Coastal and Shelf Science, 41: 429-458.

Tamsalu, R., 1998. The coupled 3D hydrodynamic and ecosystem model FINEST. Meri -Report Series of the Finnish Institute of Marine Research, No. 35, 166 pp.

Tamsalu, R. and Myrberg, K. 1998. A theoretical and experimental study of the self-similarity concept. Meri, 37. Report series of the Finnish Institute of Marine Research.

Tyrväinen M., 1978. Upper layer observations and simulations using Kraus and Turner's model in the Gulf of Finland. Nordic Hydrolody, 9(3/4):207-218

UNESCO 1976 Seventh Report of the Joint Panel of Oceanographic Tables and Standards – UNESCO Techn. Papers Mar. Sci., No 24

Virtanen, M., Koponen, J., Dahlbo, K., Sarkkula, J., 1986. Three-dimensional water-quality-transport model compared with field observations. Ecological Modelling, 31: 185-199.

Witting, R., 1910. Suomen Kartasto.- Karttalehdet Nr. 6b, 7, 8 ja 9. Rannikkomeret (Atlas de Finlande. Cartes N:os 6b, 7, 8, et 9. Mers environnates).

Witting, R., 1912. Zusammenfassende Übersicht der Hydrographie des Bottnischen und Finnischen Meerbusens und der Nördlichen Ostsee. Finnlands Hydrographis-Biologische Untersuchungen, No.7.