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A BAROCLINIC PROGNOSTIC MODEL OF THE GULF OF FINLAND

BY

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ABSTRACT

A 2.5- dimensional baroclinic prognostic hydrodynamic model has been developed for the Gulf of Finland. The vertical structure of salinity and temperature is based on a self-similarity structure of the sea. The model results showed that the buoyancy-driven circulation is of great importance in the area studied. Buoyancy-driven circulation is mainly caused by salinity. Horizontal salinity fields calculated by the model for different months were compared with measurements. The results were successful. The results showed there are quasi-stationary fronts of salinity and velocity in the Gulf. The maintenance of these fronts is based on the opposite effects of river water discharge and salty water input from the Baltic Proper. These processes are modified by the baroclinic circulation and bottom topography.

Introduction

Currents in the Baltic Sea are generated mainly by two mechanisms: wind stress and buoyancy variations. The buoyancy structure is strongly dependent on the variations in salinity. There are remarkable salinity gradients both in horizontal and vertical directions, which are caused by the exchange of water between the Baltic Sea and the North Sea, and by river water inflow to the sea. The hydrodynamic processes are strongly modified by the variations in bottom topography.

As a result of the above mentioned processes the vertical structure of the pycnocline has a two-layer structure: a quasi-homogenous layer and a halocline layer. Above the halocline, mostly wind-driven circulation dominates while in the halocline layer buoyancy (salinity and temperature) currents play an essential role.

1. Hydrodynamic baroclinic prognostic two-layer model

The equations describing large-scale currents are used as an initial set of equations. 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 get averaged hydrodynamic characteristics. Several assumptions, some of which are universal, some only specifics to the Baltic Sea are introduced (see Mälkki and Tamsalu, 1985).

We will now concentrate ourselves as an example on the equation of the conservation of salinity. This equations takes the following form after the simplifications:

$$\frac{\partial S}{\partial t}+div\left(US+\langle U'S'\rangle\right)+\frac{\partial wS}{\partial z}=-\frac{\partial\langle w'S'\rangle}{\partial z} \qquad (1)$$

Where

U -horizontal velocity vector with components u and v,U′-fluctuation of the velocity vector with components u′and v′,w -vertical velocity, w′-fluctuation of the vertical velocity, T -temperature, S - salinity, S_0 -mean salinity, S′ -fluctuation of the salinity, C-water quality ingredient concentration.

The splitting-up method is frequently used to calculate the hydrodynamic equations. In the first-order accurancy in time, mass transport (advection and macroturbulent) are calculated. The macroturbulent term is parameterized in a traditional way. After that the equations will be integrated in the vertical direction; at first from the bottom H to the sea-surface and then from the mixed layer bottom h to the sea-surface. Finally, we get:

$$\frac{\partial\overline{\varphi}}{\partial t}+\overline{u}\frac{\partial\overline{\varphi}}{\partial x}+\overline{v}\frac{\partial\overline{\varphi}}{\partial y}-\frac{\partial}{\partial x}A\frac{\partial\overline{\varphi}}{\partial x}-\frac{\partial}{\partial y}A\frac{\partial\overline{\varphi}}{\partial y}=F \qquad (2)$$

$$\begin{aligned}&\frac{\partial\varphi_1^*}{\partial t}+\left(\overline{u}+u_1^*\right)\frac{\partial\varphi_1^*}{\partial x}+\left(\overline{v}+v_1^*\right)\frac{\partial\varphi_1^*}{\partial y}-\frac{\partial}{\partial x}A\frac{\partial\varphi_1^*}{\partial x}-\frac{\partial}{\partial y}A\frac{\partial\varphi_1^*}{\partial y}=\\&=F-u_1^*\frac{\partial\overline{\varphi}}{\partial x}-v_1^*\frac{\partial\overline{\varphi}}{\partial y}\end{aligned} \qquad (3)$$

where

$$F=-\frac{\partial}{\partial x}\int_0^H u^*\varphi^* dz-\frac{\partial}{\partial y}\int_0^H v^*\varphi^* dz,\ \overline{\varphi}=\frac{1}{H}\int_0^H\varphi dz,\ \varphi_1^*=\frac{1}{h}\int_0^h\varphi dz-\overline{\varphi}$$

$$\overline{u}=\frac{1}{H}\int_0^H u dz,\ u_1^*=\frac{1}{h}\int_0^h u dz-\overline{u}$$

$$\varphi = \begin{bmatrix} U & & & & \\ & V & & & \\ & & T & & \\ & & & S & \\ & & & & C \end{bmatrix}$$

For the second-order accuracy in time, the other terms of the equation (1) can be calculated.

Integrating equation (1) in the vertical direction, at first from the bottom to the sea-surface and then in the upper mixed layer, we obtain:

$$\frac{\partial \overline{S}}{\partial t} = \frac{q_s^{\,0}}{H} \qquad (4)$$

$$\frac{\partial S_1^*}{\partial t} = \frac{q_s^{\,0} - q_s^{\,h}}{h} - \frac{q_s^0}{H} \qquad (5)$$

where

$q_{s.}^0$ is $\langle S' w' \rangle$ in the sea-surface respectively

q_s^h is $\langle S' w' \rangle$ in the mixed-layer bottom respectively

h is a mixed-layer thickness

1.1 Self-similarity structure

The observations carried out in different points of the Baltic Sea have indicated that salinity, temperature, oxygen and nutrients have a universal vertical structure. There are an homogeneous upper layer and a self-similarity structure in the pycnocline layer. In the seasonal pycnocline layer, there are two different self-similarity structures: firstly, the case of entrainment when the homogeneous layer is rising (storm) and secondly the case of collapse when the mixed layer is decreasing (storm subside).

The self-similarity structure was determined for the first time by Kitaigorodskii and Miropolski (1970) using North-Atlantic temperature data. This self-similarity structure describes the situation when the mixed layer is rising. O. Phillips (1966) described the salinity structure in the Red Sea by the "universal" function.Reshetova and Chalikov (1977) analyzed the Oceanic temperature and salinity data and described the self-similarity function. The analyses of the experimental data revealed a very large range in the empirical estimates of this function.Tamsalu (1982) noted that the self-similarity function depends on the evolution of the mixed layer thickness.The self-similarity structure has been discussed in several articles. An overview of this problem is given by Zilitinkevich (1991).

The discovery of self-similarity is always a beautiful event in natural sciences. It simplifies the calculations and enables the presentation of experimental data in a more compact form. Using the self-similarity structure, all hydrodynamic and ecosystem equations become integrated in the vertical direction. Hence the three-dimensional problem becomes a two-dimensional one.

Using the self-similarity structure, all hydrodynamic and water quality ingredients φ will be presented as follows:

$$\varphi = \overline{\varphi} + \varphi_1^* \qquad 0 \le z \le h$$

$$\varphi = \overline{\varphi} + \varphi_1^* \left[1 - \kappa^{-1}\Theta(\varsigma)\frac{H}{H-h} \right] \quad h \le z \le H \qquad (6)$$

where

$$\kappa = \int_0^1 \Theta d\varsigma$$

2. Buoyancy-driven baroclinic circulation

The long-term variability of salinity in the Baltic Sea has been studied by several authors. All observations show that the salinity has generally somewhat increased during this century (Hela, 1966). The increase of salinity is coupled with strong salinity water inflows through the Danish Sounds. The inflows depend on the large-scale atmospheric pressure patterns. Despite of the increasing salinity no indication of any major changes in the stability conditions has been found (Fonselius, 1969). On the other hand, it has generally been observed that the salinity of the Baltic Sea has decreased during the last years due to the lack of strong saline inflows. The salinity distribution of the Baltic Sea is also strongly coupled with the river run-offs. The input of fresh water from rivers is time-dependent. Periods of low river run-offs are connected with high salinities; high run-offs with low salinities. River run-off problems have been studied for example by Mikulski (1970). A summary of the salinity distribution in the Baltic Sea is given by Bock (1971).

The Gulf of Finland is characterized by large horizontal salinity gradients; the mean salinity varies from about 1 PSU in the eastern part near the City of St. Petersburg to about 7-8 PSU in the western part close to the City of Hanko. The remarkable salinity gradients are maintained because of the opposite effects of saline water flux from the Baltic Proper and river water input of about 2700 m^3s^{-1} from the river Neva. The long-term salinity variation in the Gulf of Finland has been studied by Launiainen (1982).

During January 7-27, 1993 there took place a remarkable saline water pulse via the Danish Sounds. A water volume of about 300 km^3 penetrated into the Baltic Sea. The ecological consequences of this pulse are an important field of investigation.

3. Case study

3.1 Principles of model version and parameters

The model simulations were carried out to prognose currents, salinity, temperature and the thickness of the mixed layer in a real situation.

The following characteristic parameters were used: grid step dx=dy= =4663 m, time step dt= 600s, bottom friction R= $1.3*10^{-3}+\sqrt{\bar{u}^2+\bar{v}^2}$, coefficient of macroturbulence $\mu=2*10^{-3}*dx^{4/3}$, Coriolis-parameter $f=2\omega\sin\varphi$, drag-coefficient. $C_d=(0.63+0.066U_a)$.

The following boundary conditions were used:

At the coastal area we have:

$$u=v=0;\ \frac{\partial T}{\partial n}=\frac{\partial S}{\partial n}=0$$

At the open boundary we have:

$$\frac{\partial u}{\partial n}=\frac{\partial v}{\partial n}=\frac{\partial T}{\partial n}=0, S/_\Gamma=G_s$$

where

n is the normal to the coastal line.

Atmospheric conditions: air temperature T_A, wind speed U_a, evaporation E_A, cloudiness C_d are given for the total Gulf of Finland area as a function of time and uniform as a function of space. The atmospheric data from the island of Keri (59° 45 min , 25° 00 min) was used.

The largest river water inputs were taken into account (Kymi, Narva, Neva). These values have been given by Mikulski (1970). The model run was started at 25.4. The initial field was a 10 year simulation with the non-linear salinity and momentum equations without the temperature model and the atmospheric model. In the beginning of the main simulation the vertical mean of temperature was put to 1° C . The model results shown in the following figures represent monthly mean values.

The two-layer 2.5 dimensional hydrodynamic prognostic model FINEST is realized by numerical methods. Finite-difference equations are composed by using F. Mesingers' (1981) schemes.

Routine CTD-observations carried out onboard R/V Aranda were used to verify results of salinity and temperature simulations. The salinity data is from the year 1992. The model verifications were carried out during the period June- October, when most of the data was collected.

3.2 Discussion of model results

3.2.1 Vertical mean of salinity

According to the model results, horizontal structure of the vertical mean of salinity is characterized by a large west-east gradient. The mean salinity varies from about 0.2 PSU at the River Neva-area up to 7 promilles in the westernmost part. In the central part of the Gulf of Finland mean salinity is 5-6 PSU (fig. 1).

The horizontal salinity structure can be said to consist of three major frontal zones; in the easternmost part, in the central part, and in the western part near the Estonian coast. These fronts seem to be quasi-stationary; their positions do not change with the function time. So, the fronts are not very sensitive to variations in the atmospheric forcing. There are several factors which have a joint effect on the formation of these salinity fronts. Salinity water penetrates from the Baltic Proper into the Gulf along the slope of the bottom without any major thresholds. Depending on the meteorological conditions and the values of salinity in the Baltic Proper, this more saline water mass penetrates ahead to the Gulf of Finland and a frontal area forms. On the other hand, the fresh water input from rivers have an opposite effect on the salinity balance in the water mass. Depending on the strength of these two processes, a frontal zone in the west-east direction is formed somewhere in the eastern part of the central Gulf of Finland. The fronts represent a transition area between the relative saline water in the western Gulf of Finland and less saline water in the easternmost part. Formation of a frontal area in the mouth of the Neva is controlled by the largest river discharge in the Baltic Sea: River Neva ($2700 m^3 s^{-1}$). The development of these fronts is further controlled by the baroclinic horizontal circulation and by bottom topography.

The model results were compared with salinity measurements. Generally concluding, the model results fit well with the observations. In a large area of the Gulf, salinity differences between the model results and observations are only of the order of 0-0.3 PSU. It can be concluded that the model describes correctly the general horizontal salinity structure as well as frontal areas and their locations. However, there is a tendency that the model overestimates salinity by about 0.5-0.8 PSU in certain areas. These areas are found in the northern part of the central Gulf. This phenomenon has a clear explanation. Until now, the river water discharges have been modelled to come into the Gulf through the whole water depth, while the river discharges should take place only in the upper mixed layer. Because of this the upper layer salinity in the model is too large, which also becomes visible in the mean salinity.

3.2.2 Salinity in the upper and in the bottom layer

Salinity in the upper and in the bottom layer shows the same main features as the mean salinity. There are however some important differences too. The surface fronts (not shown) have also quite a permanent location, except the front in the western part of the Gulf is practically missing in the upper layer, which indicates that the saline water penetrates into the Gulf in the bottom layer. The salinity in the bottom layer (not shown) proves this assumption. A sharp tongue of saline water with values of 7-8 PSU forms a front in the westernmost part of the Gulf. The two other fronts show no major changes compared to the upper layer.

3.2.3 Current distribution

As was stated earlier, the opposite effects of saline water input from the Baltic Proper and river water discharge cause large salinity gradients (fronts) in the Gulf of Finland. Salinity gradients cause density differences, which further induce wind-independent currents -**baroclinic circulation.**

The quasi-stationarity of salinity fronts becomes visible in the current fields where quasi-stationary areas of high current speeds (baroclinic) exist even in the monthly average maps (fig.2). Simulations of long-term average currents with a wind-driven model in the Gulf of Finland show speeds only of some centimeters per second. The frontal areas of salinity and velocity are missing (Myrberg, 1992).

The Gulf of Finland can be roughly divided according to the current fields into three different regions. Firstly, the western part of the Gulf with a pronounced pycnocline, is characterized often with cyclonic-anticyclonic flow patterns. The current directions in the upper (fig. 2) and bottom (not shown) layer are often opposite. Secondly, in the central Gulf of Finland the most dominating feature is the frontal area with currents of high northward values. Maximum current speeds given by the model reach values of 50 cm/s. Such high speeds have been observed in the area (Sarkkula, 1991). Thirdly, the easternmost Gulf has a complex divergent vortex-structure in the current field connected to the enormous large salinity gradient. (4 PSU/70 km).

A number of small-scale vortices become visible in the flow fields. These vortices rapidly change their size and intensity with the functions of space and time. Such vortices do not appear if a linear model is used; they are produced by non-linear interactions. Bottom topography plays an important role in this development.

3.2.4 Temperature in the upper mixed layer

Temperature in the upper mixed layer given by the model was verified against measurements at three standard stations LL7 (59° 51 min, 24° 50 min), LL9 (59° 42 min, 24° 02 min) and LL11 (59° 34 min, 23° 18 min) from the beginning of June to the end of October. Comparison with the station LL7 (fig. 3) showed that the temperature produced by the model fits well with observations up to July-August. During this summer period the model overestimates temperatures by 2-4 $^{\circ}C$. In late October the situation is the opposite. The model temperatures are 1-2 $^{\circ}C$ too low. Comparison with station LL9 (fig. 3) gave excellent results throughout the spring and summer. Again, in the late autumn the model temperature was too low. Comparison with station LL11 (fig. 3) gave the same features as the two previous stations.

3.2.5 Vertical mean of temperature and thickness of the upper mixed layer

Both the upper mixed layer depth (not shown) and vertical mean of temperature (not shown) are strongly coupled with the bottom topography. The highest temperatures are reached at the coastal areas and lowest in the deepest areas during spring and summer. In the autumn, the temperature gradient locates in a west-east direction. So, in the spring and summer isolines of temperature are parallel to the depth isolines. In the autumn these isolines are perpendicular to each other. An interesting feature is that area of the coldest water, " the cold eye", moves slowly eastwards. The frontal structure, which was found in temperature and currents fields cannot be found in the corresponding temperature fields. This fact further deepens the conclusion that buoyancy-driven currents are mostly driven by salinity gradients.

The thermocline begins to develop in early June. During the summer there is at coastal areas a well-mixed layer through the whole water body. Thickness of the upper mixed layer increases towards the central Gulf and towards the west. Resemblance with bottom topography is obvious. Deepening of the mixed layer by wind mixing and convection begins in September and continues through the autumn.

4. Conclusions and discussion

A 2.5-dimensional baroclinic prognostic model based on a self-similarity structure of the sea has been developed. The model has been applied to the Gulf of Finland, an estuarine in the Baltic Sea characterized by large horizontal salinity gradients.

According to our results we can conclude that the circulation in the Gulf of Finland is strongly baroclinic from its origin, so the circulation cannot be described by pure wind-driven models. In the Gulf of Finland, and generally in the whole Baltic Sea, buoyancy-driven baroclinic circulation is mainly driven by salinity, an opposite case compared to the World Ocean. The main field of the study is therefore to investigate the role of salinity in the circulation.

The modeling work proceeded step by step. The first model version was the numerical solution of the non-linear salinity transport and momentum equation without the temperature and atmospheric models. The river water discharges were taken to be zero. Results of this model version showed that the combined effect of baroclinicity and bottom relief plays an important role in describing the saline water inflow from the Baltic Proper to the Gulf of Finland. This inflow is characterized by strong salinity gradients and high current speeds in a narrow frontal zone. The whole model version was used to simulate horizontal salinity fields during different seasons. In these results two other quasi-stationary salinity fronts were found. Their development is strongly controlled by the opposite effects of saline water inflow from the Baltic Proper and fresh water input from the rivers. The current fields showed a structure closely coupled with the salinity fields. In the areas of the salinity fronts high current speeds up to 50 cm/s are frequently found.

Finally we can conclude that the hydrodynamics of the Gulf of Finland have a strongly baroclinic character. In terms of salinity and currents, the Gulf seems to be very unhomogeneous and a division into three subbasins can be found. This fact is of great importance for the ecological modelling of this area, the subject of the second part of this article.

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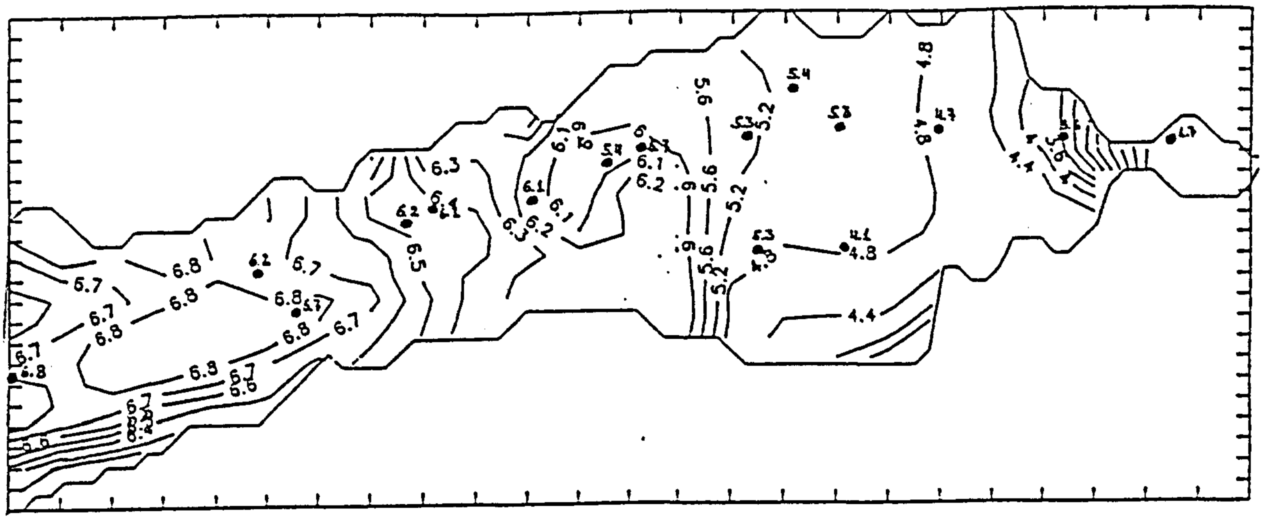
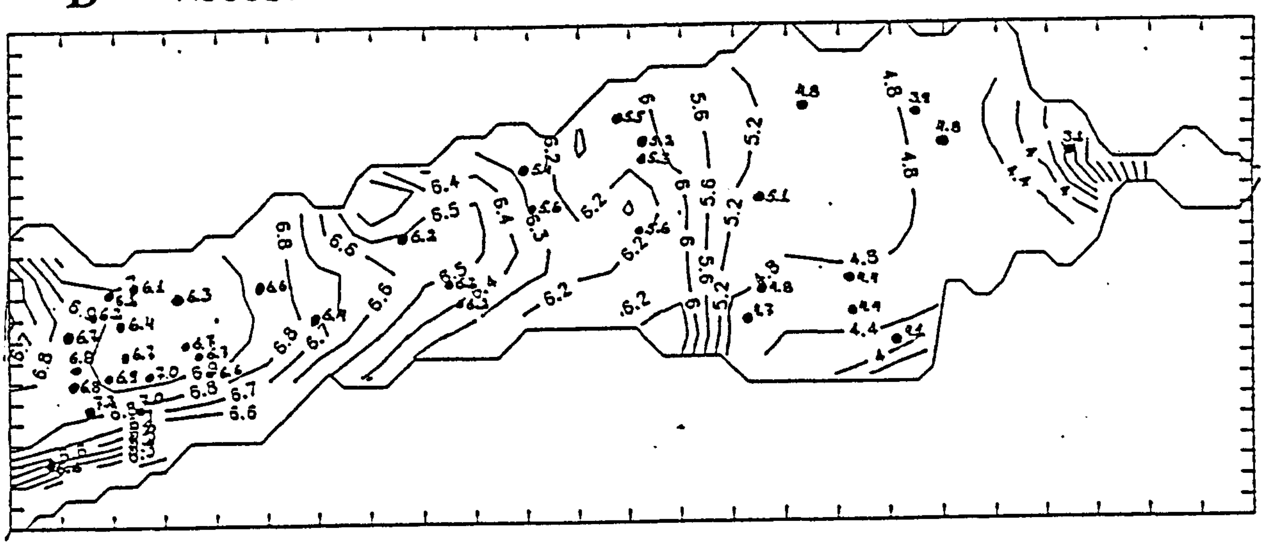
A JULY



B AUGUST



C OCTOBER

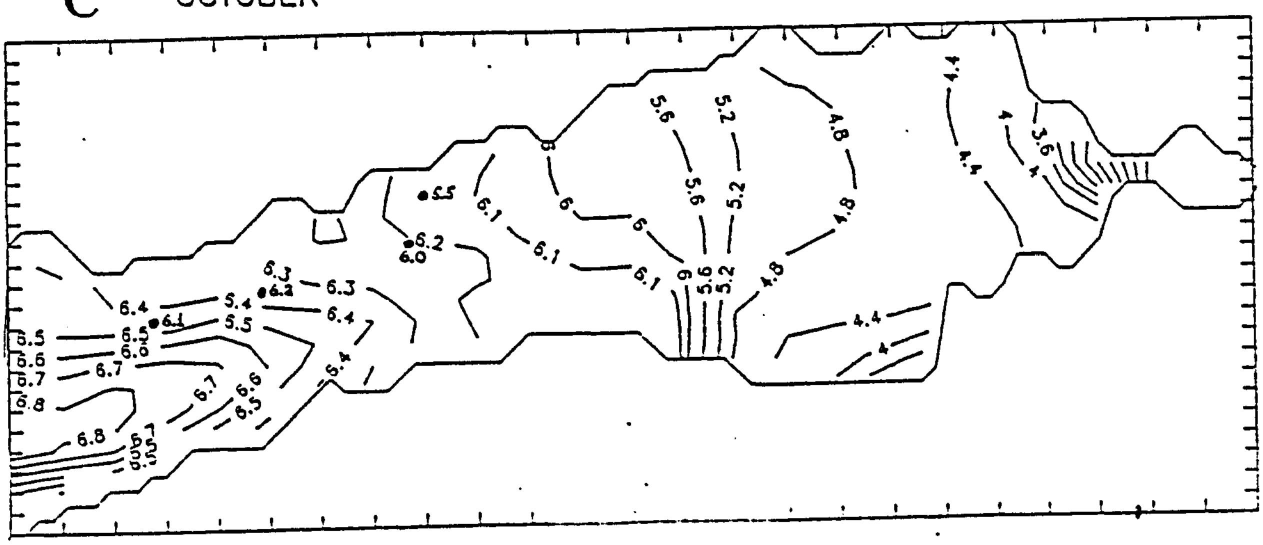


Figure 1. Horizontal fields of the vertical mean of salinity. The figures July (A), August (B), October (C) present monthly mean values. Observed values are marked with a black point with the corresponding value. Isoline analyses of the model results have been done at intervals of 0.1 PSU in the western part and at intervals of 0.4 PSU in th eastern part for practical reasons.

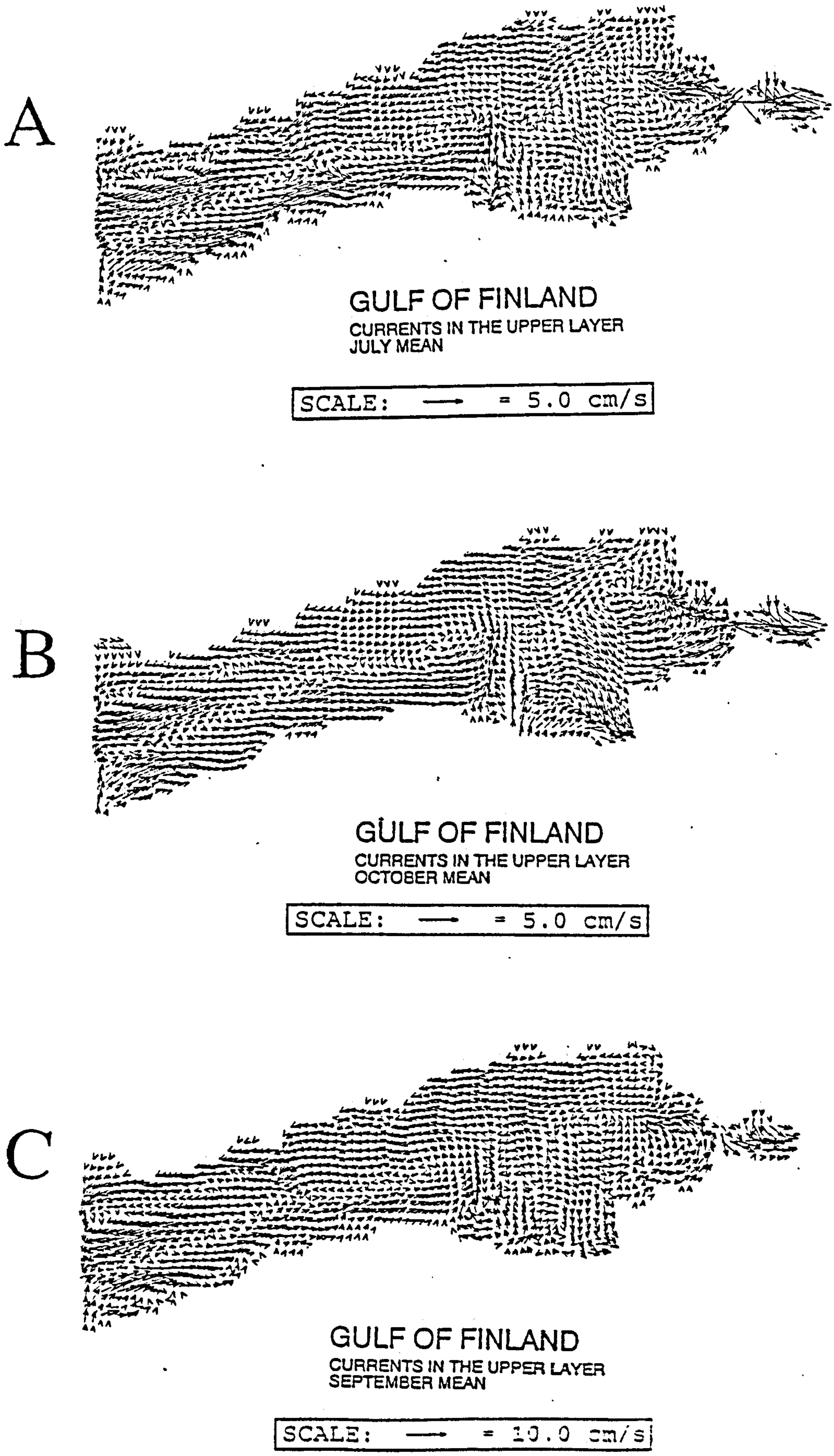


Figure 2. Horizontal current fields in the upper mixed layer during different months. The scale of vectors is given. The figures July (A), September (B), October (C) present monthly mean values.

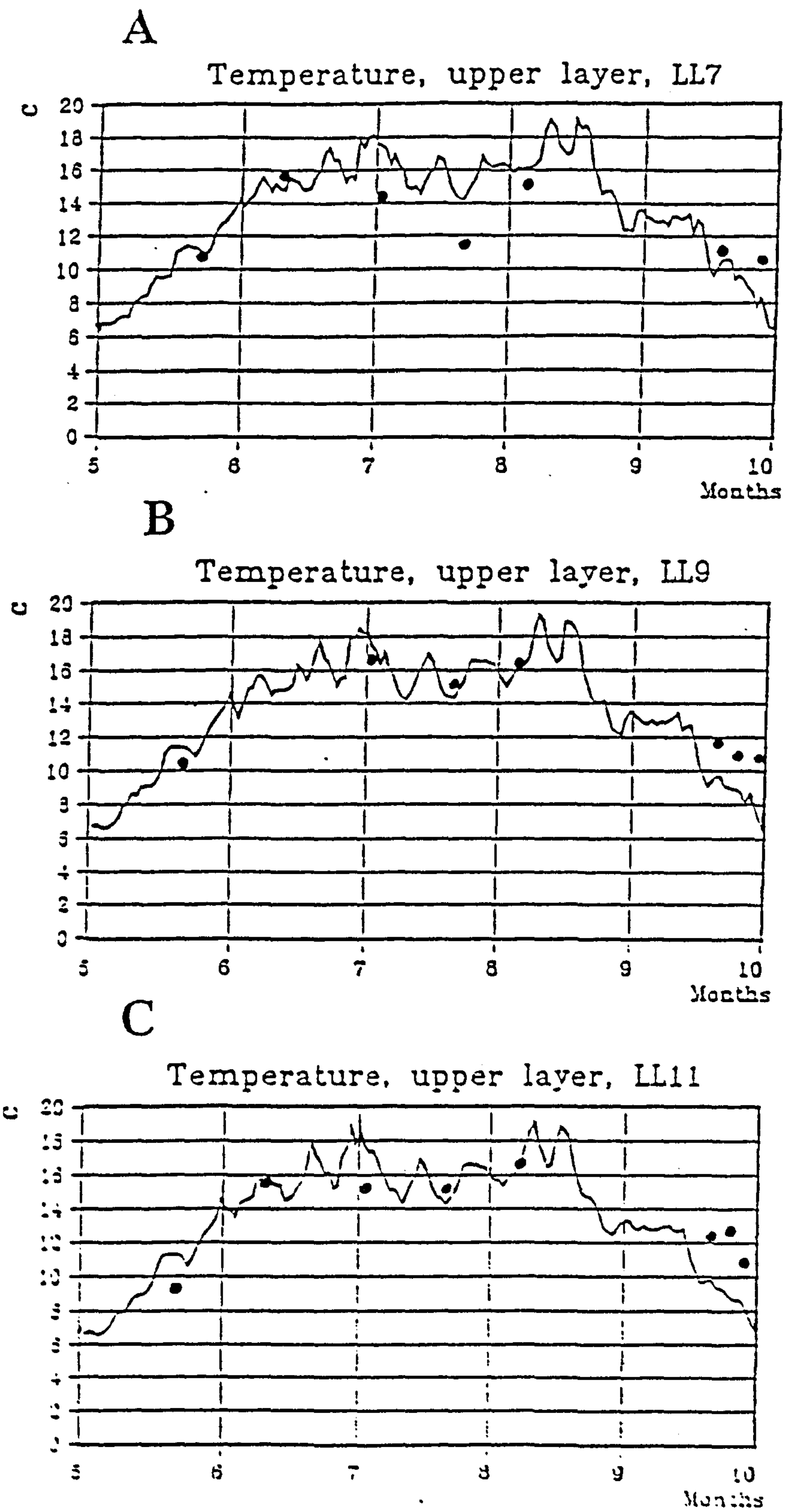


Figure 3. Temperature in the upper mixed layer at three tations LL7 (A), LL9 (B) and LL11 (C). Observed values are marked with a black point.