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KAI MYRBERG

Analysing and modelling the physical processes of the Gulf of Finland in the Baltic Sea

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Analysing and modelling the physical processes of the Gulf of Finland in the Baltic Sea

Kai Myrberg

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Contents

List of original publications

The basic material for this thesis is to be found in the following articles, referred to in the text by Roman numerals:

I Alenius, P., Myrberg, K. and Nekrasov, A. 1998. Physical oceanography of the Gulf of Finland: a review. Accepted for publication in *Boreal Environment Research.*

II Tamsalu, R., Mälkki, P. and Myrberg, K. 1997. Self-similarity concept in marine system modelling. *Geophysica* 33, No. 2: 51-68.

III Tamsalu, R. and Myrberg, K. 1998. A theoretical and experimental study of the self-similarity concept. Accepted for publication in *Meri* - Report series of the Finnish Institute of Marine Research.

IV 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.

V 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.

Some unpublished results are also presented in this review.

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Analysing and modelling the physical processes of the Gulf of Finland in the Baltic Sea

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Myrberg, K. 1998. Analysing and modelling the physical processes of the Gulf of Finland in the Baltic Sea. Monographs of the Boreal Environment Research No. 10, 1998.

Abstract

In this thesis the physical processes of the Gulf of Finland are studied in various ways: 1) By presenting the results of a literature review of the main physical factors influencing the physics of the Gulf. These results are also used as a guideline for the modelling of the Gulf. 2) By investigating the vertical structure of the Gulf water mass, especially in terms of the so-called self-similarity theory. 3) By carrying out model simulations using two- and three-dimensional models, where salinity, temperature, thickness of the mixed layer, currents, and water levels are simulated for the Gulf of Finland and the results of which are verified with measurements.

After the Second World War, joint research covering the whole Gulf was not possible until the 1990's. Now the Gulf can once again be studied as an entity. The basic features, such as currents, water levels, salinity and temperature are basically understood, but detailed knowledge using joint modelling and measuring campaigns is still inadequate. However, many applications, such as coastal management, the operational use of models and basic research need high-resolution measurements of physical parameters and their related dynamics.

The vertical structure of e.g. salinity and temperature can be described by the so-called self-similarity concept. It is an effective and compact mathematical formulation. The self-similar profile of a marine system variable (salinity, temperature, buoyancy), originally depending on the vertical co-ordinate and time, can be described as a function of a non-dimensional vertical co-ordinate only. Thus, the self-similar approach reduces the dimension number of the problem. Self-similar profiles strongly depend on the stage of development of the mixed layer thickness. Self-similar profiles can be found in nature when integration over the inertial period (about 14 h) is taken. The self-similarity of the vertical turbulent fluxes is assumed to be the real source of the self-similarity. The observations give support to this idea. The flux-self-similarity approach may be an important way to parameterize vertical turbulence in models.

Two- and three-dimensional models have been used for the studies of the physics of the Gulf of Finland. The model simulations have been especially focused on studying salinity and temperature, but also currents, water levels and the thickness of the upper mixed layer have been included. The simulated years, for which verification material exists, are 1992 and 1994-1995. The monthly mean simulations of salinity (for 1992) by the two-dimensional model showed the highly baroclinic nature of the Gulf, with large related horizontal gradients of salinity (frontal areas). The accuracy of the model simulations was good and the location of the fronts was correct. The seasonal time evolution of the upper layer temperature was forecast

quite accurately. The current simulations showed the strong coupling between flow field and high salinity gradients, supporting the idea of a baroclinic circulation. The use of the space-dependent wind and temperature fields from the atmospheric HIRLAM (High Resolution Limited Area Model) model clearly reduced the errors in the prognosed surface salinity compared with simulations, in which the atmospheric forcing was derived from observations from a single station. The surface temperature simulations did not show a corresponding improvement in the case of HIRLAM forcing due to the inaccuracies in the atmospheric temperature field. The control simulation for 1994-1995 showed that the two-dimensional model can reproduce surface salinity accurately during the spring-autumn period. The temperature simulations showed, however, that the spring and autumn cases, when the mixed layer is developing, cannot be described accurately by the two-layer model. The three-dimensional model results were more accurate than these results of the two-dimensional model. The present resolution of the sea model as well as of the meteorological models should be improved. Then, such features as upwelling, the dynamics of small-scale vortices and coastal open sea interaction can be modelled. The sea model also needs high-resolution measured data for verifications of these meso-scale processes. The sea models' capability to accurately simulate physical processes is important for ecological models too, as these need detailed physical forcing. Hence measurements, modelling and up-to-date knowledge of the sea-area studied must be closely linked.

Key words: Gulf of Finland, physical processes, self-similarity, hydrodynamic modelling, salinity, temperature, atmospheric forcing, hydrodynamic-ecological model

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1 Introduction

The Baltic Sea is one of the largest brackish water areas in the world. It has a very restricted water exchange with the open ocean via the narrow Danish Sounds. Consequently, the sea is nearly non-tidal and is characterised by a significant fresh water surplus due to voluminous river runoffs. Hence the salinities are much lower than normal oceanic values. Due to these factors, there is a continuous two-layer salinity stratification, which plays an important role in the basic physics of the sea. The currents in the Baltic Sea are mainly caused by wind stress. However, the pronounced spatial and temporal variations in temperature and salinity result in thermohaline circulation also playing an important role in the circulation. The mean depth of the sea is only about 55 m and hence the total volume of the Baltic Sea is small, being e.g. only about 4 % that of the Black Sea. The sea can be divided into several sub-basins. In all parts of the sea, the bottom topography is a very important factor in modifying the physical processes.

The Baltic Sea has a meridional extension of about 650 km and a latitudinal extension of more than 1500 km. The complex physics of the sea and its relatively limited size make it a challenging marine environment, a "marine laboratory", which allows us to study different physical processes by using measurements with a relatively high spatial and temporal resolution. The measurements support model simulations in the form of good verification material to test the models' reliability in describing the physics of the sea.

In spite of the relative small size of the Baltic Sea, its different sub-basins have quite different physical processes. The main topic of this thesis is the investigation of the physical processes of the Gulf Finland, a sub-basin in the Baltic Sea. The Gulf lies in the north-eastern Baltic Sea between 59°11'N, 22°50'E and 60°46'N, 30°20'E. 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, 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.

The Gulf is today an actively-investigated area, and basin-wide studies can be carried out again for the first time since the 1930's, due to the political changes in the area. Unfortunately, the environmental problems in the Gulf are considerable. Thus knowledge of the physical processes of the Gulf is important for both basic research and for assessing the state of the marine environment. Knowledge of its physics constitutes important basic information for hydrodynamic modelling of the sea. The human impact can then be studied by hydrodynamic-ecological models.

The main structure of this thesis is as follows:

Today the physical oceanography of the Gulf of Finland can once again be studied as an entity. However, the 50 years' break in joint research activities covering the whole Gulf means that even most recent summary reports about the physics of the Gulf are very old. We have here to refer to the works of Witting (1909, 1910), Palmén (1930) and Palmén and Laurila (1938). After World War II most of the papers dealing with the physics of the Gulf have concentrated on local problems covering only a part of the area. In Chapter 2 (paper **I**) a literature review of the physics of the Gulf is presented. The main features of the general circulation and the horizontal and vertical structures of the water masses (salinity and temperature) are discussed. Surface waves, sea level, ice conditions and air-sea interaction are briefly reviewed, too. The gaps in our knowledge of the physics of the Gulf are also outlined, and goals for future field work and the needs of numerical modelling are discussed (see paper **I** for details).

Chapter 3 (papers **II**, **III**) is devoted to a study of the vertical structure of the Gulf. In the Gulf of Finland, as well as in the whole Baltic Sea, there is usually a two-layer vertical structure. The upper layer is quasihomogeneous with intense turbulence while below it there is a stratified layer in which turbulence is intermittent. Kitaigorodskii and Miropolsky (1970) applied the so-called self-similarity approach for the first time in marine research. They found that in such a two-layer structure, the vertical profile of the water temperature, being a function of the vertical coordinate and time, can be described in the thermocline layer by a non-dimensional temperature, which depends on a non-dimensional vertical coordinate only. In this way, a two-dimensional problem becomes a one-dimensional problem. This is called the self-similarity of the marine system variable (temperature, salinity etc.). In paper **II** the history of the self-similar approach to marine research is presented. The theoretical background of self-similarity for vertical turbulent fluxes is also described. In papers II and III discussion is presented as to why self-similar profiles can be found for temperature and salinity but not for currents. The hypothesis is made that the self-similarity is principally formed at the turbulent scale of the motion by the vertical fluxes of salinity and temperature. In paper **III** the self-similarity of single marine system variables as well as the flux-self-similarity profiles are derived and compared with CTD (Conductivity-Temperature-Depth) measurements carried out in the Gulf of Finland.

Chapter 4 deals with the modelling of the hydrodynamic processes of the Gulf of Finland (papers **IV**, **V**). Firstly, a brief survey is made to see what hydrodynamic numerical models have been recently developed for or applied to the Baltic Sea area. Reviews of Baltic Sea modelling have been given by Svansson (1976) and Omstedt (1989). The model simulations in this thesis are carried out using the Finnish-Estonian model FinEst, which is a hydrodynamic-ecosystem model. The hydrodynamic model has a fully three-dimensional version and a two-dimensional version. The three-dimensional model equations are introduced and the derivation of the equations for the two-dimensional model version are also presented.

The FinEst-model has been developed specially for ecosystem studies. Of the hydrodynamic parameters, salinity and temperature have variations which play the most important role in ecosystems. An accurately-simulated salinity field is good 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 and verification of the results concentrate on investigating salinity and temperature variations and structures. On the other hand, simulations of currents by the hydrodynamic model, and verification of these results is a large task to undertake. Flow measurements of very high resolution should be available, as well as model versions with higher horizontal and vertical resolutions than at present. These simulations, therefore, form an important task for future modelling work.

The numerical simulations are carried out by the two-dimensional, two-layer model versions (papers **IV** and **V**). Paper **IV** is focused on a study of the main features of the baroclinicity of the Gulf of Finland, namely the horizontal salinity and temperature fields, flow fields and thickness of the upper mixed layer on the time-scale of a month in 1992. Model results are compared with CTD measurements. A statistical error analysis is carried out. In paper **IV**, the vertical profile of salinity and temperature is based on the self-similarity theory. In paper **V** a further developed two-dimensional model is used. Special attention is paid to the role of atmospheric forcing. In the first simulation in paper **V** the atmospheric forcing derived from the observations of a single weather station is used, while in the second, atmospheric input derived from the HIRLAM (High Resolution Limited Area Model) meteorological model is used. A statistical error analysis is carried out between the daily measurements of salinity, temperature, thickness of the upper mixed layer and water levels in August 1992 and the corresponding model results to find out the dependence of the model's accuracy on the atmospheric forcing applied. The role of atmospheric forcing on the current fields is investigated too. Simulations for the years 1994-1995 are carried out by using the HIRLAM input as a control simulation for the case study of the year 1992. The simulations are carried out by using the two-dimensional and three-dimensional models of the Gulf of Finland. Verifications are carried out against CTD measurements. A statistical error analysis is carried out. The results of the different model versions are also compared with each other. The results of the 1994-95 simulations are only given here in this summary.

1.1 Main aims of the study

1. To determine the current state of our knowledge of the physics of the Gulf of Finland by a literature review.

a) To study the physics of the Gulf of Finland, denoted hereafter as the **GOF**, as an entity. The general circulation, the horizontal and vertical structures of water masses, the sea-level, surface waves, ice conditions and air-sea interaction will be analysed.

b) The gaps in our present knowledge of the physics of the Gulf are to be outlined.

c) To give guidelines for future measurements and modelling of the physics of the Gulf of Finland.

2. To study the vertical structure of the Gulf of Finland

a) To present the main features of the vertical structure of the water masses in time and space.

b) To summarise the present knowledge of the self-similarity approach and to find out when and where the self-similarity approach is valid; i.e. how well this approach fits with the observations.

c) To introduce the flux-self-similarity approach and discuss its role in the formation of self-similar profiles. To show how the approach fits with observations.

3. To model the physics of the Gulf of Finland

a) To model the general hydrodynamics of the GOF, i.e. the spatial and temporal variations of salinity, the temperature, currents, water levels and thickness of the upper mixed layer on different time scales, and to verify the results with observations. The main interest is focused on the summer season. The main parameters to be verified are salinity and temperature because of their importance in ecosystem behaviour. The model results are also compared with some climatological means. The question of how the model's present resolution can describe the highly baroclinic structure of salinity, temperature and currents is also investigated.

b) To determine the role of atmospheric forcing in affecting the accuracy of model results and how well the present resolution of atmospheric models available can describe the atmospheric conditions over the Gulf.
c) To discover how the accuracy of the two- and three-dimensional models differ from each other.
d) To study the seasonal variability in the models' accuracy.

1.2 The author's contribution

The author is fully responsible for paper V. In paper I the author has reviewed all the literature and drafted about an equal part of the manuscript with Pekka Alenius, excluding the part concerning the eastern Gulf, which was drafted by Alexei Nekrasov. In paper II, the author was responsible for the literature review and for drafting the manuscript. The mathematical considerations were written by Rein Tamsalu. In paper III, the data analysis and programming were done in co-operation between the author and Rein Tamsalu. The results in the manuscript were drafted by the author while the mathematical part is due to Rein Tamsalu. In paper IV, the numerical model simulations and the analysis of the models' simulations as well as the corresponding part of the manuscript, were prepared by the author. The model used in paper IV, as well as the mathematical formulations, was provided for use by Rein Tamsalu. The author is fully responsible for the simulations shown only here in this summary (Chapter 4.2.3, simulation 3).

2 The physical processes of the Gulf of Finland

After reviewing the relevant literature, the present state of our understanding of the physics of the Gulf has been summarised (paper I). This has been a large and complicated task to perform, because the limited possibilities for carrying out joint large-scale research in the Gulf has resulted in some processes being still quite poorly understood. However, the gaps of our knowledge have been revealed, and goals for future work can be outlined. A look is given at the basic numerical facts of the geography and hydrography of the GOF. Also, a short summary of the characteristics of the main physical features of the GOF are given, mainly dealing with currents and related processes as well as with the general structure of temperature and salinity, which play an important role in this thesis. The marine meteorological conditions are also discussed, because of their important role in the modelling of the sea. The vertical structure is mainly discussed in Chapter 3 in connection with papers **II** and **III**. Other physical processes, such as waves, water level, tides, upwelling, horizontal turbulence and sea ice, are mentioned here only briefly.

2.1 General characteristics of geography and hydrography

The Gulf of Finland (Fig. 2.1) is an elongated basin in the north-eastern Baltic Sea. In contrast with the other sub-basins of the Baltic Sea, the GOF 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 GOF. However, this is more a convention than a real physical boundary. The length of the GOF so defined is about 400 km and its width varies between 48 and 135 km. The surface area of the GOF (Table 2.1) is 29 571 km^2. The mean depth of the GOF 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 drainage area of 420 990 km^2 is 20 % of the total drainage area of the Baltic Sea (see Falkenmark and Mikulski 1975, Astok and Mälkki 1988).

Table 2.1. Typical parameter values for the Gulf of Finland and for the whole Baltic Sea (after Falkenmark and Mikulski 1975, except: renewal time of water after Witting 1910, Aitsam and Astok 1972, Astok and Mälkki 1988, and precipitation-evaporation from HELCOM 1986).

Parameter	GOF	Baltic Sea
surface area	29571 km^2	c.420 000 km^2
volume	1103 km^3	c.230 00 km^3
drainage basin	420 990 km^2	164 9550 km^2
mean/max. depth	37 m/123 m	55 m/459 m
precipitation	593 mm a^{-1}	613 mm a^{-1}
evaporation	490 mm a^{-1}	500 mm a^{-1}
river runoff	114 km^3a^{-1}	441 km^3a^{-1}
renewal time of water	1-3 years	c. 30 years

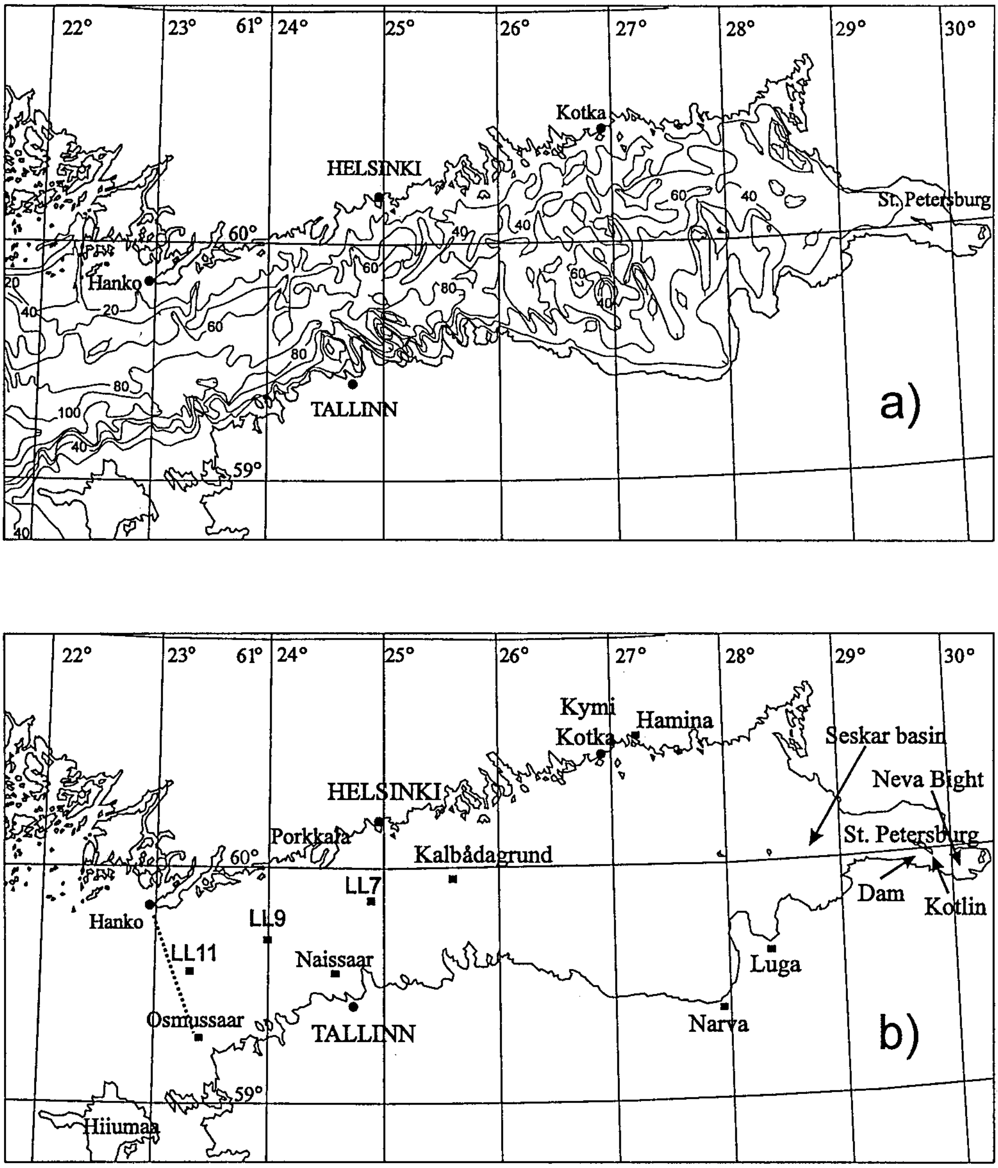


Fig. 2.1. (A) The bottom topography of the Gulf of Finland, (B) relevant geographic locations in the Gulf of Finland (from Alenius et al. 1998).

The central GOF is quite deep (over 60 m) up to longitude 28°E (Fig. 2.1). The south-eastern part is somewhat shallower and the easternmost part is very shallow. The southern coast of the western GOF is rather steep, whereas the northern coastal waters are shallower and more broken, with small islands. Certain peninsulas, such as Hanko and Porkkala, steer the currents on the Finnish coast; currents are also steered by the island of Naissaar and the ridge between it and the Estonian coast. The large and wide eastern basin gets narrower and shallower east of Narva. It is broken by two peninsulas on its southern coastline. The transition zone between longitudes 28°E and 29°E with decreasing width and depth is sometimes called "the Seskar basin". It plays an essential role in the transportation of water and substances and, because of the intensification of deposition processes there, acts as a kind of buffer. The easternmost part of the GOF, the Neva Bight, 22 km long and 14-15 km wide, is a very shallow area, the mean depth there being only some 5 m. The topographic features of the GOF are rich and play an important role in the modification of the circulation.

The GOF, like the whole Baltic Sea, has a positive water balance. The balance is determined by the salty water input from the Baltic Proper, by river runoff and by the output of relatively fresh water from the GOF. Precipitation exceeds evaporation on average in the GOF, but there are seasonal and inter-annual variations (see Table 2.1). There are also large differences between the estimates (see e.g. Ehlin 1981, HELCOM 1986, Omstedt et al. 1997). The mean value of the annual total river runoff to the GOF is 114 km^3a^{-1}, which is about 25 % of the total fresh water input to the whole Baltic Sea (Table 2.1). The largest single river input in the whole Baltic Sea is the River Neva, located at the eastern end of the GOF, and having a mean discharge of 75.5 km^3a^{-1}. The other main rivers are the River Kymijoki and the River Narva (runoff 9.5-12.5 km^3a^{-1}) and the River Luga (runoff 3 km^3a^{-1}; see Mikulski 1970). The river runoffs have a yearly cycle with the largest values in spring and the smallest in winter. The water exchange between the Gulf of Finland and the Baltic Proper is a key element in the water balance of the GOF, but not too many estimates have been given about it in the literature. According to Witting (1910) the renewal time of the GOF water (Table 2.1) is about 1-2 years (600 km^3 out, 480 km^3 in to the GOF per year). Aitsam and Astok (1972) and Astok and Mälkki (1988) have estimated that the renewal time is rather longer, about 3 years.

The salinity has both horizontal and vertical gradients all along the Gulf except in the Neva Bight. The salinity increases from east to west and from north to south. The surface salinity varies from 5-7 per mill in the western GOF to about 0-3 per mill in the east. Between Helsinki and Tallinn, the surface salinity is typically between 4.5-5.5 per mill (Fig. 2.2). The bottom salinity in the western GOF can typically reach values of 8-9 per mill or even higher, up to 10 per mill, after the saline water pulse into the Baltic Sea in 1993. In the western GOF a permanent halocline exists throughout the year between depths of some 60-80 m (Fig. 2.3). The existence of the halocline prevents vertical mixing of the water body down to the bottom. Towards the east, the difference between surface and bottom salinities decreases (see Chapter 3.1). The surface layer salinity decreases from winter to mid-summer while at the same time the salinity of the deep layers increases (Fig. 2.4). Between March and July, the surface layer salinity can decrease e.g. from 6 to 4.5 per mill while the salinity increases at a depth of 60 metres from 7 to 9 per mill. The surface layer salinity variations are easily understood as being related to the melting of the ice cover and the increased spring-time Neva runoff. The surface layer outflow seems to generate an inflow into the GOF in the deeper layers (Haapala and Alenius 1994).

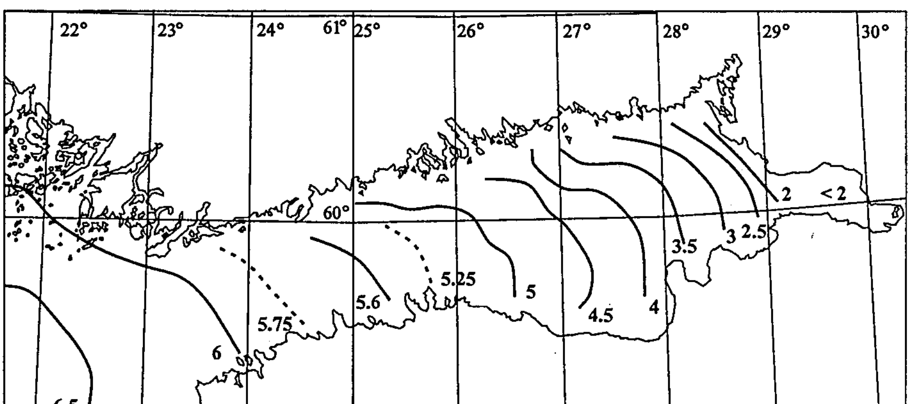


Fig. 2.2. The average surface salinity in per mill in the Gulf of Finland (redrawn from Jurva 1951).

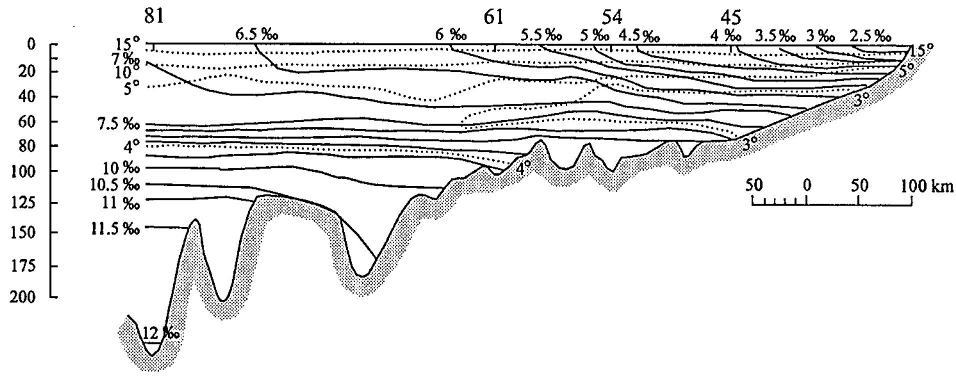
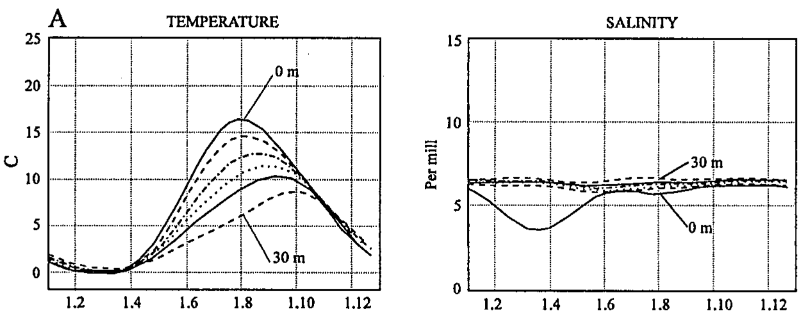


Fig. 2.3. Typical vertical section of salinity and temperature through the Gulf of Finland and Northern Baltic Sea in summer. Salinity isolines are shown as continuous lines and temperature isolines as dashed lines. The numbered locations are: 45 = Suursaari, 54 = off Helsinki, 61 = off Hanko and 81 = east of Gotland (redrawn from Jurva 1951).

The sea temperature structure also has both horizontal and vertical gradients like salinity, but seasonal changes dominate the variations of temperature. In summer, when the thermocline exists, the temperature stratification is strong and stable (Fig. 2.3). The overall horizontal distribution of the surface temperature in the GOF is usually quite homogeneous (Fig. 2.5). However, horizontal gradients can be locally intense due to upwellings or in spring in connection with the melting of ice. The annual variations in temperature are large. The thermocline forms in May, when the temperature of maximum density (2.5-3.5 °C) is reached. After that the surface temperature increases and maximum values occur in late July - early August. In the GOF the average maximum varies between 15 °C in the west to 17 °C in the east (Fig. 2.4). The highest values are over 20 °C near the coasts.



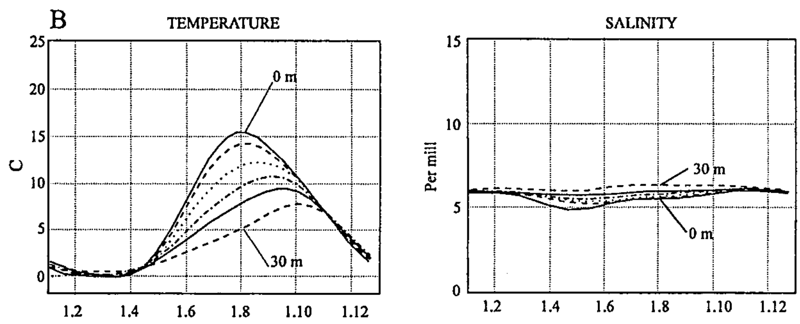


Fig. 2.4. (A) The annual course of temperature (left) and salinity (right) at Tvärminne, based on observations in 1960-1991. (B) The same, but for Harmaja (from Haapala and Alenius 1994).

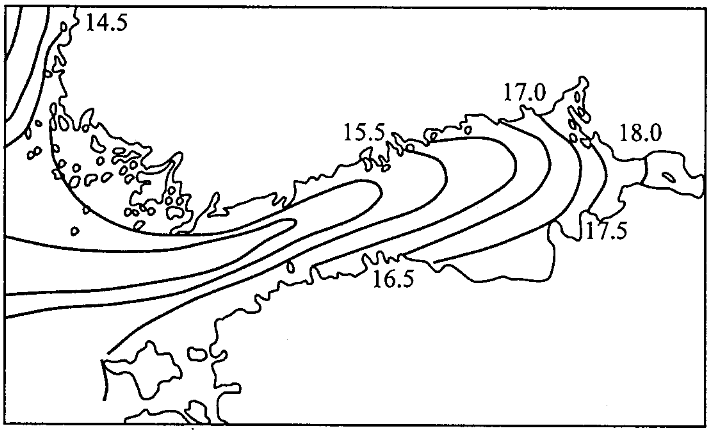


Fig. 2.5. The average surface temperature in degrees in August (redrawn from Jurva 1951).

2.2 Physical processes

Circulation

The main forcing factor for currents in the GOF is the wind stress. Density-driven currents also play an important role in the overall circulation due to the pronounced horizontal density (buoyancy) gradients caused by the variations of salinity and temperature. The sea-surface slope that results from the permanent water supply to the eastern part of the GOF also contributes appreciably to the existing circulation pattern. The GOF is large enough to see the effects of the earth's rotation, too (Witting 1912, Palmén 1930, Hela 1946).

The classical studies by Witting (1912) and by Palmén (1930) on the general circulation in the GOF already established that the residual circulation is counter-clockwise, comprising currents with horizontally variable speed and stability. The relatively poor stability (between 6 and 26 %), meaning the ratio between the mean vector velocity and the scalar mean speed, shows that the mean cyclonic circulation, with residual vector velocities of 1-2 cm/s, is a statistical quantity, not a constant phenomenon (see Fig. 6 in paper I). The low stability of the currents shows that there is no permanent circulation system in the GOF. The instantaneous currents depend on the variable wind stress and buoyancy structure. Even with the large fresh water input from the rivers in the eastern GOF, the mean westward vector velocity is almost an order of magnitude smaller than the average speed near the Finnish coast. The stability of the currents is smaller along the northern coast than along the southern coast, which means that although a long-term mean circulation may exist, the instantaneous currents can be very variable in both speed and direction. Periodic processes, such as inertial oscillations and seiches, make the current system even more variable. Despite the difficulties in determining the mean circulation, many studies have been devoted to this problem: e.g. Palmén (1930), Hela (1952), Sarkkula (1991). According to these studies, in which many different approaches have been used, the background mean current speed was found to be some centimetres per second. However, in a real situation the wind and density-driven currents are coupled by strong nonlinear interactions that can be seen as eddy-like formations. The spatial and temporal variability of currents, based on measurements from moored current instruments, have been more recently studied by several authors: the variability of the currents has been reported to be conspicuous for its 18-20 days periods (Talpsepp et al. 1994). Unidirectional currents prevail over several days and then change direction (Laakkonen et al. 1981). Eddy-like short lifetime structures that affect the circulation in the near bottom layer have been reported by Mälkki and Talpsepp (1988). In different parts of the GOF it has been found that the mean circulation is of the order of 3-5 cm/s (Laakkonen et al. 1981, Alenius 1986). Study of the eastern end of the GOF has attracted special interest due to the construction of the Leningrad dam in the 1970's. The area, mainly studied by Russian scientists, is from a dynamic point of view an estuar of the GOF where the current system has a special nature. The main and general feature of the current fields in the eastern GOF area is their nonstability, with pulsating components usually exceeding the mean (residual) value. This is clearly seen in the scattering ellipses of the observed instantaneous current vectors (see paper **I**, Figs. 7-8).

In the following, some of the physical processes closely linked to circulation are shortly summarised. *Upwelling* is an important process in bringing nutrient-rich water from deeper layers to the surface, in mixing water masses and in generating frontal areas. During upwelling, the surface temperature can drop by about 10 degrees in a few days. The biological consequences of upwelling can be significant. Upwelling in the GOF at the Finnish coast has been studied in many papers (Hela 1976, Kononen and Niemi 1986, Haapala 1994). There it is associated with a south-westerly wind, which has to last for about 2-3 days at least to cause upwelling. Upwelling takes place typically in summer when strongly stratified conditions exist and the effect of wind stress is distributed through a shallow water layer. A wind impulse of about 4000-9000 kg $m^{-1}s^{-1}$ is needed to cause upwelling (Haapala 1994). Vertical velocities can reach values of $4\text{-}10*10^{-3}$cm s^{-1} (Hela 1976).

Horizontal turbulence in the coastal regions of the GOF plays a significant role in the transportation, distribution and spreading of substances. The parameter of most practical use in ecosystem modelling (for optimisation of the location of sewage discharge outlets) is the coefficient of eddy diffusivity, which has a wide range of estimates between $0.1*10^5 cm^2s^{-1}$ -$39*10^5 cm^2s^{-1}$ (see paper **I** for details).

Sea-level variations are forced by three main factors: variations in the wind direction and speed, air pressure fluctuations and changes in the density of the sea water (Lisitzin 1958, 1974). Sea-level measurements have already been made in Finland for 100 years, since 1887, Hanko being the first station. These measurements are worth mentioning as important material for climate change studies, because the measurements are made relative to bed rock and can be considered as being very reliable. The only relevant disturbing effect is the land uplift, which in the GOF is 2.3 mma^{-1} (Vermeer et al. 1988). Several studies have been devoted to the sea-level problem (see e.g. Witting 1911, Hela 1944, Lisitzin 1944, 1959a, 1966, Stenij and Hela 1947). High water levels have been a real nuisance for the population of St. Petersburg. Since 1703 the city has been flooded more than 280 times. The highest water level measured was 421 cm in 1824. A significant part of the sea-level oscillations is caused by free standing waves, *seiches*, that are manifested when an external force ceases. The period of an uninodal oscillation of the system Baltic Proper-the GOF is 26.2 h on average (Lisitzin 1959b). The *tidal motions* in the GOF, as in the whole Baltic Sea, are negligible, their mean amplitudes being only some millimetres or centimetres (Listizin 1944).

Horizontal structure of salinity and temperature -fronts

The thermohaline structure of the GOF is governed by spring-summer solar heating and stratification, autumn-winter surface cooling and convection, voluminous river discharges and the irregular inflow of bottom saline water. Variations of temperature are mainly due to the large variations of incoming solar radiation throughout the year. Local upwelling can cause rapid changes in sea-surface temperatures. The horizontal variation of salinity in an east-west direction is 6-7 per mill/400 km, which gives an impression of the highly baroclinic nature of the GOF (see Fig. 2 in paper **I**). Thus, salinity plays the major role in the buoyancy variations in the GOF, as in the whole Baltic Sea, which is the opposite situation to that in the oceans, where temperature plays the major role (see e.g. Mälkki and Tamsalu 1985).

There is a strong coupling between horizontal salinity and temperature structures on the one hand, and circulation processes on the other. Areas with large horizontal gradients of salinity and temperature are often formed. These areas can occur between meso-scale circulation patterns or in transition zones between sea-areas. Areas with pronounced gradients of salinity and/or temperature are often called *fronts*. We can define an oceanic front to be an area with a pronounced buoyancy (density) gradient, which can be caused by a salinity gradient, a temperature gradient or by both. The close coupling between biological and physical processes in such fronts has aroused during the last decade great interdisciplinary interest in the frontal dynamics in the GOF. The GOF is a suitable area for the generation of fronts due to its large natural salinity variations.

The quasi-permanent salinity front in the south-western GOF has been the subject of intensive investigation; dynamic analyses of the frontal area have been carried out, and the related biological activity has been studied. Talpsepp (1993) concluded that the main factors influencing the location and intensity of the front are topographic steering and coastal upwelling. Pavelson et al. (1996) found that the shape and location of the front are also controlled by wind-induced advection, while Kononen et al. (1996) discovered that stratification conditions on the less saline and on the more saline side of the front clearly differ from each other, which is an important factor for mixing conditions. The frontal dynamics in the GOF has also been studied e.g. by Pavelson (1988), Mälkki and Talpsepp (1988), Talpsepp (1993), Elken (1994) and Laanemets et al. (1997). The results of these works have been summarised in paper **I** and the frontal processes have been further discussed in connection with modelling in papers **IV** and **V**. The horizontal temperature field in the GOF is also non-homogeneous in space and time. The main effect that produces these fronts is coastal upwelling, complemented by coastal jets, eddies, differential heating and cooling, and water exchange between basins with different water characteristics (Kahru et al. 1995).

The statistical *ice conditions* in the GOF are well-known (see e.g. Jurva 1937, Palosuo 1965, Leppäranta and Seinä 1982, Seinä 1994), but the influence of the ice cover on the underlying water masses has been studied much less than the ice conditions themselves (see Fig. 10 in paper I).

Marine meteorological conditions

The GOF is narrow and surrounded by land areas in all directions except to the west. Thus, patterns of atmospheric temperature and wind stress are very inhomogeneous because of the variable surface roughness and variable heat exchange between the sea and the atmosphere. The wind distribution (see e.g. Launiainen and Laurila 1984) shows that the most common wind direction is south-west; the mean wind speed at the open-sea station of Kalbådagrund in the GOF is about 7-8 m s^{-1} (data from 1977-82; measurement height of about 35 m). The physical processes are very much wind-dependent. The dependency is not only confined to wind speed itself but also to the horizontal variability of the wind field - the curl of the wind stress. The number of representative wind stations in the GOF area is very limited. The only real open-sea meteorological observation station in the GOF is at present the automatic weather station at Kalbådagrund (59°58'N, 25°37'E; see Fig. 2.1). The other stations are for the most part located near the coastline. Launiainen and Saarinen (1982) compared atmospheric parameters between Kalbådagrund and the coastal automatic sea-mast station in the Loviisa area (60°22'N, 26°22'E). They found that the wind speeds over the open sea are much higher than those near the coast, besides which the ratio between these wind speeds is not constant. The wind speed difference is especially dependent on wind direction, a fact which represents the effects of variable surface roughness and orography. The atmospheric surface layer stability also plays a significant role. The wind pattern over the GOF is also characterised during both spring and summer by the sea-breeze in coastal areas. The main factors contributing to the sea breeze are the temperature difference between land and sea-areas and the effects of the prevailing flow.

The limiting factor for the growth of *surface waves* in the GOF is the narrowness of the Gulf and the decrease of effective fetch due to refraction caused by the bottom topography (Kahma and Pettersson 1994). For estimating waves from wind speeds and fetch, nomograms published by Kahma (1986) can be used. Surface wave statistics for the GOF have been reported by Kahma and Pettersson (1993). According to Pettersson (1992), the maximum wave height in the GOF area occurring once in 100 years is 7.1 m.

Discussion and conclusions

Having summarised the published literature on the physics of the GOF, this chapter gives some thoughts on subjects that should be studied further, and some indications as to which processes are less understood than others.

1. Discussion about the general circulation of the GOF is commonly focused on the background flow or mean cyclonic circulation. This is probably correct for long-term processes. However, short-term forecasts of the marine variables need information about the transient processes in the current field on time scales, say, from some hours to some weeks. Transient processes are also based on different dynamics than the mean flow. The time scale for transients describes the variability in current speed and direction, energy transfer between different scales, coastal-open sea interaction and water exchange between the Baltic Proper and the GOF. The study of transient processes needs at least the following:

a) modern measurement techniques, enabling one to collect data at high spatial and temporal resolutions. Measurements employing techniques like ADCP and batfish are needed over many years to collect statistically reliable data sets and enough verification material for numerical models. Measurements and modelling have to be well co-ordinated.

b) the horizontal resolution of numerical models should be higher in the future. There is a need for a resolution of about 1-3 kilometres, which is the scale of the internal Rossby-radius of deformation in the GOF (see Fennel et al. 1991).

c) for task b, more accurate knowledge of bottom topography and more powerful computers are needed.

d) more accurate atmospheric input for air-sea interaction studies and as input for numerical models is needed (see Chapter 4 in paper V). The horizontal resolution of the atmospheric models presently available is too coarse for the GOF, where the distributions of atmospheric temperature and wind stress are very inhomogeneous due to the narrowness of the GOF.

2. The high-resolution structures of salinity and temperature, like the frontal areas, are not well enough known by the same reasoning given above in the case of currents. The frontal areas are important not only because of their biological activity but also due to the need to study the dynamics behind the frontogenesis. The semi-permanent fronts in the GOF es-

pecially need more investigation and more high-resolution data.

3. Investigation of the following topics could increase our knowledge of the GOF and further improve the model results:

a) study of the turbulent processes (mixing in water). More detailed knowledge of the parameters of turbulence increases the possibilities of forecasting the dispersion of pollutants between the coast and the open sea.
b) flow measurements under the ice will improve our knowledge of the mean flow conditions in wintertime, which are still quite unknown.
c) comprehensive field activities should be focused on regions playing a particular role in the physics of the GOF e.g. the entrance of the GOF, the Seskar basin acting as a buffer zone for substance fluxes, the semi-permanent frontal area, etc.. On the other hand, certain relatively restricted areas could be selected for detailed investigations serving as control sites for model verification.

3 The vertical structure

3.1 Vertical stratification in the Gulf of Finland

The variations in the stratification of the Gulf of Finland as well as of the whole Baltic Sea are dominated by the variations in the vertical structure of salinity. The main factors determining the stratification conditions are the large seasonal variation in the incoming solar radiation, as well as large seasonal and interannual variations in the atmospheric forcing, the water exchange between the Baltic Proper and the Gulf of Finland, and river runoff.

The vertical structure of salinity in the Gulf of Finland has either a one-layer or a two-layer structure. In the western part, with depths of more than 60 m, a permanent halocline exists between 50-70 m. The deepening of the halocline due to vertical convection and mechanical mixing is restricted to seasons without a seasonal thermocline. The lower limit for the deepening of the halocline is the strong buoyancy gradient, which cannot be eroded by winds. Deep waters below the halocline are thus decoupled from the direct atmospheric forcing. In the shallow eastern GOF, no permanent halocline exists, and the salinity increases linearly from the surface towards the bottom. The difference between the surface and bottom salinity decreases towards the east. The effects of river runoffs become clearly visible in long-term changes of salinity as well as in the seasonal variations of salinity (see paper **I** for details; Mälkki and Tamsalu 1985, Fig. 2.3).

The vertical structure of temperature is governed by the energy balance at the sea-surface and by direct penetration of solar radiation into the water body. The temperature stratification is also strongly determined by the variations in the vertical structure of salinity. The thermocline forms in May, when the temperature reaches the maximum density temperature, which is about 2.5 degrees in the western GOF and 3.5 degrees in the eastern GOF. The depth of the thermocline in summer is about 15-20 m. In the eastern GOF and near coasts, where no permanent halocline exists, the water body can be well-mixed in summer due to strong winds and/or cool periods. In general the thermocline begins to erode in late August, when the energy balance at the sea-surface becomes negative. Vertical convection and mechanical mixing deepen the thermocline, and in October-November the seasonal thermocline vanishes. The time evolution of the temperature below the surface layer is more complicated than that at the surface (Haapala and Alenius 1994). The annual date of maximum temperature varies linearly with depth only in the surface layer (0-30 m). In the mid-layer, between depths of 30 and 60 m, the date of the maximum temperature follows a logarithmic rate of change, while below a depth of 60 m depth observations are very scattered, showing no systematic behaviour (see Fig. 4 in paper **I**; see Figs. 2.3-2.4).

During the summer season, which is the main interest in this thesis, the Gulf of Finland can be said to consist of four different layers in terms of salinity and temperature (Mälkki and Tamsalu 1985). The well-mixed layer extends from the sea-surface down to a depth of about 15-20 m. Below that is a cold interfacial layer, which terminates at the depth of the permanent halocline (50-70 m). In this layer the water temperature decreases with depth from the surface temperature (about 15-20 degrees) to the temperature of the mixed layer at end of the previous winter (about 2-3 degrees). This water mass is called old winter water. Below the permanent halocline the temperature slightly increases. In the eastern part of the GOF, the permanent halocline is missing and thus the two lowest layers are absent.

3.2 The self-similarity approach

The historical development of the self-similarity theory in marine science and the theoretical considerations are discussed in paper **II**. The extension of the theory to cover the self-similar profiles of the vertical fluxes of marine system variables together with the latest experimental proof of self-similar profiles in the Gulf of Finland are presented in papers **II**, **III**.

Theoretical background and history

Marine dynamics is characterised by a wide range of spatial and temporal scales from microturbulence to global variations. Nihoul and Djenidi (1987) argued that the marine system can be described by fairly well-defined "spectral windows" i.e. domains of length scales and time scales associated with identifiable phenomena. The marine weather (diurnal and synoptic variations) and the long-term variability form a two-layer vertical structure for buoyancy (temperature or salinity) as described in Chapter 3.1. At first there is a quasihomogeneous layer with intense turbulence beneath which is a stratified layer with intermittent turbulence, which is often caused by the breaking of internal waves. The vertical structure on the time scale of marine weather and long-term variability can be described by the so-called self-similarity concept.

Barenblatt (1996) has provided the following definition: "a time-developing phenomenon is called self-similar if the spatial distributions of its properties at various different moments of time can be obtained from one another by a similarity transformation (the fact that we identify one of the independent variables with time is of no significance). Establishing self-similarity has always represented progress for a researcher: self-similarity has simplified computations and the representation of the properties of the phenomena under investigation. In handling experimental data, self-similarity has reduced what would seem to be a random cloud of empirical points so as to lie on a single curve or surface, constructed using self-similar variables chosen in some special way". Barenblatt (1996) adds that self-similar solutions were used as a first step in starting numerical calculations on computers. Due to these facts, the search for self-similarity was undertaken at the outset, as soon as a new domain of investigation was opened up. Self-similarity has continued as before to attract attention as a profound physical fact indicating the presence of a certain type of stabilisation of the processes under investigation, valid for a rather wide range of conditions. In all branches of geophysical fluid dynamics using similarity considerations, scaling laws and self-similar solutions play an important, often decisive role.

This self-similarity approach has been applied to the investigation of various problems, such as turbulent flows in atmospheric surface layers, wall layers of turbulent shear flows, the dynamics of turbulent spots in fluids with strongly stable stratification, etc.. These applications have been reported by several authors (see e.g. Guderley 1942, von Weizsäcker 1954, Barenblatt and Zelodvich 1972, Barenblatt and Monin 1979). The self-similarity approach has been used later e.g. in theoretical biology (Barenblatt and Monin 1983). A comprehensive study of self-similar theory with various applications and with a large number of references has been made by Barenblatt (1996).

The self-similarity concept was introduced in the marine sciences for the first time by Kitaigorodskii and Miropolsky (1970). The self-similarity of a marine system variable, for example temperature (or salinity, buoyancy, etc.), in a two-dimensional co-ordinate system will be described in a non-dimensional form (see Fig. 3.1).

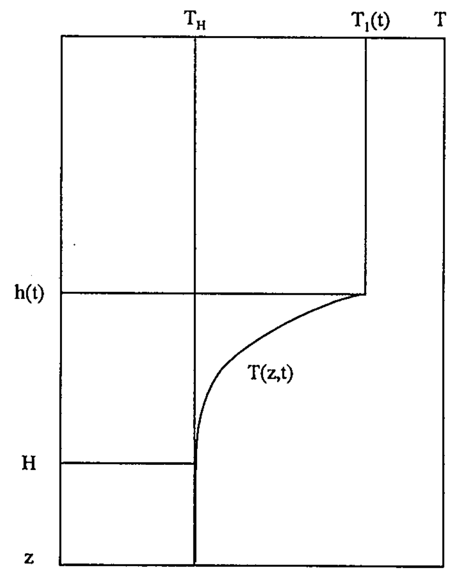


Fig. 3.1. Schematic temperature profile in the mixed layer and thermocline (see explanation of the symbols in the text; redrawn from Zilitinkevich and Mironov 1992).

$$\theta = \frac{T_1(t) - T(z,t)}{T_1(t) - T_H} \quad (3.1)$$

by a non-dimensional co-ordinate:

$$\xi = \frac{z - h(t)}{H - h(t)} \quad (3.2)$$

So,

$$\theta = f(\xi) \quad (3.3)$$

where:

$T_1(t)$ is the temperature in the upper mixed layer, T(z,t) is the temperature profile in the vertical direction, T_H is the temperature at the lower boundary of the ocean active layer, which is approximated to be constant, z is the vertical co-ordinate, h(t) is the thickness of the upper mixed layer, H is the depth of the ocean (active layer), t is time.

The main requirements for the validity of the self-similarity concept for time-dependent marine system variables are:

- the concept is restricted to the main thermocline layer
- the large-scale stratification is stable
- time-integration of the variable over the inertial period must be carried out.

After the first study of Kitaigorodskii and Miropolsky (1970), several publications have been devoted to self-similarity theory in marine science (see paper II). Reshetova and Chalikov (1977) extended self-similarity to cover salinity profiles. According to Zilitinkevich and Rumjantsev (1990) and Mironov et al. (1991) the results of Miropolsky et al. (1970) and Reshetova and Chalikov (1977) revealed so great a scatter of points on the empirical curves $\theta(\xi)$ that the self-similarity concept became doubtful. However, Tamsalu (1982) and Mälkki and Tamsalu (1985), using the measured data of Nõmm (1988), found that the self-similar profile depends strongly on the development of the mixed layer thickness. There are two different self-similarity structures: firstly, in the case of entrainment when the homogeneous layer is deepening and secondly, in the case when the mixed layer is decreasing (storm subsiding). Observational support for self-similarity profiles has also been presented by e.g. Mironov et al. (1991) and Zilitinkevich and Rumjantsev (1990) in studies of Russian lakes. Linden (1975) has found self-similar profiles in laboratory experiments. Shapiro et al. (1995) found a self-similar structure of salinity and temperature in Mediterranean vortex lenses.

An approximate analytical expression for $\theta(\xi)$ can be found (see Fig. 1 in paper II) by using a fourth-order polynomial approximation of the classical type of Karman and Polhausen in boundary layer theory (Polhausen 1921). So, $\theta(\xi)$ can be given as:

$$\theta(\xi) = a_0 + a_1\xi + a_2\xi^2 + a_3\xi^3 + a_4\xi^4 \qquad (3.4)$$

with the following boundary conditions in the non-dimensional system:

$\theta=0$ when $\xi=0$

$\theta=1$, $\theta'=0$ when $\xi=1$

$$\int_0^1 \theta d\xi = \kappa \qquad \int_0^1\int_0^\xi \theta d\xi d\xi' = \overline{\kappa}$$

where θ' is a total derivative.

The functions $\kappa, \overline{\kappa}$ ($\kappa_s, \overline{\kappa}_s$ for salinity and $\kappa_T, \overline{\kappa}_T$ for temperature; $\kappa_s \approx \kappa_T, \overline{\kappa}_s \approx \overline{\kappa}_T$) can be determined e.g. for temperature from empirical data using (3.1) and (3.2) as follows (Mälkki and Tamsalu 1985):

$$\kappa_T = \left(T_1 - \int_0^1 T d\xi\right) / (T_1 - T_H) ;$$

$$\overline{\kappa}_T = \left(T_1 - \int_0^1\int_0^\xi T d\xi T d\xi'\right) / (T_1 - T_H)$$

In considering the low frequency variations, the small-scale variability of these functions has to be filtered out by averaging with respect to time. In Figure 3.2 the variability of κ_T and the time-integrated profile $t^{-1}\int_0^t \kappa_T dt'$, calculated according to bathythermograph measurements at 15 minutes intervals, are shown. The function κ varies between 0.5 and 0.9 (Fig. 3.2), but after one inertial period (about 14 h), $t^{-1}\int \kappa_T dt$ and $t^{-1}\int \overline{\kappa}_T dt$ remain fairly stable. Mälkki and Tamsalu (1985) also found that the values of $\kappa_T, \overline{\kappa}_T$ depend on the mixed layer development. In the case of entrainment (mixed layer depth increasing) it was found that $\kappa_T = 0.75$, $\overline{\kappa}_T = 0.3$ while in the case of detrainment (mixed layer depth decreasing) $\kappa_T = 0.6$, $\overline{\kappa}_T = 0.2$.

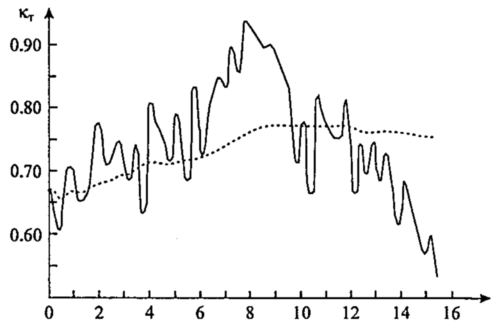


Fig. 3.2. The variation of the function κ_T as a function of time (hours) according to bathythermograph measurements at 15 minute intervals (solid line) and the variability of $t^{-1}\int \kappa dt$ (broken line) as a function of time t (from Mälkki and Tamsalu 1985).

Assuming that θ is a function only of ξ and using (3.4) with the corresponding boundary conditions and abovementioned values for $\kappa, \bar{\kappa}$ we finally obtain for the case of entrainment (**case A**):

$$\theta(\xi) = 1 - (1 - \xi)^3 \quad (3.5)$$

and for the case of detrainment (**case B**) (see Fig. 1 in paper **II**):

$$\theta(\xi) = 1 - 4(1 - \xi)^3 + 3(1 - \xi)^4 \quad (3.6)$$

The self-similarity studies of Mälkki and Tamsalu (1985) described above are the most comprehensive for the Baltic Sea. The studies were carried out in the Gulf of Finland, the Gulf of Bothnia, the Gulf of Riga and in the Baltic Proper during several years in the 1970's (R. Tamsalu, personal communication). Finding different curves for cases in which entrainment (3.5) and detrainment (3.6) take place clarified the concept of self-similarity. A single self-similar profile, derived from one vertical CTD sounding, is often located between curves A and B.

The practical interpretation of self-similarity is the following. A number of vertical profiles e.g. for salinity are chosen (Fig. 3.3A) from different locations in the sea at any arbitrary moment. If the self-similar concept is applied to these profiles, then according to (3.1-3.6) all the calculated (self-similar) profiles join the same non-dimensional curve (Fig. 3.3B) in the thermocline layer when the time-integration over the inertial period is carried out.

The theoretical background for the existence of self-similar profiles has been somewhat unclear up to now. Barenblatt (1978) and Turner (1978) have speculated that in cases, in which the mixed layer is increasing (entrainment), the thermocline is to be treated as a quasistationary thermal and diffusion wave (see also Barenblatt 1996). It is likely that the energy needed to erode the sharp gradient below the surface layer in the upper thermocline will be supplied by the breaking of internal waves. Zilitinkevich and Rumjantsev (1990) concluded that the mechanism proposed by Turner (1978) should also include the effects of buoyancy in order to work properly.

<u>The flux-self-similarity</u>

Tamsalu (1982) made the hypothesis (R. Tamsalu in a personal communication with A. Leonov and Y. Miropolsky 1977) that in the three-dimensional concept, the development of self-similar profiles takes place at the turbulent scale of the motion; the self-similarity of the vertical turbulent fluxes of the marine system variables is the key factor (see Fig. 3 in paper **II**). Thus, the traditional self-similarity of marine system variables is a product of this flux-self-similarity. The dimensional vertical flux $\langle w'T' \rangle$ can be calculated using the method proposed by Osborn and Cox (1972):

$$\langle w'T' \rangle \frac{d\langle T \rangle}{dz} = -\chi \left\langle \left(\frac{\partial T'}{\partial z} \right)^2 \right\rangle \quad (3.7)$$

where: χ is the molecular heat conductivity, T' is the fluctuation of temperature for each profile, w' is the fluctuation of the vertical velocity, the brackets $\langle\ \rangle$ denoting ensemble averages.

The experimental non-dimensional fluxes $Q(\xi)$ have the following expressions depending on the vertical structure of temperature in cases A and B (see paper **III** for details).

$$Q = \frac{\langle w'T' \rangle_h - \langle w'T' \rangle_z}{\langle w'T' \rangle_h - \langle w'T' \rangle_H} \quad ;\text{case A} \quad (3.8)$$

$$Q = \frac{\langle w'T' \rangle_h - \langle w'T' \rangle_z}{\langle w'T' \rangle_{max}} \quad ;\text{case B} \quad (3.9)$$

where: $\langle w'T' \rangle_h$ is the temperature flux at level z=h, $\langle w'T' \rangle_H$ is the temperature flux at the bottom of the seasonal thermocline, $\langle w'T' \rangle_{max}$ is the maximum of temperature flux in the stratified layer, the brackets $\langle\ \rangle$ denoting ensemble averages.

The vertical integration of the abovementioned fluxes (3.8) and (3.9) is based on use of experimental data collected during a four-day cruise in the Gulf of Finland in 1995 (see the section "Verification of self-similar profiles with CTD-data"). It was found that the integral $\int_0^1 Q d\xi = m_2$ had approximately constant values, depending on the stage of the mixed layer (case A=entrainment; case B=detrainment)

$$\int_0^1 Q d\xi = m_2 \quad ; m_2 \approx 0.8 \text{ (case A)},$$
$$m_2 \approx 0.4 \text{ (case B)} \quad (3.10)$$

The theoretical derivation of the non-dimensional vertical fluxes is based on the integration of the vertical equation of temperature (buoyancy)

$$\frac{\partial T}{\partial t} = -\frac{\partial \langle w'T' \rangle}{\partial z} \quad (3.11)$$

In this procedure (3.11) will be written in non-dimensional form according to (3.2) and the self-similarity approach (3.1), (3.4)-(3.6) and (3.10) will be used. The theoretical derivation of the non-dimensional vertical fluxes is shown in detail in papers **II** and **III**. Finally, we obtain the theoretical profiles

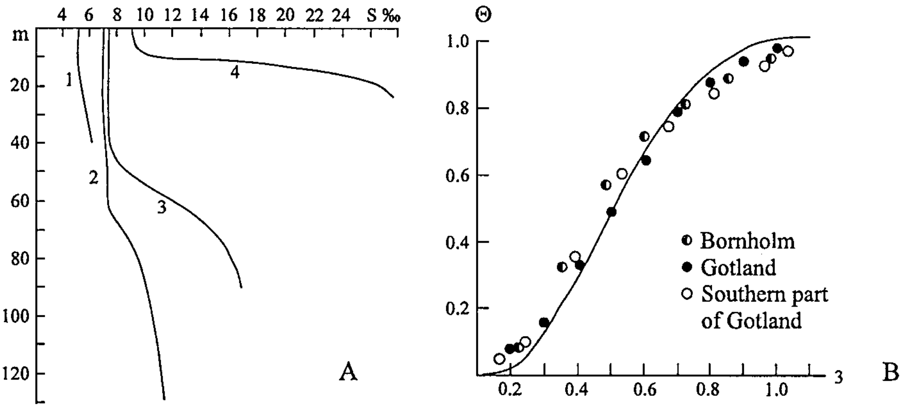


Fig. 3.3. (A) Vertical profiles of salinity in various regions of the Baltic Sea (1. Gulf of Finland, 2. Gotland Deep, 3. Bornholm Deep, 4. Fehrman Belt), (B) self-similarity profile of salinity (from Mälkki and Tamsalu 1985).

for the non-dimensional vertical fluxes of temperature (buoyancy) $Q(\xi)$:

$$Q(\xi) = 1 - (1 - \xi)^4 \text{ ; case A} \qquad (3.12)$$

$$Q(\xi) = 12\xi(1 - \xi)^4 \text{ ; case B} \qquad (3.13)$$

Verification of self-similar profiles with CTD-data

The validity of the self-similarity concept has been tested in various water bodies by several scientists. The validity of self-similar and, for the first time, flux-self-similar profiles were once again examined by verifying the theoretical profiles with the experimental ones derived from CTD measurements. The idea was to carry out CTD observations at one station. The analyses presented below are based on the measurements carried out on board R/V Aranda at station JML (59°34'N, 23°37'E) in the Gulf of Finland during a four-day expedition in July 1995. A detailed description of this experimental study is given in paper **III**. The measured profiles (81 CTD casts) were divided into entrainment type A and detrainment type B according to the vertical profile of temperature (see paper **III** for details). Type A was found in 61 profiles and type B in 20 profiles. The profiles have been investigated in the depth range 0-35 m. Below 35 metres, the temperature changes were negligible. The non-dimensional parameters θ and ξ were derived from the CTD profiles according to (3.1)-(3.2) for temperature (buoyancy). The experimental profiles were compared with the theoretical self-similar profiles (see Fig. 2 in paper **III**), which are derived using expressions (3.5) and (3.6). The dimensional vertical flux of temperature, derived according to (3.7), is presented against the non-dimensional vertical coordinate (see Fig. 3 in paper **III**). The theoretical flux-self-similarity curves given by (3.12) and (3.13) were compared with the experimental curves derived from (3.8) and (3.9) (see Fig. 4 in paper **III**).

Discussion and conclusions

The following main conclusions can be drawn:

1. The measurements carried out on board R/V Aranda in July 1995 showed that the self-similar profiles for temperature (buoyancy) are found in nature. The hypothesis that self-similar profiles have different structures depending on the stage of the mixed layer thickness received observational support in paper **III**. Most of the time during the expedition the profiles represented entrainment; the detrainment cases were not so frequent and not pure (see Fig. 1 in paper **III**). The single profiles (at one-hour intervals) do not always fit with the self-similar approach; some profiles represent transition between entrainment and detrainment. The self-similar concept thus works only when a time-integration over the inertial period is carried out.
2. The self-similar profiles for temperature have the same main features as those for buoyancy. However, the self-similar profile for salinity is more complicated. In the case of entrainment the non-dimensional salinity profile is found between the curves representing non-dimensional buoyancy in the entrainment and detrainment cases. In the detrainment case, non-dimensional salinity joins the buoyancy structure.
3. A study has been made of the theory proposed by Tamsalu (1982) that the primarily evolution of the self-similar structure of temperature (buoyancy) takes place at the turbulent scale of

the motion. In paper **II**, the equations for the non-dimensional vertical fluxes were derived and in paper **III** the experimental results were compared with the theory. The dimensional vertical flux of temperature has clearly different structures in cases of detrainment and entrainment. The comparisons of the experimentally-derived non-dimensional vertical fluxes of temperature with the theoretical structures showed good fit if entrainment was taking place. The fit was less satisfactory in the case of detrainment. The reasoning is the same as in conclusion 1.

4. The hypothesis that the self-similarity structure has its background at the turbulent scale of the motion got some observational support in terms of the existence of the flux-self-similarity. The effect of currents seems to be to destroy self-similar profiles and thus self-similar profiles can only be found if an averaging over the inertial period is carried out. The self-similarity theory can be applied in numerical modelling (see paper **IV**). Further, flux-self-similarity is potentially a useful tool for modelling in parameterizing the vertical exchange of buoyancy in layers of intermittent turbulence, where the description of vertical turbulence is problematic.
5. The four-days-long expedition was found to be too short to find enough profiles representing both entrainment and detrainment. At least a two-week expedition in spring and in autumn would be needed to ensure that there would be profiles representing all different stages of the mixed layer development.

4 Modelling

This chapter summarises the modelling part of this thesis. At first, in Chapter 4.1, a short look is taken at the present state of the art in hydrodynamic modelling. The main hydrodynamic equations of the hydrodynamic-ecological model FinEst are introduced (Chapter 4.2). The three-dimensional equations are given, as is also the derivation of the two-dimensional equations (Chapter 4.2.1). The chapter on material and methods (Chapter 4.2.2) lists the data sets, simulation periods, forcing factors, initial conditions, boundary conditions, etc., used in the model simulations. The results of the simulations by the two-dimensional model are taken from papers **IV** and **V** (Chapter 4.2.3). In addition to papers **IV**, **V**, some extension of the simulations, including three-dimensional modelling, are shown in this summary (see Chapters 4.2.1-4.2.3).

4.1 Hydrodynamic numerical modelling - an overview

The early development of hydrodynamic numerical modelling, especially for the Baltic Sea, has been reported by Svansson (1976) and more recent developments by Omstedt (1989). In these papers, the hierarchy of models from very simple box models up to complicated, fully three-dimensional models is introduced. A short summary is given here concerning two- and three-dimensional hydrodynamic models which have been developed specially for the Baltic Sea, or which have been built up for the World Ocean, but have been applied in the Baltic Sea.

The first two-dimensional numerical model was developed by Hansen (1956), using linearized barotropic equations, in order to simulate the severe flood which took place in the Netherlands in 1953. Welander (1966, 1968) has developed several versions of two-dimensional models. Welander (1968) used the linearized two-dimensional model for studies of the Gulf Stream. O'Brien (1967) and O'Brien and Hurlburt (1972) used their non-linear two-layer, two-dimensional flow model for studies of upwellings. Other important two-dimensional approaches have been introduced e.g. by Heaps (1985).

For Baltic Sea studies, several two-dimensional models have been developed. Kowalik (1969, 1972) used a barotropic two-dimensional model. Later on, simulations relating to the importance of the water exchange between the Baltic Sea and the North Sea were carried out (Kowalik and Staskiewicz 1976, Chilika 1984, Chilika and Kowalik 1984). Applications of two-dimensional barotropic models have also been used e.g. by Tamsalu (1967) for Tallinn Bay, and by Voltzinger and Simuni (1963) and Laska (1966) for storm-surge problems in several parts of the Baltic Sea. Several approaches using two-dimensional models have been made in Finland too. Uusitalo (1960) employed a barotropic model version to investigate currents in the Gulf of Bothnia. Sarkkula and Virtanen (1978) applied a two-dimensional model to the Bothnian Bay around the River Kokemäki for water management purposes. Jokinen (1977) used a barotropic model for his studies of the Gulf of Bothnia, while Häkkinen (1980) applied such a model to the whole Baltic Sea, including the Danish Sounds, to calculate water levels. Myrberg (1991) used a two-dimensional, two-layer linear model for studies of the climatological circulation in the Gulf of Finland and the Gulf of Bothnia.

During the 1970's three-dimensional model development got actively under way in many research institutes around the world. The first such model was developed by Bryan (1969), whose model was used for studies of the World Ocean. In the first versions, the rigid lid approximation was used. The model has later been modified many times (Killworth et al. 1991) and the latest modified free-surface version is commonly used. Simons (1974) developed a three-dimensional model for the Great Lakes in Canada. Blumberg (1977) and Blumberg and Mellor (1987) have developed a three-dimensional model, in which a sigma-co-ordinate system is used in the vertical direction. This model is also widely used in different institutes. Davies (1980) has used his models for many different locations e.g. for sea areas around the U.K.. Among the numerous three-dimensional models, the following approaches are also worth mentioning. Müller-Navarra (1983) has carried out simulations for the Baltic Sea and North Sea areas; operational modelling is also an ongoing activity. Backhaus (1985) has developed a model for the North Sea, but applications to other sea-areas have been made too. Marchuk and Sarkisijan (1988) have summarised a wide spectrum of climate models and numerical methods and analysed the results of these model simulations. Oberhuber (1993) has constructed an isopycnal general circulation model.

For the Baltic Sea area, several three-dimensional model approaches are available. Kullas and Tamsalu (1974, 1977) developed a three-dimensional sigma-coordinate model for the Baltic Sea Proper to study the seasonal variability of the temperature and salinity structure. Kaleis et al. (1974) and Sarkisjan et al. (1975) calculated the baroclinic currents in the Baltic Proper by a diagnostic baroclinic model. Many of the three-dimensional models mentioned in the previous section have also been used in the Baltic Sea. Simons (1976, 1978) applied his model to the Baltic Sea and studied the role of topography, stratification and boundary conditions in the wind-driven circulation. Kielmann (1981) continued the studies of currents and water levels using Simons' model. Funkquist and Gidhagen (1984) have applied Kielmann's model version. Krauss and Brügge (1991), Elken (1994) and Lehmann (1995) have applied the Bryan-Cox-Semtner-Killworth free-surface model version (Killworth et al. 1991) for studying various aspects of the physics of the Baltic Sea. Fennel and Neumann (1996) have studied the meso-scale current patterns in the southern Baltic using the MOM 1 (MOM=Modular Ocean Model) version of the Bryan-Cox model with a horizontal resolution of one nautical mile. Klevanny (1994) has developed a modelling system of two- and three-dimensional models for studying various water bodies: rivers, lakes and seas (including the Baltic Sea). Andrejev and Sokolov (1992) and Andrejev et al. (1992) have developed a three-dimensional model, which has been used e.g. for dispersion studies in the Gulf of Finland. Later still, a data assimilation system for data analysis in the Baltic Sea has been developed by the above-mentioned group (Sokolov et al. 1997). In Finland, a three-dimensional model has been developed by Koponen (1984) based originally on Simons' model. The model has been used for various kinds of case studies and for operational use (Koponen et al. 1994). Tamsalu (1998) has recently developed a three-dimensional modified sigma-coordinate model for the Baltic Sea; this model is studied in this paper.

4.2 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 (see Fig. 4.1) of the model have been developed. In the following, the derivation of the main equations is shown. The model has been applied in many studies both in the Baltic Sea and in the Mediterranean. The Baltic Sea research has been concentrated in the Gulf of Finland both on physical studies (papers **IV**, **V**) and on ecosystem studies (Tamsalu and Ennet 1995). 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).

The FinEst model has been planned first and foremost for ecosystem studies, where physical parameters act as background information to the biochemical model. Of the hydrodynamic parameters, salinity and temperature have variations which play the most important role in ecosystem behaviour. An accurately-simulated salinity field is good 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 simulations described below, including verification of the results, concentrate on investigating the variations and structures of salinity and temperature. On the other hand, simulations of currents by the hydrodynamic model, and verification of these results is a large task to undertake. Flow measurements of very high resolution should be available, as well as model versions with higher horizontal and vertical resolutions than at present. These simulations, therefore, form an important task for future modelling work.

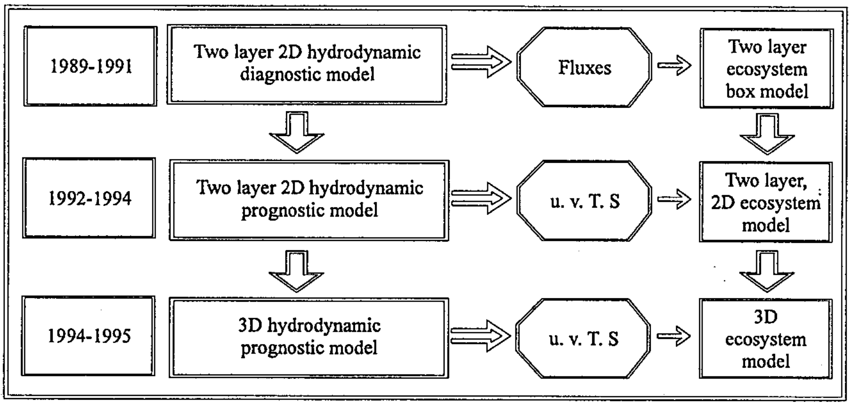


Fig. 4.1. The different stages of the hydrodynamic-ecological model FinEst.

4.2.1 Derivation of the three- and two-dimensional model equations

In the following, the basic assumptions used in the model equations are given. Both the three- and two-dimensional model equations are derived, and the numerical methods are briefly described too.

<u>Basic assumptions of the model equations</u>

The equations describing large-scale currents are used as an initial set. Starting from the basic hydrothermodynamical equations for momentum transfer, conservation of mass, diffusion of salt and entropy transfer, averaged equations are derived in order to obtain averaged hydrodynamic characteristics. Several assumptions, some of which are universal, some specific to the Baltic Sea, are introduced:

1. The equation of entropy transfer is replaced by the equation of heat conduction in a fluid.
2. Molecular processes are completely disregarded.
3. The effect of the curvature of the earth is disregarded.
4. The horizontal components of the earth's rotation vector are disregarded;
5. The vertical components of the momentum equation are replaced by the hydrostatic equation.
6. Except in the hydrostatic equation and in terms related to buoyancy, the density is replaced by the mean density (the Boussinesq approximation).

The vertical structure of the sea can be physically divided into two layers. In the upper mixed layer of the sea the microturbulence (vertical turbulence) is caused mainly by the breaking of wind waves and by the instability of the wind drift. Turbulence is continuous in this layer. Experimental investigations have shown (see e.g. Miropolsky 1981) that outside the boundary layers turbulence is weak and intermittent in character. Taking into account the different hydrophysics in the different layers, the equations can be written in the co-ordinate system $\sigma_i = (z_i - h_i)/D_i$, where i=1,2; i=1 represents the upper layer, i=2 the lower stratified layer, $D_1 = (h_2 - h_1) = (h_2 - Z)$ is the mixed layer thickness; $h_1 = Z$ is the sea level oscillation; $D_2 = (h_3 - h_2) = (H - h_2)$ is the thickness of the lower stratified layer; h_2 is the interface between the upper and lower layer; $h_3 = H$ is the sea depth (see Fig. 4.2).

According to the system described above, the equations of motion can be written as follows:

The momentum equation can be written in a general form:

$$\frac{\partial c_i}{\partial t} + (L_1 + L_2)c_i = F_i \tag{4.1}$$

The continuity equation is written:

$$\frac{\partial u_i D_i}{\partial x} + \frac{\partial v_i D_i}{\partial y} + \frac{\partial \omega_i}{\partial \sigma_i} = 0 \tag{4.2}$$

The equation for the vertical variations takes the form:

$$\frac{1}{\rho_0}\frac{\partial p_i}{\partial \sigma_i} = gD_i\frac{(\rho_i - \rho_0)}{\rho_0} = b_i D_i \tag{4.3}$$

Buoyancy is a function of salinity and temperature:

$$b_i = f(T_i, S_i) \tag{4.4}$$

where:

$$\omega_i = w_i - u_i \frac{\partial \delta_i}{\partial x} - v_i \frac{\partial \delta_i}{\partial y}; \; \delta_i = h_i + \sigma_i D_i$$

$$c_i = \begin{Bmatrix} u_i & & & \\ & v_i & & \\ & & T_i & \\ & & & S_i \end{Bmatrix}$$

$$F_i = \begin{Bmatrix} -\frac{1}{\rho_0}\frac{\partial p_i}{\partial x} - b_i \frac{\partial \delta_i}{\partial x} - f v_i & & & \\ & -\frac{1}{\rho_0}\frac{\partial p_i}{\partial y} - b_i \frac{\partial \delta_i}{\partial y} + f u_i & & \\ & & \frac{1}{c_p \rho_0 D_i}\frac{\partial I}{\partial \sigma_i} & \\ & & & 0 \end{Bmatrix}$$

$$L_1 c_i = u_i \frac{\partial c_i}{\partial x} + v_i \frac{\partial c_i}{\partial y} + \frac{1}{D_i}\left(\frac{\partial \langle u_i' c_i' \rangle D_i}{\partial x} + \frac{\partial \langle v_i' c_i' \rangle D_i}{\partial y}\right)$$

$$L_2 c_i = \frac{1}{D_i}\left(\omega_i - \frac{\partial \delta_i}{\partial t}\right)\frac{\partial c_i}{\partial \sigma_i} + \frac{1}{D_i}\frac{\partial \langle \omega_i' c_i' \rangle}{\partial \sigma_i}$$

Here:

x is directed to the east, y is directed to the north and z is directed downwards, $u_i, v_i, w_i, \omega_i, c_i$ represent averaged values, $u_i', v_i', w_i', \omega_i', c_i'$ represent turbulent fluctuations, U_i is the velocity vector with components u_i, v_i and w_i, ω_i is a modification of the vertical velocity in the model's co-ordinate system, T_i is the temperature, T_0 is a mean temperature, S_i is the salinity, S_0 is a mean salinity, p_i is the pressure, ρ_i is the density, ρ_0 is a mean density, b_i is the buoyancy, g is the acceleration due to gravity, f is the Coriolis parameter, I is the solar radiation, c_p is the specific heat of water, α is the coefficient of thermal expansion, β is an expansion coefficient for salinity (for details, see Zilitinkevich, 1991). The brackets $\langle \; \rangle$ denote an ensemble average, L_1, L_2 are differential operators, F_i is a diagonal matrix (all the other elements than those shown above are zeros).

In equation 4.1, the differential operator L_1 represents horizontal macroturbulence and advection. The differential operator L_2 represents vertical microturbulence and vertical advection. The matrix F_i includes horizontal pressure gradients, buoyancy variations, the Coriolis effect and the penetration of solar radiation into the water body.

Parameterization of turbulent fluxes

The turbulent fluxes are parameterized using the coefficients of eddy viscosity.

$$\langle u_i' c_i' \rangle D_i = -\mu D_i \frac{\partial c_i}{\partial x};$$
$$\langle v_i' c_i' \rangle D_i = -\mu D_i \frac{\partial c_i}{\partial y}; \qquad (4.5)$$
$$\langle \omega_i' c_i' \rangle D_i = -\nu \frac{\partial c_i}{\partial \sigma_i}$$

Here: μ is the coefficient of turbulent eddy viscosity, $\nu(Ri)$ is the coefficient of microturbulence, Ri is the Richardson number.

Boundary conditions

At sea level, where $\sigma_1 = 0$

$$\langle u_1' \omega_1' \rangle = -\tau_x^0; \langle v_1' \omega_1' \rangle = \tau_y^0; \langle T_1' \omega_1' \rangle = -q_T^0;$$

$$\langle S_1' \omega_1' \rangle = -q_S^0; \omega_1 = \frac{\partial Z}{\partial t} \qquad (4.6)$$

$\tau_x^0, \tau_y^0, q_T^0, q_S^0$ will be calculated using atmospheric data (Launiainen and Vihma 1990; Launiainen and Cheng 1995), where τ_x^0, τ_y^0 are the wind stress components in the x- and y-directions at the sea-surface,

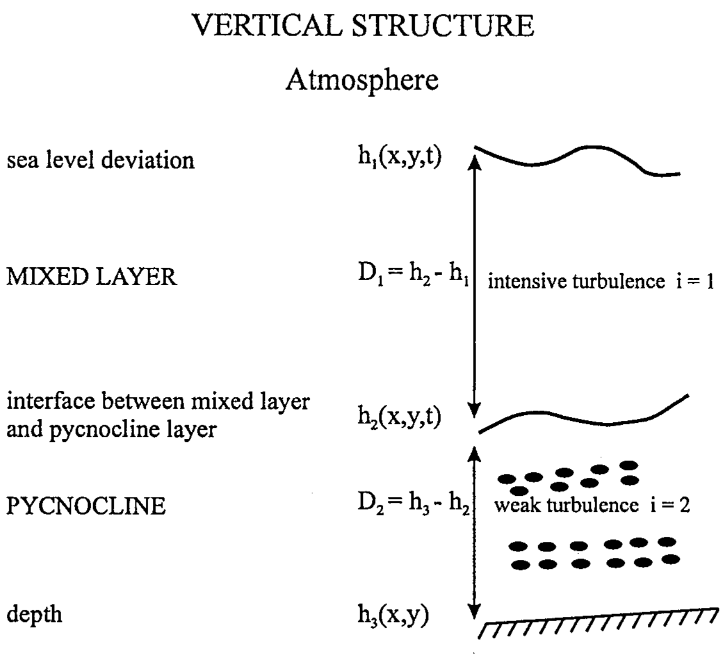


Fig. 4.2. The vertical structure of the three-dimensional FinEst-model. For explanation of the symbols, see also Chapter 4.2.1.

q_T^0 is the heat flux at the sea-surface, q_S^0 is the salt flux at the sea-surface.

At the bottom of the sea, where $\sigma_2 = 1$

$$\langle u_2' \omega_2' \rangle = r u_2; \langle v_2' \omega_2' \rangle = r v_2; \langle T_2' \omega_2' \rangle = 0;$$

$$\langle S_2' \omega_2' \rangle = 0; \omega_2 = 0 \qquad (4.7)$$

The bottom friction is parameterized as follows: $r = 1.5 * 10^{-3} \sqrt{u_2^2 + v_2^2}$.

At the coastal boundary we have:

$$u_i = v_i = 0; \frac{\partial T_i}{\partial n} = \frac{\partial S_i}{\partial n} = 0 \qquad (4.8)$$

At the open boundary we have:

$$\frac{\partial u_i}{\partial n} = \frac{\partial v_i}{\partial n} = \frac{\partial T_i}{\partial n} = 0; S_i = \Gamma \qquad (4.9)$$

where n is normal to the coastline and Γ is experimental data for salinity at the model's boundary.

The two-layer model

Paper **V** and the additional two-layer model results (simulation 3) are based on the equations shown below. The equations are derived for variables in the upper and lower layers. The first and slightly different version of a two-layer model is described in detail in paper **IV**. In that model, the vertical profile of salinity and temperature was based on the self-similar vertical structure (see Chapter 3). The equations were derived for the upper layer and for the vertical means of the variables. The variables in the lower layer were calculated using the self-similar structure (for details, see paper **IV**).

In the upper mixed layer the hydrodynamic fields can be written as follows:

$$U_1 = U_1(t, x, y, \sigma_1);$$
$$T_1 = T_1(t, x, y); S_1 = S_1(t, x, y) \qquad (4.10)$$

Integrating equation (4.1) over the mixed layer, using (4.10), we obtain:

$$\frac{\partial \bar{c}_1}{\partial t} + \bar{L}_1 \bar{c}_1 = \bar{F}_1 \qquad (4.11)$$

where a bar above a symbol denotes the vertically-integrated variables in the corresponding layer.

$$\bar{c}_1 = \int_0^1 c_1 d\delta_1$$

$$\bar{L}_1\bar{c}_1 = \bar{u}_1\frac{\partial \bar{c}_l}{\partial x} + \bar{v}_1\frac{\partial \bar{c}_l}{\partial y} - \frac{1}{D_1}\left(\frac{\partial}{\partial x}\mu D_1\frac{\partial \bar{c}_1}{\partial x} + \frac{\partial}{\partial y}\mu D_1\frac{\partial \bar{c}_1}{\partial y}\right)$$

$$\bar{F}_1 = \begin{Bmatrix} -\pi_{x1} - f\bar{v}_1 + \tau_{x1}/D_1 & & & \\ & -\pi_{y1} - f\bar{u}_1 + \tau_{y1}/D_1 & & \\ & & \frac{\alpha_1}{c_p\rho_0}I_0(1-e^{-\gamma h}) + q_{T1}/D_1 & \\ & & & q_{S1}/D_1 \end{Bmatrix}$$

$$\pi_{x1} = g\frac{\partial Z}{\partial x} + \frac{1}{2}\frac{\partial}{\partial x}\left(D_1\bar{b}_1\right)$$

$$\pi_{y1} = g\frac{\partial Z}{\partial y} + \frac{1}{2}\frac{\partial}{\partial y}\left(D_1\bar{b}_1\right)$$

$$\tau_{x1} = \tau_x^0 - \tau_x^h \; ; \; \tau_{y1} = \tau_y^0 - \tau_y^h$$

$$q_{T1} = q_T^0 - q_T^h \; ; \; q_{S1} = q_S^0 - q_S^h$$

where:

$I = I_o e^{-\gamma z}$, I_0 is the solar radiation at the sea-surface, γ is the coefficient of attenuation of solar radiation, τ_{x1}, τ_{y1} are the tangential stress components in the upper layer in the x- and y-directions, τ_x^h, τ_y^h are the tangential stress components between the upper and lower layer in the x- and y-directions, q_{T1}, q_{S1} are the heat and salt fluxes in the upper layer, q_T^h, q_s^h are the heat and salt fluxes between the upper and lower layer. In the lower layer the hydrodynamic fields can be determined as follows:

$$U_2 = U_2(t,x,y,\sigma_2);$$

$$T_2 = T_2(t,x,y,\sigma_2); S_2 = S_2(t,x,y,\sigma_2) \qquad (4.12)$$

Integrating equation (4.1) over the lower layer using (4.12) we get:

$$\frac{\partial \bar{c}_2}{\partial t} + L_2\bar{c}_2 = \bar{F}_2 \qquad (4.13)$$

where:

$$\bar{c}_2 = \int_0^1 c_2 d\delta_2$$

$$\bar{L}_2\bar{c}_2 = \bar{u}_2\frac{\partial \bar{c}_2}{\partial x} + \bar{v}_2\frac{\partial \bar{c}_2}{\partial y} - \frac{1}{D_2}\left(\frac{\partial}{\partial x}\mu D_2\frac{\partial \bar{c}_2}{\partial x} + \frac{\partial}{\partial y}\mu D_2\frac{\partial \bar{c}_2}{\partial y}\right)$$

$$\bar{F}_2 = \begin{Bmatrix} -\pi_{x2} - f\bar{v}_2 + \tau_{x2}/D_2 & & & \\ & -\pi_{y2} + f\bar{u}_2 + \tau_{y2}/D_2 & & \\ & & q_T^h/D_2 & \\ & & & q_S^h/D_2 \end{Bmatrix}$$

where $\bar{F}_2$ is a diagonal matrix.

$$\pi_{x2} = g\frac{\partial Z}{\partial x} + \frac{(D_1+H)}{2}\frac{\partial \bar{b}_1}{\partial x} + \bar{b}_1\frac{\partial D_1}{\partial x} + \bar{b}_2\frac{\partial H}{\partial x} + c_0 D_2\frac{\partial}{\partial x}\left(\bar{b}_2 - \bar{b}_1\right)$$

$$\pi_{y2} = g\frac{\partial Z}{\partial y} + \frac{(D_1+H)}{2}\frac{\partial \bar{b}_1}{\partial y} + \bar{b}_1\frac{\partial D_1}{\partial y} + \bar{b}_2\frac{\partial H}{\partial y} + c_0 D_2\frac{\partial}{\partial y}\left(\bar{b}_2 - \bar{b}_1\right)$$

where:
The matrixes $\bar{F}_1, \bar{F}_2$ include the vertically-integrated forms of the horizontal pressure gradients, buoyancy variations, Coriolis effect, tangential stress components, heat and salt fluxes and solar radiation in the corresponding layers, $\bar{L}_1, \bar{L}_2$ represent advection and horizontal macroturbulence in the corresponding layers.

Here we use the relation:

$$2\int_0^1\int_0^{\sigma_2} b_2 d\sigma_2 d\sigma_2 - \bar{b}_1 = 2c_0\left(\bar{b}_2 - \bar{b}_1\right)$$

$$c_0 = const \cong 2/3$$

$$\tau_{x2} = \tau_x^h - r\bar{u}_2 \; ; \; \tau_{y2} = \tau_y^h - r\bar{v}_2$$

$$\tau_x^h = \left(\bar{u}_2 - \bar{u}_1\right)\Lambda^h ; \; \tau_y^h = \left(\bar{v}_2 - \bar{v}_1\right)\Lambda^h$$

$$q_T^h = \left(\bar{T}_2 - \bar{T}_1\right)\Lambda^h \; ; \; q_S^h = \left(\bar{S}_2 - \bar{S}_1\right)\Lambda^h$$

where: τ_{x2}, τ_{y2} are the tangential stress components in the lower layer.

The parameterization of the tangential stresses, heat and salt fluxes are depending on the stage of the upper mixed layer:

$$\Lambda^h = \frac{\partial D_1}{\partial t} \quad \text{if} \quad \frac{\partial D_1}{\partial t} > 0 \quad \text{(entrainment)}$$

$$\Lambda^h = 0 \quad \text{if} \quad \frac{\partial D_1}{\partial t} \leq 0 \quad \text{(detrainment)}$$

The calculation of the water level variations and the determination of the thickness of the upper mixed layer for the two-dimensional and for the three-dimensional model versions are shown in detail in papers **IV**, **V** and by Tamsalu (1998).

Numerical methods

The so-called split-up method (Marchuk 1975) is used to solve the marine system equations. For first-order accuracy in time $\left(t_i \leq t \leq t_{i+1/2}\right)$, the mass transport (advection and macroturbulence) is calculated. So,

$$\frac{\bar{c}_i^{t+1/2} - \bar{c}_i^{t}}{\Delta t} + \bar{\Lambda}_1 \bar{c}_i^{t+1/2} = 0 \qquad (4.14)$$

For second-order accuracy in time $\left(t_{i+1/2} \leq t \leq t_{i+1}\right)$, the other terms of equations (4.11) and (4.13) are calculated:

$$\frac{\bar{c}_i^{t+1} - \bar{c}_i^{t+1/2}}{\Delta t} + \bar{\Lambda}_2 \bar{c}_i^{t+1} = \bar{F}_i^{t} \qquad (4.15)$$

where Δt is the time step, $\bar{\Lambda}_i$ is the finite-difference operator of $\bar{L}_i$, i=1,2.

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). The model grid used is given in Figure 4.3. In the half grid-step positions, the variables have been calculated using interpolation. The horizontal resolution of the model is 5 minutes in longitude and 2.5 minutes in latitude, which means about 4.5*4.5 kilometres. The time step used is 10 minutes. The model consists of 8 levels in the well-mixed layer and 8 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 various types of boundary conditions at different grid points are given in Figure 4.4.

		♦i,j+1		
	♥i-1/2,j+1/2	♣i,j+1/2	♥i+1/2,j+1/2	
♦i-1,j	♣i-1/2,j	♦i,j	♣i+1/2,j	♦i+1,j
	♥i-1/2,j-1/2	♣i,j-1/2	♥i+1/2,j-1/2	
		♦i,j-1		

Fig. 4.3. The model grid in the FinEst-model.

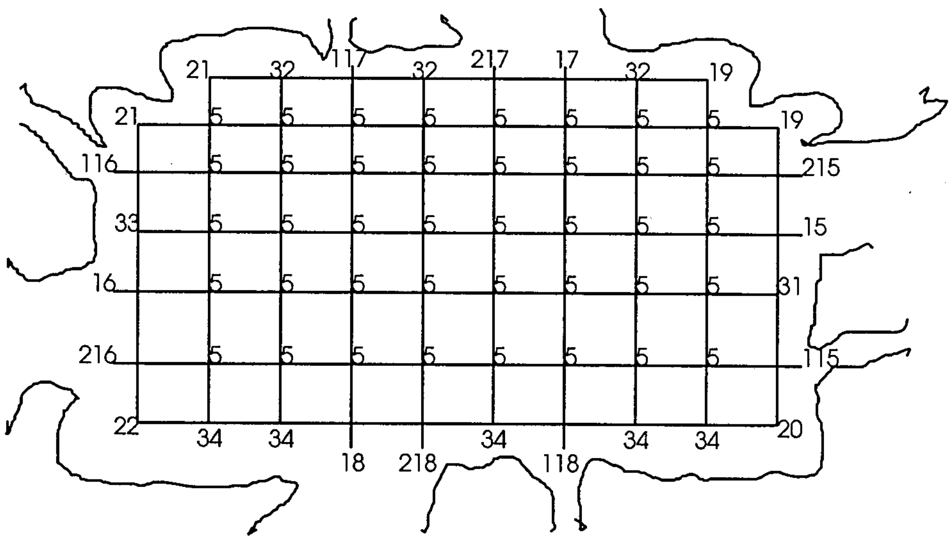
4.2.2 Material and methods

Main model simulations

Simulations by the two-dimensional model were concentrated for the Gulf of Finland on the years 1992 and 1994-1995. The three-dimensional model simulations were carried out for the years 1994-1995. 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 as the initial conditions, boundary conditions, forcing factors and time periods of the simulations. Table 4.1 includes relevant information of the model simulations too. The following main simulations were carried out:

Simulation 1: Model simulations by the first version of the two-dimensional model (paper **IV**), where mostly the monthly mean fields of salinity and temperature and currents are simulated and verified with CTD data for 1992. Both the horizontal structure and the time-evolution of the variables are investigated. A statistical error analysis of the model results is carried out. The atmospheric forcing used is derived from observations from the Keri meteorological station.

Simulation 2. Model simulations by the second version of the two-dimensional model (paper **V**), where the main interest is in simulations of the daily changes of temperature and salinity fields and the upper mixed layer thickness in 1992. The time evolution of temperature, salinity and water levels are also simulated (simulations 2A,B). Atmospheric input derived from observations of the Kalbådagrund meteorological station is used (simulation 2A). In simulation 2B, meteorological forcing from the HIRLAM model is used, and the role of the atmospheric forcing is investigated by verifying the results with CTD data and water level data. The results of simulations 2A and 2B are compared with each other, and a statistical error analysis of the model results is performed.



Here

5 - inner point
31 - closed boundary to E
33 - closed boundary to W
19 - closed corner to NE
21 - closed corner to NW
15 - open boundary to E
17 - open boundary to N
115 - river to E 116 - river to W
117 - river to N 118 - river to S
215 - open boundary with sea level data to E
216 - open boundary with sea level data to W
217 - open boundary with sea level data to N
218 - open boundary with sea level data to S

32 - closed boundary to N
34 - closed boundary to S
20 - closed corner to SE
22 - closed corner to SW
16 - open boundary to W
18 - open boundary to S

Fig. 4.4. Grid point types in the FinEst-model.

Simulation 3. The two- and three-dimensional models are verified against CTD observations in 1994-1995. Three different periods, October 1994, June 1995 and August-June 1995, when CTD measurements were intensively carried out, are studied. A statistical error analysis of the model results is carried out. The HIRLAM meteorological input is used. The results of the simulations carried out by the two-dimensional and three-dimensional models are compared with each other.

External forcing for the model

Two kinds of atmospheric input have been used in the simulations: meteorological data derived from the observations of a single meteorological station (Keri, Kalbådagrund) and meteorological data from the HIRLAM model (Gustafsson 1991). The atmospheric data (daily mean values) from Keri Island (59°45' N, 25° 00'E) for 1992 consist of the following measurements (at a height of 10 m): air temperature, wind speed and direction, relative humidity and total cloudiness. These atmospheric data were used in simulation 1 (see Table 4.1). In simulation 2A the atmospheric data (6 h intervals) from the automatic weather station of Kalbådagrund (59°58'N, 25°37'E) were used. The following parameters were available: wind speed and direction, atmospheric temperature and relative humidity (height of observations: about 35 m). Since the total cloudiness is not observed at Kalbådagrund, the values of cloudiness were taken from the observations of the Isosaari weather station (60°07'N, 25°03'E).

In simulations 2B and 3 the atmospheric input from the HIRLAM meteorological model (provided by FMI; FMI=Finnish Meteorological Institute) was used. The fields used for wind speed and direction and atmospheric temperature in simulation 2B were 6 h forecasts from the lowest model level, namely

32-35 m. In simulation 3, the wind forcing was from the same level, but the 10 m parameterized air temperature was used (for details, see Chapter 4.2.3). In general, it was found that the HIRLAM wind speeds are on average somewhat smaller than those observed. Thus, in simulation 2B, the interpolated HIRLAM winds were multiplied according to a regression equation based on a correlation between the interpolated HIRLAM winds and the corresponding observed winds (see eq. 20 in paper V; see also Fig. 1 in paper V). In simulation 3, a multiplication of the interpolated HIRLAM winds by a factor of 1.2 has been performed for the same reason. The horizontal resolution of the model version of HIRLAM used here is about 55* 55 km in the horizontal direction, which is too coarse to adequately describe the wind and temperature patterns over the GOF. It should be mentioned that the high-resolution version of the Finnish HIRLAM model (with a horizontal resolution of about 25*25 km) was not available for the author. During 1992-95 the wind speeds were clearly smaller than those observed by about 10-30 %, the lowest wind speeds being at the beginning of the period. The atmospheric temperature pattern forecast by the HIRLAM model cannot describe the temperature difference between sea and land accurately (for details, see paper V). Relative humidity and total cloudiness products are not easily available from HIRLAM; observations from the abovementioned meteorological stations have therefore also been used throughout simulations 2B and 3. In the two-dimensional model simulations, an areal interpolation was carried out in order to place the HIRLAM data on the grid of the sea model. This procedure is described by Cheng and Launiainen (1993). For the three-dimensional model simulations, the corresponding interpolation procedure is described by Tamsalu (1998).

In simulation 1 the long-term mean yearly *river runoffs* of the main rivers of the GOF, including the Rivers Neva, Kymijoki, Narva and Luga, were taken into account. In simulations 2-3 the mean monthly river runoffs for the abovementioned rivers were taken into account, and the runoffs of small rivers were added to the these.

In all simulations, except simulation 1, the sea level observations from Hanko (59°50'N, 23°00'E) on the Finnish side or Heltermaa (58°53'N, 23°03'E) on the Estonian side were used for data input. Daily means of water levels were used.

Verification data

The verification data used in simulations 1-3 consists of two different parts: CTD data and water level data.

The CTD observations carried out in 1992 and in 1994-95 were made on several cruises of R/V Aranda. In 1992, most of the observations (about 130) were collected during the cruise in August (see R/V Aranda Cruise Report 10, 1992). In 1994-95 cruises were devoted in both years to the Gulf of Finland modelling studies. In 1994, the cruises in the western and central GOF took place in May-June (data not used here) and in the period October 10-28 (104 CTD casts, see R/V Aranda Cruise Report 13a-c, 1994). In 1995 the cruises took place in the period May 29 -June 9 (77 CTD casts, see R/V Aranda Cruise Report 9a-b, 1995) and in the period August 28-September 8 (96 CTD casts, see R/V Aranda Cruise Report 16a-b, 1995). The CTD data have 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 at which measurements were carried out. The thickness of the upper mixed layer has been determined from the first depth below the sea-surface, where $\frac{\partial T}{\partial z} > 0.1°C/m$.
The vertical mean of salinity and temperature are simply the mean of all the observations in the vertical profile. In the statistical analysis the temperature and salinity observations have been compared with model results at the model's grid point nearest to the observational point.

The water level data have been used both for model verification and also for data input purposes. The water level observations (daily means) 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.

Initial and boundary conditions

The boundary conditions for salinity and temperature were determined from the CTD observations. For simulations 1 and 2A-B, mainly focused on August 1992, the boundary conditions for the surface and bottom salinities and for temperature were defined for the model from the CTD measurements in the transition area between the Baltic Proper and the GOF. For 1994-1995 (simulation 3), 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.

In simulation 1, the initial field was achieved step by step using long model runs with a simplified version of the model equations (see paper IV). In simulation 2, the initial fields for salinity and temperature at the sea-surface and at the bottom were

Table 4.1. The model simulations in the GOF and the corresponding simulation period, atmospheric forcing, input and verification data.

Simulation	main period	atm. forcing	init. cond.	hydrological input data	bound cond. (open)	verific.data
sim1	April 15-October 31, 1992	station Keri, daily mean	climatology+ simulation with simplified equations	yearly mean river runoff	surface and bottom salinity, bottom temperature from CTD observ. in the west	CTD data from 1992
sim2	April 15-October 31, 1992	station Kalbådagr./ Isosaari (cloud.)/ (2A) HIRLAM model 6h interval (temp. and wind)/ Isosaari (cloud.)/ Kalbådagr. (humid.) (2B)	climatology+ control simulation	monthly mean river runoff, daily mean water level (Hanko or Heltermaa)	surface and bottom salinity, bottom temperature from CTD observ. in the west	CTD data from 1992, water levels
sim3	April 15-October 31, 1994, January 1-June 10, 1995, June 11-September 10, 1995	HIRLAM model 6h interval Isosaari (cloud.)/ Kalbådagr. (humid.)	CTD data	monthly mean river runoff, daily mean water levels (Hanko, Heltermaa)	surface and bottom salinity, bottom temperature from CTD observ. in the west	CTD data from 1994-1995

taken from the atlas of Bock (1971). After that a several years run of control simulation was carried out. In simulation 3, focused on October 1994, the CTD data measured in May-June 1994 were used as initial conditions (surface and bottom salinity and temperature). In the simulation for June 1995 and for August-September 1995 the CTD measurements from the previous GOF cruise were used as initial conditions. The same procedure was used for both the two-dimensional and three-dimensional models of the GOF.

4.2.3 Simulations of the Gulf of Finland

Simulation 1

The main topics of simulation 1 are:

a) To study the general hydrodynamic structure in the Gulf of Finland of different variables (salinity, temperature, currents, thickness of the upper mixed layer) and baroclinic processes such as frontal areas, on the time-scale of a month during spring, summer and autumn. To describe how the model results fit with the climatological means.

b) To verify the model with CTD measurements both in space and time and to discuss the results of the simulations, especially the salinity structure and the dynamics behind it.

c) To test how the two-dimensional model approach works in the Gulf of Finland.

d) To test how the vertical profile of salinity and temperature based on self-similarity theory works.

The main results are:

The simulation supported the idea of the highly baroclinic nature of the GOF. The salinity varies from about 0-2 per mill in the River Neva area to about 6-7 per mill in the western GOF. The monthly mean fields of the vertical mean of salinity showed that there exist three main frontal areas with pronounced horizontal salinity gradients $\nabla_{HO}S$. The following maximum gradients in the corresponding area are approximations from the model results (Fig. 2 in paper **IV**): (1) in the easternmost part $\nabla_{HO}S \approx 0.6$ per mill/10 km, (2) in the central part $\nabla_{HO}S \approx 0.8$ per mill/10 km and (3) in the western part $\nabla_{HO}S \approx 0.3$ per mill/10 km at the mouth of the GOF. These fronts become visible when time-averaging e.g. over a month, but their existence is not so clear on instantaneous maps (see simulation 2). In the upper layer the eastern front (1) is strongest while in the bottom layer the western front (3) is the most intense. The formation of these fronts is strongly controlled by the saline water input from the Baltic Proper and by the fresh water input from the eastern GOF, as well as by the variable meteorological forcing. The fronts represent a transition area between the relatively saline water in the western GOF and less saline water in the eastern GOF. The penetration of saline water from the Baltic Proper near the bottom and the related large salinity gradients in the western GOF, front (3), can be explained according to the model results by the JEBAR (JEBAR=Joint Effect of Baroclinicity and the Bottom Relief, see e.g. Cane et al. 1998). Thus the stratification in the GOF, and its related physical processes, is strongly determined by the saline water inflow into the GOF from the Baltic Proper. The eastern extremity of the GOF is strongly controlled by the River Neva with the corresponding salinity gradients (front (1); see Figs. 3-4 in paper **IV**).

The error analysis (equation 23 in paper **V**) of the vertical mean of salinity shows that the mean error of the model results in the GOF area (Table 4.2) was between 6-8 %, having a variation from 4.4 % (western GOF) in October to 14.3 % (western GOF) in July. The error usually increases towards the east, moving further away from the model's boundary which is supported by observations. In addition, relatively high salinity gradients in the east make it difficult to prognose the salinity structure accurately (see also paper **V**).

Table 4.2. The error (as a percentage) in simulations of the vertical mean of salinity by the two-dimensional model in July, August and October 1992: the western GOF, the central GOF, the eastern GOF and the whole GOF. The number of observations (No) is shown too. If the number of observations in the corresponding sea-area is less than 10, the percentage error is shown in bold type.

	No	WGOF	CGOF	EGOF	whole GOF
July	15	**14.3**	6.2	**11.4**	6.1
August	130	5.2	7.1	**9.3**	6.2
October	4	**4.4**	---	---	---

The time-evolution of the surface temperature was simulated at different stations in the GOF. The model, in which the daily mean atmospheric input was used, could reproduce the main changes in the seasonal evolution of the upper layer temperature, but errors of 2-4 °C were still observed (see Fig. 7 in paper **IV**). Frontal activity such as seen in the case of salinity was not observed in the simulations of the horizontal structure of the vertically-averaged temperature (monthly averages). In spring and summer, isolines of temperature are parallel to the depth isolines (see Fig. 9 in paper **IV**). In autumn these isolines are perpendicular to each other. The time-evolution of the thickness of the upper mixed layer was qualitatively correct. The mixed layer deepens due to mechanical mixing and convection from values of 10- 20 m in July to about 15-35 m in October (see Fig. 8 in paper **IV**).

The quasi-stationary salinity fronts become visible in the current fields (see Figs. 5-6 in paper **IV**) where areas of strong currents (baroclinic) exist in the monthly mean maps. The long-term mean currents simulated by a wind-driven model in which horizontal density variations were neglected, showed a mean current speed of only some cm s^{-1} (Myrberg, 1991). This shows how important the baroclinicity of the GOF is and how it also modifies the current fields. The frontal areas of salinity are coupled with maximum current speeds of up to 20-50 cm/s (see paper **IV** for details).

Compared with climatology (Fig. 2.2) and with measurements, the surface salinity was overestimated by about 0.5-1 per mill in the GOF (Fig. 3 in paper **IV**). This is due to the fact that the surface salinity is sensitive to atmospheric forcing, which in simulation 1 was a daily mean forcing derived from the observations of a single station. According to model results (Fig. 7 in paper **IV**) the surface temperature was some 0-3 degrees higher than the climatological mean (Fig. 2.4) and the measured temperatures during the summer season. The seasonal time-evolution of temperature according to the model results and measurements differs from the climatological mean, because the highest sea-surface temperatures were recorded 1-2 weeks later than average.

<u>Simulation 2</u>

The main topics of simulation 2 are as follows:

a) The tests are focused on studying the hydrophysical variables in the uppermost layer of the GOF in 1992. The model results are verified with observations of salinity, temperature, thickness of the upper mixed layer and water levels on a daily time scale. The aim is also to describe how the model results fit with the climatological means.

b) Special attention is paid to the role of atmospheric forcing. In the first simulation (**2DK-model**) the atmospheric forcing derived from the observations of a single weather station (Kalbådagrund) was used. The results of this simulation are compared with the results of model runs for which the atmospheric input is taken from the HIRLAM meteorological model (**2DH-model**).

The main results are:

The simulations of surface salinity (see Fig. 2 in paper **V**) satisfactorily showed the complicated horizontal structure with pronounced gradients (errors 2.5 % by the 2DK model and 2.0 % by the 2DH model, Table 4.3). The open boundary in the west is supported by observations at irregular intervals. This explains the fact that the realistic variability of salinity cannot be simulated by the model there. The differences between the 2DK and the 2DH models is thus smallest near the open boundary. The employment of input from the HIRLAM atmospheric model clearly improved the model results in the central GOF (errors 13.1 % with the 2DK model, 6.0 % with the 2DH model). The most pronounced difference is in the eastern GOF, where the error in the 2DK simulations was 27.5 %, but with HIRLAM input, the error was only 10 %. The HIRLAM space-dependent wind fields better describe the situation over the eastern GOF than do the open sea winds of the Kalbådagrund weather station; strong westerly winds there cause too much eastward water transport and too strong a mixing. As a result, the thin fresh water layer vanishes and the model overestimates the surface salinity. Due to the large fresh water input from the rivers, large horizontal gradients occur in the eastern GOF, so that the exact location of the fronts is sensitive to atmospheric forcing.

In the temperature simulations (see Fig. 3 in paper V), the seasonal time-evolution of the surface layer temperature was simulated by the model with errors usually less than 1-2 degrees. In the 2DK results, the horizontal variation of surface layer temperature was negligible, while in the 2DH results major gradients became visible due to the spatially-variable atmospheric temperature. However, the accuracy of the 2DH model results when compared with measurements is only slightly better than that of the 2DK model (6.0 % with the 2DK model, 5.6 % with the 2DH model for the whole GOF, Table 4.4.). This can be explained by the lack of a resolution in the atmospheric model sufficient to describe the air temperature pattern accurately enough over the sea-area, especially near the coasts. The daily variations in the HIRLAM 35 m temperature fields are pronounced, especially in spring when the land surface is heated, but the sea is cold. Another possibility is to use the parameterized HIRLAM temperature at a height of 10 m (see simulation 3).

The thickness of the upper mixed layer (see Fig. 5 in paper V) can be predicted by the model in the open sea-area, but local upwelling and other rapid changes in the upper mixed layer thickness, etc., are difficult to simulate by the two-dimensional model. The correct time and place of the strong deepening of the mixed layer in late August is difficult to simulate, too is forecasting the related abrupt changes in surface temperature and salinity. Successful simulation of upwelling needs a model in which the vertical velocity is calculated and a special parameterization for upwelling is devised.

Table 4.3. The error (as a percentage) in surface salinity simulations produced by the 2DK and the 2DH models for various parts of the GOF in August 1992. The western GOF, the central GOF, the eastern GOF and the whole GOF. The number of observations (No) is also shown.

	No	WGOF	CGOF	EGOF	whole GOF
2DK	130	2.5	13.1	27.5	7.3
2DH	130	2.0	6.0	10.0	4.0

Table 4.4. The error (as a percentage) in surface temperature simulations produced by the 2DK and the 2DH models for various parts of the GOF in August 1992. In temperature calculations the Celsius scale has been used. The number of observations (No) is also shown.

	No	WGOF	CGOF	EGOF	whole GOF
2DK	130	5.3	7.6	8.3	6.0
2DH	130	4.2	6.7	8.3	5.6

The current fields showed (see Fig. 6 in paper V) some interesting differences between the 2DK and the 2DH model results. When typical westerly winds dominate, the 2DK model seems to produce higher currents than the 2DH model in coastal areas, because the wind measurements from Kalbådagrund overestimate the wind speed at the shoreline as well as in the eastern GOF. Thus the 2DK model also has a tendency to produce higher eastward current speeds in the eastern GOF than the 2DH model. This leads to an overestimation of surface salinity there. The overall time-evolution and main peaks of the water level variations (see Fig. 7 in paper V) can be described by the present model. The role of atmospheric forcing was not clearly revealed. The data input of water levels at the mouth of the GOF plays a crucial role in the model's ability to produce reliable water levels in the coastal areas of the GOF.

The 2DH model results for the horizontal structure of the surface salinity have a good resemblance to the measurements as well as to the climatological means (see Fig. 2.2). The surface salinity varies from about 6.5 per mill in the western GOF to about 0-3 per mill in the eastern GOF (Fig. 2 in paper V). The 2DH model results for the horizontal structure of the surface temperature (Fig. 3 in paper V) show that the simulated temperature is about 14-16 degrees, which is close to measured values and close to climatology (Fig. 2.5), in which the mean surface temperature in August is some 15-17 degrees. Both model results and climatology show that the highest surface temperatures occur in the easternmost shallow GOF. The simulation of the time evolution of surface temperature shows quite high temperatures in July (Fig. 4 in paper V), about 3-4 degrees higher than the climatological means (Fig. 2.4). However, only a few observations are available for this period. The seasonal time-evolution of temperature according to the model results and measurements differs from the climatological means, because the highest sea-surface temperatures were recorded 1-2 weeks later than on average. The seasonal time-evolution of surface salinity showed that the lowest values are reached in spring-early summer, which is in accordance with the climatological means (see Fig. 2.4).

Simulation 3

In simulation 3, the CTD data collected in 1994-95 are used for the model verification of both two- and three-dimensional models (see section on verification data). The primary motivation of the simulations is to monitor the models' ability to reproduce the salinity and temperature fields in the GOF in comparison with simulations 1-2. The secondary motivation is to carry out a statistical analysis using a comparatively large number of CTD soundings (279 casts). The following detailed topics are investigated:

1) How the models' accuracy to reproduce the surface salinity and temperature fields depends on the season.

2) Is there a difference between the two-dimensional and the three-dimensional model's accuracy in reproducing the surface salinity and temperature fields if the same external forcing and data input is used.

3) How the use of atmospheric temperature forcing from HIRLAM's different levels (the 10 m level versus the 35 m level) affects the results of the sea model.

4) How accurate the model results are compared with the natural variability in the sea.

The main results are given according to the two-dimensional model (the **2D**) and the three-dimensional model (the **3D**) simulations:

1. The salinity is simulated in all cases quite accurately (see Tables 4.5, 4.7), the errors being between 3.4 % and 6.9 % (the 2D model) and between 2.4 % and 7.4 % (the 3D model). The most inaccurate simulation was June 1995, when the boundary conditions for salinity were very changeable due to the early stages in the formation of the seasonal thermocline. The surface salinity changed up to 0.5 per mill in the western GOF during the 8 day expedition. The boundary conditions for salinity were therefore not accurate. A good fit with observations (errors 3.4 % in the 2D, 3.2 % in the 3D) was found in August-September 1995, when changes in the stratification conditions and salinity at the models' open boundary were smallest. The 2D model produced the most accurate results during this period. The summer season with stable stratification is the most suitable period for any layered model to work properly. By the same reasoning, the late October 1994 case also gave an accurate salinity forecast (error 3.6 % in the 2D model). The 3D model produced the best fit with observations in October 1994 (error 2,4 %; see below). The 2D and 3D model results for salinity in August-September 1995 are shown in Figures 4.5A,B.

2. The salinity simulations gave on average the most accurate results near the open boundary (see equation 4.9), which is supported by measurements. The errors in the surface salinity usually increase eastwards in both models: the surface salinity gradients increase eastwards and thus errors in the prediction of salinity are easily larger there.

3. The 3D model was very sensitive to initial conditions. For this reason, the initial conditions from observations in spring 1994 and spring 1995 ensured good accuracy for the salinity simulations in October 1994 and August-September 1995. The largest errors, which were found in spring 1995, were partly due to an inaccurate description of the development of the mixed layer, but also due to inaccurate initial conditions. The 2D model is not very sensitive to initial conditions, which is typical for an integrated model, in which the degree of freedom is much more restricted than in the 3D model.

4. The temperature simulations, in which the HIRLAM 10 m temperatures were used as input (Tables 4.6, 4.8) gave less satisfactory results than the salinity simulations. The seasonal variability in the accuracy is also pronounced. The 3D model gives better results during all the seasons than the 2D model. The results of the temperature simulations by both models were the best in the August-September case (errors 9.4 % in the 2D, 7.6 % in the 3D) because the stable stratification and relatively constant thickness of the upper mixed layer favour successful simulations. Possible problems with atmospheric forcings are also smallest due to the small difference between the atmospheric temperature over the sea and the land during late summer. The accuracy of the results is clearly worst in June 1995 (errors 32.8 % in the 2D, 30.1 % in the 3D). Evidently, the models cannot describe the thickness of the mixed layer accurately in spring and this particularly causes inaccuracies in the temperature simulations. The error of the simulations in October 1994 was 25.2 % in the 2D model and less in the 3D model, 18.1 %. The inaccuracies in the results are coupled with the problems in describing the deepening of the upper mixed layer due to autumn storms and convection. The 2D and 3D model results for temperature in

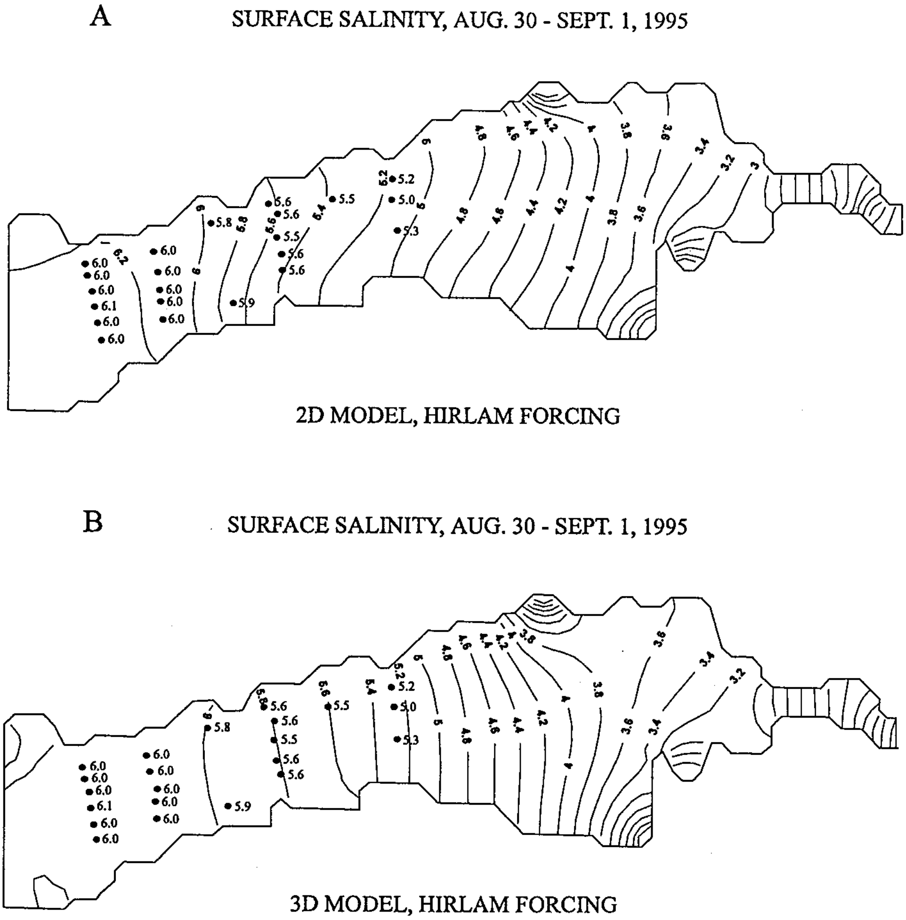


Fig. 4.5. Surface salinity fields in the Gulf of Finland. (A): Simulated by the two-dimensional model. (B): Simulated by the three-dimensional model. The figures represent means of August 30-September 1, 1995. Positions of the salinity measurements carried out between August 30-September 1 are marked with a black dot (according to the model results, changes in the horizontal salinity field were small during August 30-September 1). The isoline analysis of the model results is shown at intervals of 0.2 per mill.

August-September 1995 are shown in Figures 4.6A,B.

5. The role of atmospheric temperature was found to be important. In Figure 4.7 the HIRLAM 35 m, 10 m and measured temperatures at Kalbådagrund (35 m) are given for the May-June, 1995 and August-September, 1995 simulation periods. The HIRLAM temperatures represent the model's grid point nearest to Kalbådagrund (co-ordinates of the grid point: 60° 05'N, 25°67'E; co-ordinates of Kalbådagrund: 59°58'N, 25°37'E). In spring 1995, the HIRLAM 35 m and the measured temperatures at 35 m seem to fit quite well. Both temperatures are relatively high and have a clear diurnal cycle. On the other hand, the 10 m parameterized HIRLAM temperature is much lower than the 35 m temperature and has a very small diurnal cycle. The maximum difference between the 10 m and 35 m temperatures is 13 degrees, which is unrealistically high (Fig. 4.7A). The problems can be caused by the fact that the temperature difference between the land and the sea was pronounced in May-June 1995. In August-September 1995 (Fig. 4.7B) and in October 1994 the difference between the 10 m and 35 m HIRLAM temperatures is realistic, but both temperatures are usually somewhat higher than those observed.

The 3D model was tested using both HIRLAM 10 m and 35 m temperatures in June 1995 and in October 1994, when the difference between these HIRLAM temperatures is largest. When the

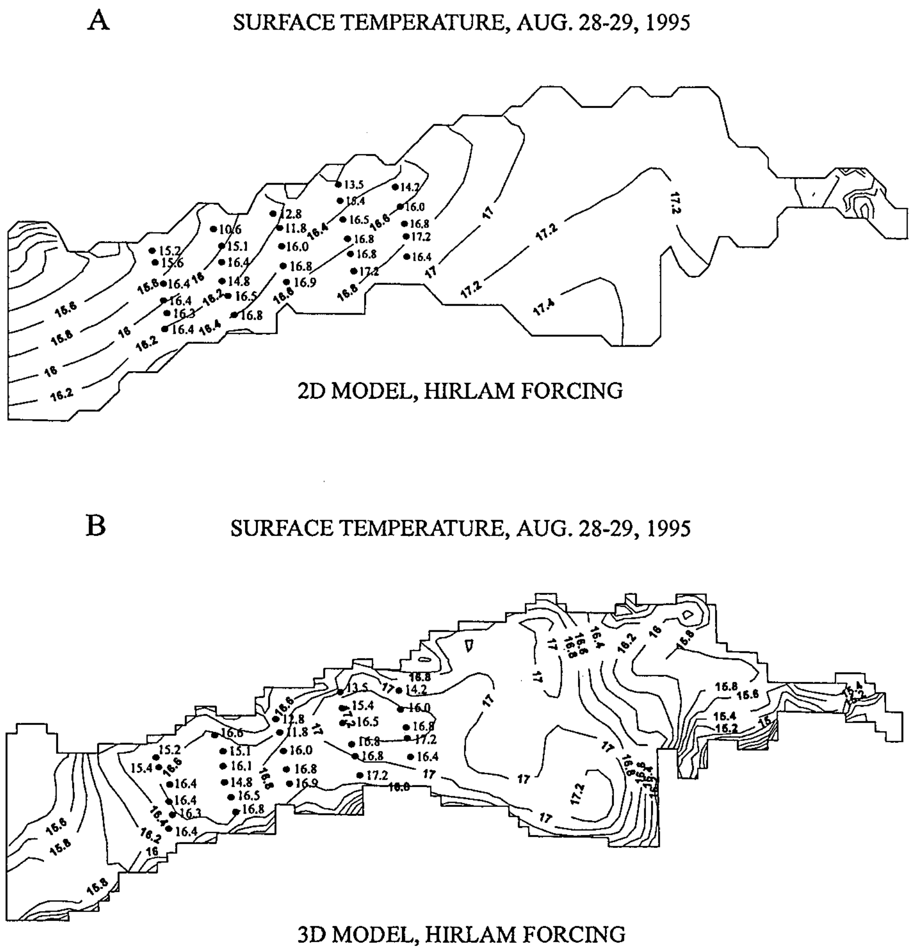


Fig. 4.6. Surface temperature fields in the Gulf of Finland. (A): Simulated by the two-dimensional model. (B): Simulated by the three-dimensional model. The figures represent means of August 28-29, 1995. Positions of the temperature measurements carried out between August 28-29, 1995 are marked with a black dot (according to the model results, changes in the horizontal temperature field were small during August 28-29). The isoline analysis of the model results is shown at intervals of 0.2 degrees.

HIRLAM 10 m temperature is used as input in spring 1995, the model's error is 30.1 %, but with the 35 m temperature, the error is 50.0 %. In October 1994, the 3D model's error is 18.1 % (10 m temperature) and 30.1 % (35 m temperature).

6. The accuracy of the model results has been given as percentages (mean errors). No systematic errors of the model results have been found; the model results are situated symmetrically around the measured values. The accuracy of the results can also be analysed e.g. as follows: The length of the GOF is about 400 km and the surface salinity varies between 0 and 6.5 per mill, i.e. the salinity changes on average by 1 per mill per 60 kilometres. During the stratified season the error in the salinity simulations was typically between 2-3 %. If the average surface salinity in the GOF is about 4.5 per mill, it means that the model's error on the spatial scale is between 5 and 8 kilometres while the model's resolution is 4.5*4.5 kilometres. The model's error is thus about the same as the model's horizontal resolution. Occasionally, the model's error was between 10-15 %, which leads to an error of 25-30 kilometres on the spatial scale. These larger errors were connected with simulations of the eastern extremity of the GOF, where a high salinity gradient exists (see simulation 2) or with use of the early version of the two-dimensional model with inaccurate atmospheric

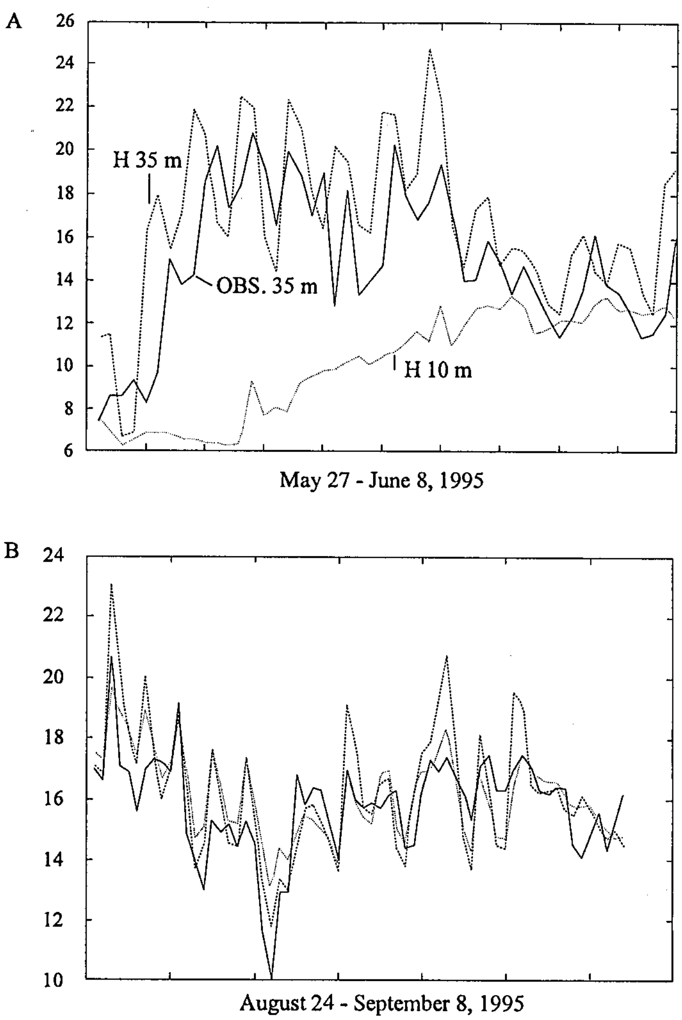


Fig. 4.7. Atmospheric temperatures at Kalbådagrund: according to measurements at a height of 35 m (solid line), according to the HIRLAM model at the grid point near Kalbådagrund at a height of 10 m (dashed line) and 35 m (broken line). a) May 27-June 8, 1995, b) August 24-September 8, 1995.

forcing (simulation 1). The mean errors of the temperature simulations during the stratified season are about 5-10 %. If an average surface temperature of 15 degrees is used for summer, the error in the model simulations is 0.75-1.5 degrees, which is a fairly good result. Outside the stratified seasons, the model's accuracy is quite poor, the error being typically some 3-5 degrees. The inaccurate temperature simulations during spring pose a definite problem in ecosystem calculations, in which temperature plays a key role.

Table 4.5. The error (as a percentage) in simulations of surface salinity in 1994-95 by the 2D model in the GOF: the western GOF, the central GOF, the eastern GOF (**no observations**) and the whole GOF. The number of observations (No) is also shown.

	No	WGOF	CGOF	EGOF	whole GOF
1994/Oct.	106	2.5	6.5	---	3.6
1995/June	77	6.9	6.9	---	6.9
1995/Aug.-Sept.	96	3.2	4.1	---	3.4

Table 4.6. The error (as a percentage) in simulations of surface temperature in 1994-95 by the 2D model in the GOF: the western GOF, the central GOF, the eastern GOF (**no observations**) and the whole GOF. The number of observations (No) is also shown.

	No	WGOF	CGOF	EGOF	whole GOF
1994/Oct.	106	25.5	24.4	---	25.2
1995/June	77	35.0	30.0	---	32.8
1995/Aug.-Sept.	96	10.6	5.8	---	9.4

The results of the statistical analysis of the three-dimensional model's results are the following:

Table 4.7. The error (as a percentage) in simulations of surface salinity in 1994-95 by the 3D model in the GOF: the western GOF, the central GOF, the eastern GOF (**no observations**) and the whole GOF. The number of observations (No) is also shown.

	No	WGOF	CGOF	EGOF	whole GOF
1994/Oct.	106	2.3	2.9	---	2.4
1995/June	77	7.7	6.8	---	7.4
1995/Aug.-Sept.	96	3.0	3.6	---	3.2

Table 4.8. The error (as a percentage) in simulations of surface temperature in 1994-95 by the 3D model in the GOF: the western GOF, the central GOF, the eastern GOF (**no observations**) and the whole GOF. The number of observations (No) is also shown.

	No	WGOF	CGOF	EGOF	whole GOF
1994/Oct.	106	19.5	13.8	---	18.1
1995/June	77	32.2	27.5	---	30.1
1995/Aug.-Sept.	96	8.1	6.1	---	7.6

These simulations showed that:

a) salinity simulations give good results both by the 2D and the 3D models, with no major difference in the models' accuracy.

b) the accuracy of the salinity simulations depends on (1) the accuracy of the boundary conditions, (2) the stratification conditions, in which the summer season with stable stratification gives the best results, (3) the initial conditions, to which the 3D model is very sensitive.

c) the temperature simulations give better results by the 3D model than by the 2D model, due to a more accurate description of the vertical structure in the former model.

d) the results of the temperature simulations by both models depend on (a) the season, the summer season giving the best results, (b) the atmospheric forcing used, especially of the atmospheric temperature (10 m or 35 m HIRLAM temperature).

5 Conclusions

In this thesis the physical processes of the Gulf of Finland have been studied: a) by presenting the results of a literature review of the main physical factors influencing the physics of the Gulf b) by investigating the vertical structure of the Gulf, especially in terms of the self-similarity approach, c) by carrying out model simulations, using two- and three-dimensional models, of salinity, temperature, the thickness of the mixed layer, currents, and water levels, and by verifying these results with measurements.

The main aim of such a structure as described above is: firstly, the sea-area of interest for physical modelling has been investigated by collecting together all available publications concerning studies of the physics of the Gulf of Finland. The investigation and summarising of the relevant literature has provided focus points for modelling and measuring campaigns as well as giving important knowledge of the gaps in our understanding of the physics of the Gulf. Secondly, an important field of investigation is the vertical structure of the sea. The idea here was to present some new ideas about this approach, the flux-self-similarity, and on the other hand to verify the self-similar profiles with measurements. Thirdly, the modelling part itself was devoted to many different tasks. The baroclinic structure of the Gulf was investigated by studying the monthly means (1992) of hydrophysical variables by a two-layer model. The atmospheric forcing used was relatively simple, based on measurements from one station. After that a more complex two-dimensional model was used to study the daily variability of the physics (1992). The atmospheric forcing was taken from a meteorological model. Special attention was also devoted to studying the effects of the meteorological forcing on the results of the sea model. In the next step a three-dimensional model was used, and its results were verified with measurements and compared with the two-dimensional model (years 1994, 1995). Tests were also made of the seasonal dependence of the models' accuracy in reproducing the surface salinity and temperature fields.

1. The knowledge of physics of the GOF and guidelines for the future work

The Gulf of Finland had not previously been studied as an entity since the 1930's, until the political changes in the 1990's again made it possible to study this sea area by carrying out basin-wide studies. Thus, the latest summary reports of the Gulf are rather old and do not include results using modern measurement techniques and modelling. The latest studies, since World War II, have been restricted to the coastal waters of the corresponding country and basin-wide studies are lacking. The measured time-series of different variables, such as currents, are also too short and the horizontal resolution of the measurements is not high enough. In the following the main results of the study of the physics of the Gulf will be given, as well as a recommendation for future work.

The basic physical processes of the GOF (paper I) have already been well-known since the beginning of this century. Knowledge of the basic geographical information is at an adequate level, but detailed *bottom topography* is needed e.g. for modelling studies. The *general circulation*, with its stability variation, had been already studied during the first decades of the century and is as well-known as the main forcing mechanisms: the wind stress and buoyancy variations. From the current measurements the variability of the current speeds are known as well as the seasonal variations. On the other hand, many applications, such as estimating the dispersion of substances, model verifications and biological research need high-resolution measurements of currents and related meso-scale dynamics. The *salinity and temperature* structure and the related thermohaline effects can be considered as more conservative than the currents. The main forcing mechanisms for the thermohaline circulation are well-understood; as are too the spatial and temporal variations of salinity and temperature. But, for the same reasons as given for currents, the high-resolution structure, such as frontal areas and eddies, and the dynamics behind it are less understood. Variations in the *sea-level* are well-known in the GOF, thanks to long-term series of water level observations. The forecasting of sea-level changes is a potentially important issue due to the possible flooding caused by high levels. The long time-series also enable us to verify whether the fingerprints of climate change are visible. Wave studies are important for coastal management and resuspension. Certainly, waves and air-sea interaction studies need more observational material: modern buoys are one solution. The relatively poor knowledge of horizontal turbulence is also a clear gap in our understanding of the physics of the GOF. Turbulence is an important process in connection with coastal-open sea interactions and in the dispersion of substances in the sea. Another relatively poorly-known feature is the currents below the ice. For example the annual average flows represent only ice-free conditions.

The abovementioned gaps in our knowledge clearly indicated the need for applying modern measurements and modelling techniques in the GOF area with high spatial and temporal resolution. To increase our knowledge of the meso-scale dynamics, eddies and fronts in particular, measurements using ADCP and batfish are needed. At the same time, new maps of the bottom topography should be constructed in order to reach the horizontal resolution required for numerical models, i.e. the internal Rossby radius of deformation, 1-3 km. When planning measurement campaigns, this resolution should be borne in mind. Once these thresholds are overcome, by then carrying out international multidisciplinary cruises, up to now quite unknown processes, such as the energy transfer between different scales, coastal-open-sea interactions and water exchange between the Baltic Proper and the GOF can at last be studied.

2. The vertical structure and the self-similarity approach

The vertical structure in the Gulf of Finland was found to be strongly dependent on space and time, being quite different for salinity and temperature. In summer time, the Gulf can be said to consist of a maximum of four different layers. The self-similarity approach, which was first introduced into the marine sciences by Kitaigorodskii and Miropolsky (1970), is principally an effective and compact mathematical formulation of the vertical structure. That is because the non-dimensional marine system variable in the main thermocline layer, originally depending on the vertical co-ordinate and time, can be described as a function of a non-dimensional vertical co-ordinate only. Thus, the self-similar approach reduces the dimension number of the problem.

The literature review (paper II) of the theory showed that after the first studies in the 1970's, interest in investigating self-similarity in the marine sciences has somewhat declined. However, the findings that the self-similar profiles strongly depend on the development of the mixed layer thickness reinvigorated the theory to some extent. This study has shown that self-similar profiles can be found in nature, but not in every profile. Integration over the inertial period should be carried out. It is also clear that some profiles represent neither pure entrainment nor detrainment cases. No self-similar profiles for currents have been found. It is possible that the transient currents destroy the self-similar structure, and thus the short-scale variability has to be smoothed out by an integration over the inertial period.

A new feature is the self-similarity of the vertical turbulent fluxes, the scale of which was proposed as the real source for self-similarity. The observations give support to this idea (paper III), but more investigations are needed before drawing a final conclusion. The flux-self-similar profiles also showed a clear difference depending on the mixed-layer development. The flux-self-similarity approach may be an important way to parameterize vertical turbulence in models. The cruise devoted to carrying out CTD measurements as verification material for the theory at a single station in the Gulf of Finland was found to be too short. Such cruises should last for longer periods, say some weeks, and take place during different seasons, to be able to gather information on the mixed layer physics during different stages of the layer's development.

3. The modelling

Both two- and three-dimensional models have been used for the studies of the physics of the Gulf of Finland. The model simulations have been focused on studying salinity and temperature distributions, but also currents, water levels and the thickness of the upper mixed layer have been investigated. The simulated years, for which verification material exist, are 1992 and 1994-95. The modelling was based on a step-by-step ideology, in which the simulations started with the simplest models and progressed towards more complex approaches.

The monthly mean simulations (1992) by the two-dimensional model, in which yearly means of river runoff and daily means of atmospheric forcing (paper IV) were used, clearly supported the idea of the baroclinic nature of the GOF, with related frontal areas in the western, central and eastern Gulf. The locations of the fronts are controlled by saline water inflow to the Gulf, river runoffs and the baroclinic circulation, as well as by variable meteorological forcing. The accuracy of the model simulations was good and the location of the fronts was correct. It can therefore be concluded that a vertical profile of salinity and temperature based on the self-similarity theory functions well. The model simulations also showed the important role of JEBAR in intrusion of the saline water from the Baltic Proper to the Gulf. The seasonal time evolution of the upper layer temperature was forecast quite accurately. The current simulations showed the strong coupling of the flow field with the highest gradients of salinity, which supports the idea of a baroclinic sea. The mixed layer thickness, with its time evolution, was also fairly realistically simulated. Simulations of the daily mean of hydrophysical variables in 1992 concentrated on testing different atmospheric forcings (paper V). Use of the HIRLAM atmospheric model reduced the errors in the prognosed surface salinity considerably compared with the use of forcing from a single station; this was especially so in the eastern GOF. The space-dependent wind field thus has clear effects on the models' accuracy. The surface temperature simulations did not show so clear an improvement in the case of HIRLAM forcing due to the inaccuracies of the HIRLAM atmospheric temperature field due to lack of resolution in the model. The abovementioned model results of the horizontal structure of the surface salinity show a good resemblance to the measurements and the climatological means with pronounced east-west gradients of salinity. The simulated temperatures and the climatology show that the highest surface temperatures occur in the easternmost shallow GOF. The seasonal time-evolution of temperature according to both the model results and the measurements differ from the climatological means, because the highest sea-surface temperatures were recorded 1-2 weeks later than average. The seasonal time-evolution of the surface salinity showed that the lowest salinities are reached in spring-early summer, which is in accordance with climatology.

The control simulation for 1994-1995 (simulation 3) by two- and three-dimensional models showed that both models are capable of simulating surface salinity accurately during the simulated seasons; spring, summer and autumn. The temperature simulations showed, however, that spring and autumn, when the mixed layer thickness is changing rapidly, do not have the most suitable conditions for a two-layer model to work accurately. The three-dimensional model results were overall slightly better than the results of the two-dimensional model. It should be remembered that inaccuracies in the boundary conditions also play an important role in a model's results, irrespective of the model type. In the salinity simulation, the model's error on a spatial scale in summer is about the same as the model's horizontal resolution; for temperature the error is slightly higher. The chosen atmospheric temperatures, namely the HIRLAM 10 m parameterized temperature or the HIRLAM 32-35 m forecast temperature showed large differences between each other, especially in spring. The 35 m temperature also has a clear diurnal cycle, which is not the case for the 10 m temperature, which was much lower than the former. Especially in spring, good results in sea-surface temperature simulations can only be reached using the 10 m temperature. These problems are connected with HIRLAM's surface parameterization and to the low resolution of the model version available. The three-dimensional model also proved to be very sensitive to initial conditions, to which the two-dimensional model is clearly less sensitive.

In the model simulations, some problems also arose. 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. The two-dimensional model is less suitable for simulations outside the stable and strongly stratified seasons. For the three-dimensional model the problem is less severe. 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. These factors are important in sea modelling. The present resolution of the sea model should also be refined, following which such features as 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 use of models of different orders of complexity should be continued to study the differences between such models. The model 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.

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LIST OF SYMBOLS USED

$\kappa = \int_0^1 \theta d\xi$,

$\overline{\kappa} = \int_0^1 \int_0^\xi \theta d\xi d\xi$,

$\kappa, \overline{\kappa}$ constants in the self-similarity concept

α the coefficient of thermal expansion

β expansion coefficient for salinity

ξ a non-dimensional vertical co-ordinate

μ the coefficient of macroturbulence

θ a non-dimensional marine system variable

σ vertical co-ordinate in modified sigma-coordinate model

ρ density

ρ_0 mean density

τ the wind stress

ν the coefficient of macroturbulence

γ the coefficient of attenuation of solar radiation

$\nabla_{HO}S$ horizontal salinity gradient

Γ experimental data for salinity at model's open boundary

a_0, a_1, a_2, a_3, a_4 constants in equation (3.4)

b buoyancy

c a marine system variable (u,v,T,S)

c_p the specific heat of water

D layer thickness in modified sigma-coordinate model

D_1 upper mixed-layer thickness

D_2 thickness of the lower stratified layer

f the Coriolis parameter

g the acceleration due to gravity

h thickness of the upper mixed layer in z-coordinate system

h_1 sea-level oscillation in the modified sigma-coordinate system

h_2 interface between the upper and lower layer in modified sigma-coordinate model

h_3 sea depth in modified sigma-coordinate system

H the depth of sea

I the solar radiation

I_0 solar radiation at sea-surface

m_2 a constant in equation (3.10)

n normal to the coastline

No number of observations

Q the non-dimensional vertical flux of a marine system variable

p pressure

q_s salt flux

q_T heat flux

r the bottom friction coefficient

Ri the Richardson number

t time

S salinity

S_0 mean salinity

S' turbulent fluctuation of S

T temperature

T_0 mean temperature

T' turbulent fluctuation of temperature

U a velocity vector with components u,v,w

u velocity component in x-direction

u' turbulent fluctuation of u

x horizontal coordinate directed to east

y horizontal coordinate directed to north

z vertical coordinate directed downwards

Z sea level oscillation

v velocity component in y-direction

v' turbulent fluctuation of v

w vertical velocity component

w' turbulent fluctuation of the vertical velocity

$w'T'$ vertical flux of temperature

$\langle \rangle$ denotes ensemble average

a bar over the symbol denotes a vertically-integrated variable in the corresponding layer

<u>Subscripts</u>

1 value of a variable in the upper mixed layer in z-coordinate system

2 value of a variable in the bottom layer in z-coordinate system

max. maximum value of a variable

i=1,2,

i=1 represents upper mixed layer

i=2 represents lower stratified layer

<u>superscript</u>

0 at the sea-surface

<u>Abbreviations</u>

CTD Conductivity Temperature Depth

FIMR Finnish Institute of Marine Research

FinEst The Finnish-Estonian hydrodynamic-ecological model

FMI Finnish Meteorological Institute

GOF Gulf of Finland

JEBAR Joint Effect of Baroclinicity and Bottom Relief

HIRLAM High Resolution Limited Area Modelling

MOM Modular Ocean Model

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