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Numerical modeling of a Major inflow to the Baltic Sea

by

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Abstract

Major inflows to the Baltic Sea cannot yet be predicted. The different processes or conditions which lead to a major Baltic inflow are well documentated, but the relevance of the different conditions and their relations to each other are not well understood. With a numerical model such events can be studied in principle. A three-dimensional baroclinic eddy-resolving model of the Baltic Sea is presented. It is used to investigate major inflows to the Baltic. Model results are verified by data of the major inflow in November/December 1951. It is shown, that, beside a strong wind forcing from western directions, a strong stratification in the Belt Sea is one of the very important condition for a major inflow. Different experiments with the same wind forcing but different haline stratifications show, that the occurence of such an event depends strongly on the haline stratification in the area of the Belt Sea. In advance of such an event there must be a longer period of outflow which leads to low salinities in the upper parts of the Danish Sounds and due to a compensating inflow unusual high salinities can be found near the bottom.

Introduction

During the last decades several major inflows of highly saline water to the Baltic Sea occured. These events took place mostly in late autumn or in early winter time and lasted between a few days up 29 days (MATTHÄUS & FRANCK, 1992). In this year a new major Baltic inflow was registered. After 16 years of stagnation this was again a major inflow which transported about $125 km^3$ of highly saline and oxygenated water into the Baltic Sea. These events occur sporadically, no periodicity can be ascertained when analysing historical data. Matthäus and Franck (1992) investigated the characteristics of major Baltic inflows by statistical means. The importance or relevance of major inflows to the ecosystem Baltic Sea has been reported by several authors. Because of the strong haline stratification a renewal of water masses in the deep layers, i.e. transport of oxygen rich and highly haline water masses originating from the Kattegat, is only possible by horizontal advection. The strong stratification prevents vertical convection across the halocline. The essential renewal of water masses in the deep basins is only possible by strong influxes of highly saline and oxygenated water.

Matthäus and Franck (1992) summarized preconditions which are thought of to play a substantial role in a major Baltic inflow. Among these the most important conditions are: meteorological forcing, i.e. strong winds from western directions are needed to produce a barotropic pressure gradient between the Kattegat and the Western Baltic, so that strong inflow can take place. During the pre-inflow period the sea level difference between Kattegat and the Western Baltic must be positiv. This conditon is automatically fulfilled if there was a longer outflow period. In correspondence with the outflow a strong haline stratification in the Belt Sea and southern Kattegat is built up. The outflow of brakish Baltic Sea water at the surface is compensated by an inflow of highly saline water in the deeper layers of the Belt Sea. This two layer system is separated by a strong halocline.

A three-dimensional baroclinic eddy-resolving model of the Baltic Sea is presented. It is used to investigate major Baltic inflows. Numerical experiments simulate the major inflow in November/December 1951. The aim of the study is twofold. First, oceanographic and meteorological preconditions which are thought of to be responsible for the occurrence of major Baltic inflows are investigated and second, the penetrating of inflowing water masses of high salinity after passing Drodgen and Darss Sill with their further flow into the deep basins is studied.

The Baltic Sea model

The model based on the free surface Bryan-Cox-Semtner model (KILLWORTH et al.,1989) which is a special version of the COX numerical ocean general circulation model, adapted to include a free surface. The horizontal resolution is 5 km and in the vertical direction 15 levels are specified (Fig. 1). The thickness of the different levels are chosen to account best for the different sill depths in the Baltic. The model comprises the whole Baltic Sea, including Bothnian Sea, Gulf of Finland as well as Belt Sea, Kattegat and Skagerrak and some artificial basin of the North Sea (LEHMANN, 1992 a,b). Effects of turbulent mixing are considered by using a vertical diffusion coefficient which is a function of the Richardson Number. Horizontal mixing of momentum is coupled with the field of relative vorticity. The three-dimensional initial fields of temperature and salinity are constructed of monthly mean maps of temperature and salinity of the Baltic (LENZ 1971, BOCK 1971). A detailed description of the model configuration is given by Lehmann (1992 b).

Wind forcing and data to verify model results are taken from Wyrtki (1954). In this paper the major Baltic inflow in November/December 1951 is described in detail.

Four experiments with different preconditions were accomplished. The first one serves as a reference model run. Initial three-dimensional distributions of temperature and salinity are taken from monthly mean maps of the Baltic Sea (BOCK 1971, LENZ 1971). All experiments were started form a mean distribution of temperature and salinity for November. The different experiments differ in the haline stratification of the Belt Sea before the inflow of highly saline water starts. Different haline stratifications can be achieved by changing the wind field over the Baltic Sea. A moderate east wind produces an outflow of brakish Baltic Sea water at the surface. In deeper layers a compensating flow of high salinity is directed into the Baltic. Due to this inflow-outflow system a two layer system is built up. The layers are separated by a strong halocline in middepths. By varying the wind field it is possible to achieve different stratifications in the Belt Sea. Correspondingly the mean sea level of the Baltic is changing.

Major Baltic inflow November/December 1951

In November 1951, after a longer period of south-east and east winds, the weather changed and strong winds mainly from west started to blow. Water masses up to 25 psu at Darss Sill and 30 psu at Drodgen Sill penetrate into the Baltic Sea. During this event a volume of about $220km^3$ with a mean salinity of 22 psu entered the Baltic. The salinity at Bornholm Deep increased to 21.5 psu (Fig. 2). This value is 5 psu higher than the mean value. Water masses with a salinity $> 15psu$ filled up the Bornholm Basin to a depth of 50 m. In advance of the major inflow the sea level of the Baltic reached values between 20-30 cm under the mean sea level. During the inflow the Baltic sea level rised up to 30-40 cm above the mean value. In total the Baltic sea level was lifted up 60 cm.

Fig. 3 represents the evolution in time of the vertical salinity distribution at Gedser Rev. The pre-inflow period was characterized by an outflow regime with strong haline stratification in the Belt Sea and a correspondingly low sea level of the Baltic. At the surface the brakish Baltic sea water with a salinity $< 10psu$ can be found. In the deeper layers the salinity increases to 24 psu. The two-layer system is separated by a very sharp halocline. The major inflow started at 22-Nov-1951 and lasted until 16-Dec-1951. During this event due to vertical turbulent mixing the halocline was completely destroyed. Between 7-Dec-1951 and 11-Dec-1951 the culminating point of the evolution was reached. Water masses with a salinity of more than 25 psu passed Gedser Rev. After 16-Dec-1951 the inflow was exhausted and due to the return flow out of the Baltic, a new haline stratification was built up.

Numerical simulation of a major Baltic inflow

Four numerical experiments (Table 1) were accomplished to study a major Baltic inflow in principle. The experiments differ in the configuration of the pre-inflow period. All experiments were started form an initial state, when three-dimensional temperature and salinity fields had been adapted to model dynamics. In experiment 1 there was no pre-inflow period. The other experiments differ in the duration of

Table 1

Experiment	1	2	3	4
Pre-inflow period [days]	0	17	23	17
Wind direction		S-E (12 m/s)	S-E (12m/s)	E (5 m/s)
Sea level [cm] 24-Nov-1951	23.5	21.6	21.6	18.8
Sea level [cm] 09-Dec-1951	75.9	79.2	79.5	98.8
Inflow [km^3]	179	197	198	273
Major inflow		X	X	X

the pre-inflow period and in the specified wind field. For all experiments the wind forcing during the major inflow was the same. In experiment 1, which served as a reference model run, no major inflow took place. In correspondence with the duration of the pre-inflow period the sea level of the Baltic changes. Although the differences are small, they have a significant effect on the volume transport into the Baltic. The smaller the value of the sea level after the pre-inflow period, the higher are the volume transports into the Baltic.

Because all experiments were forced with the same wind field, it seems, that, beside of the sea level, the initial haline stratification in the Belt Sea plays a substantial role in a major inflow. Fig 4. summarizes for the different experiments the evolution in time of the vertical haline stratification at Gedser Rev. In general, the structure of the haline stratification (Fig 4, a-d) is similar to the observed timeseries (compare Fig. 3). The differences are more or less pronounced in the numerical values. This is remarkable, because this means, that vertical mixing as well as advective processes are simulated in a realistic manner. The very crude representation of the wind field (homogenous in space) as well as uncertainties in the determination of the correct wind stress (LEHMANN 1992b) may explain the deviations from the observations. If we are able to produce a stratification in the pre-inflow period, which is very similar to the observed structure, then the further evolution of the haline stratification should be close to the observed stratification.

Fig. 5 displays for 10-Dec-1951 in a section through the Baltic Sea the vertical distribution of salinity (Experiment 3). In the period between 7-Dec-1951 to 11-Dec-1951 the culminating point of the major Baltic inflow was reached. The Belt Sea front was shifted behind the Darss Sill. Highly haline water was penetrating into the Arkona Basin. Water masses > 15 psu filled up the Arkona Basin to a depth of 20 m. At the end of the inflow the Belt Sea front moved back into the Belt Sea and the highly haline water masses began to penetrate into the Bornholm Basin. To prove, that the haline stratification at the beginning of a major inflow must be regarded as one of the important preconditions, Fig. 6 represents for 10-Dec-1951 the difference of the vertical haline stratification of Experiment 1 and 3. At the bottom of the Arkona Basin differences up to 4 psu can be found.

In all experiments a high amount of water is penetrating into the Baltic Sea (Table 1), but the content of salt of the inflowing water masses is different. The amount of salt of the inflowing water determines whether an inflow is termed major inflow or not.

The evolution in time of the major Baltic inflow can be studied in detail by examining horizontal and vertical maps of the salinity distribution of the Belt Sea. Model results of experiment 4 are compared with the salinity distributions given in Wyrtki (1954). Experiment 4 is different from the other experiments, because the wind stress is computed with a higher drag coefficient. Lehmann (1992b) showed, that discrepancies in surface elevation between model and tide gauge measurements can be reduced by varying the drag coefficient in the formula for the wind stress computation. As can be seen from Table 1, the increased wind stress is responsible for the very high amount of inflowing water masses. Although it seems, that the volume of inflow is somewhat higher than the value given by Wyrtki (1954), the amount of salt which was transported into the Baltic is less. At Bornholm Deep only a salinity of 18 psu is reached. The 15 psu isohaline can be found in a depth of 70 m. In spite of this, the overall distribution of salinity of the Belt Sea is quite well simulated (compare Fig. 7 and 8). Fig. 9 gives additional information of the corresponding horizontal current field.

The evolution in time of the vertical salinity distribution can be observed in a section through the Belt Sea (Fig. 10 & 11). During pre-inflow and inflow period the simulated distributions are very close to the observations. Between 7-Dec-1951 and 11-Dec-1951 the culminating point of the major Baltic inflow was reached. Unfortunately, as can be seen from the salinity distribution for 11-Dec-1951 (Fig. 11), the return flow in the model starts too early. So, in comparison with the observations the inflow of water masses with salinity up to 25 psu is lacking. The discrepancies of the salinity distribution at Bornholm Deep is due to this incorrect behavior of the model.

Conclusions

A three-dimensional baroclinic eddy-resolving model is used to study major Baltic inflows in principle. Model results show, that, beside of a low sea level in the Baltic, the haline stratification during the pre-inflow period is one of the important preconditions of a major Baltic inflow to occur. Furthermore the results suggest that inflows, which transport great amounts of water into the Baltic, may not be rare phenomena. During winter time heavy storms, which may lead to strong inflows, can often be observed. It should be investigated whether a strong storm may lead to a major Baltic inflow, if a suitable stratification can be constructed. With a numerical simulation this hypotheses can be proved.

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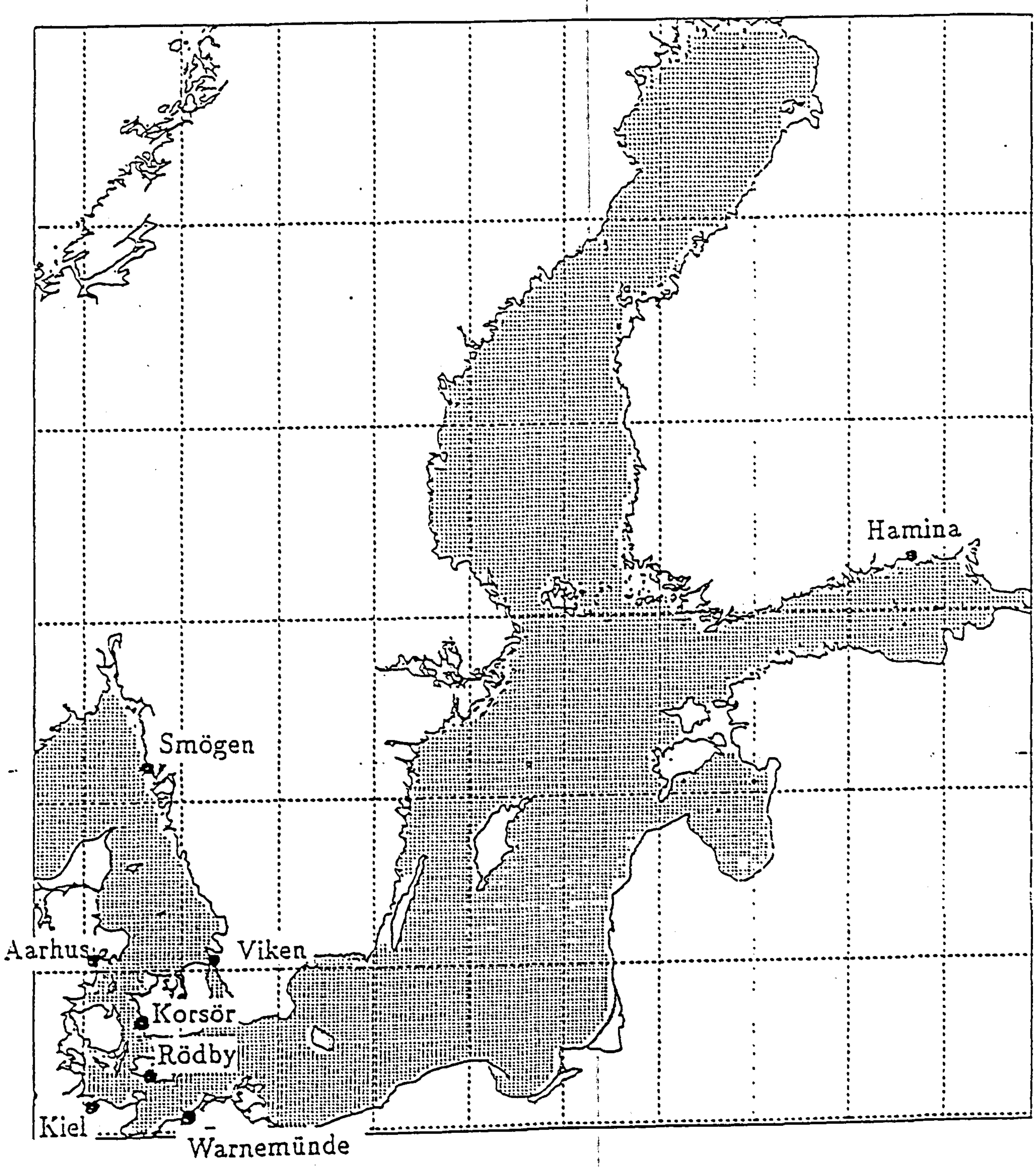

Fig. 1 Model grid, resolution 5x5 km.

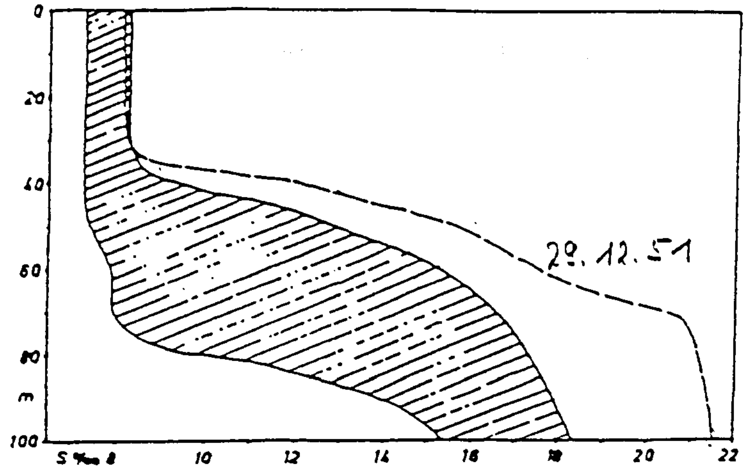

Fig. 2 Vertical distribution of salinity at Bornholm Deep,
broken line: 29-Dec-1951; shaded area:
variability of salinity profiles from 1949 until 1951.
from Wyrtki 1954

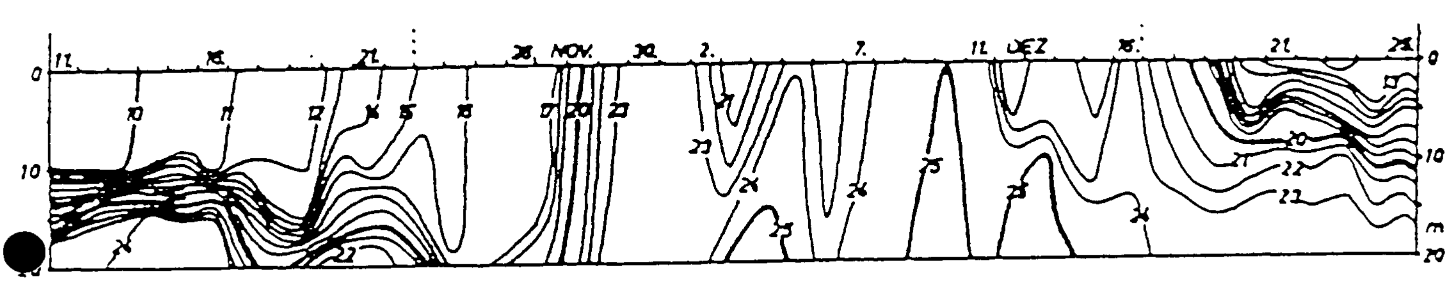

Fig. 3 Timeseries of the vertical distribution of salinity at Gedser Rev.
from Wyrtki 1954

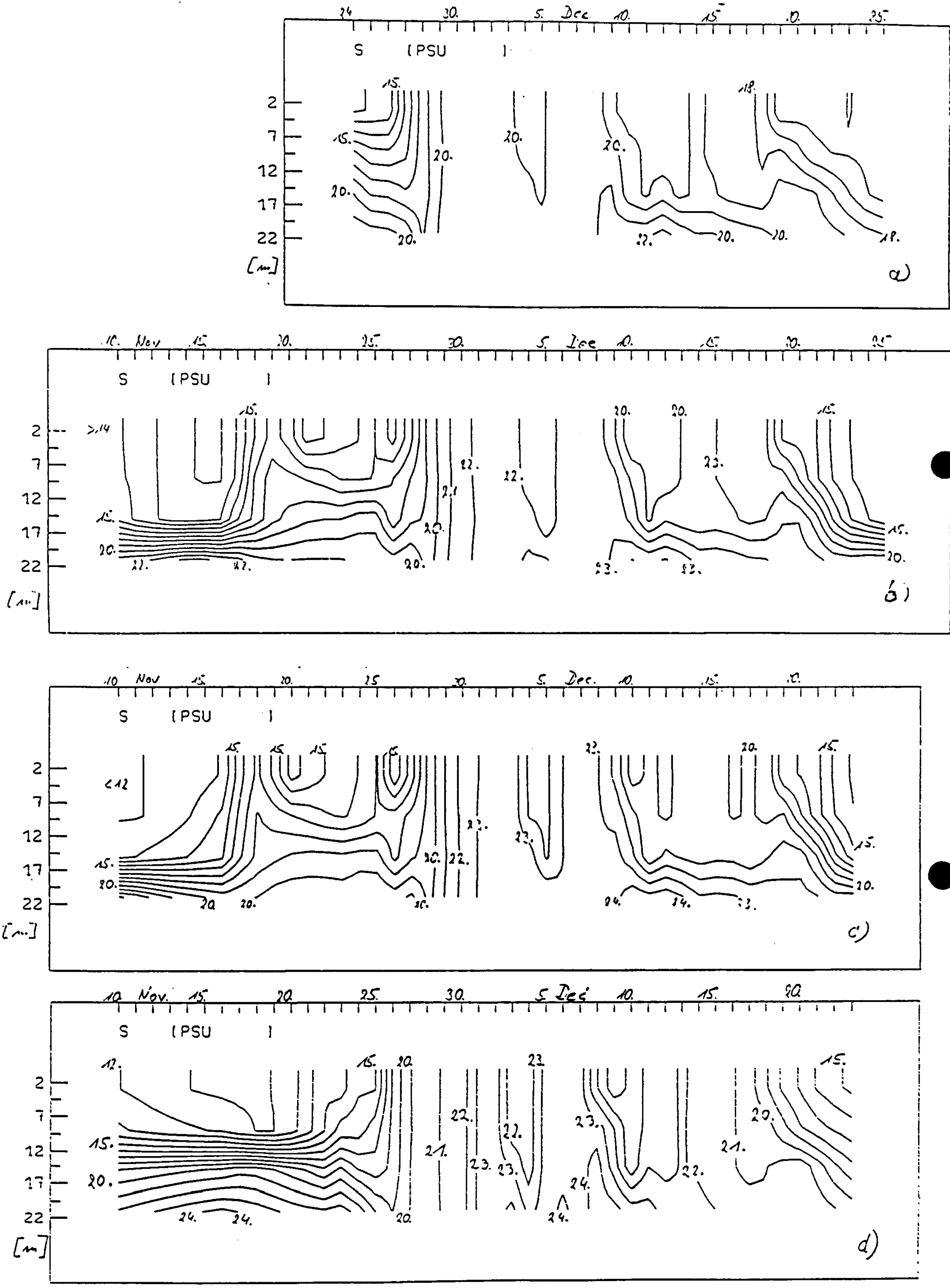

Fig. 4 Simulated timeseries of the vertical distribution of salinity at Gedser Rev for different pre-inflow periods, a-b correspond to Exp. 1- Exp.4.

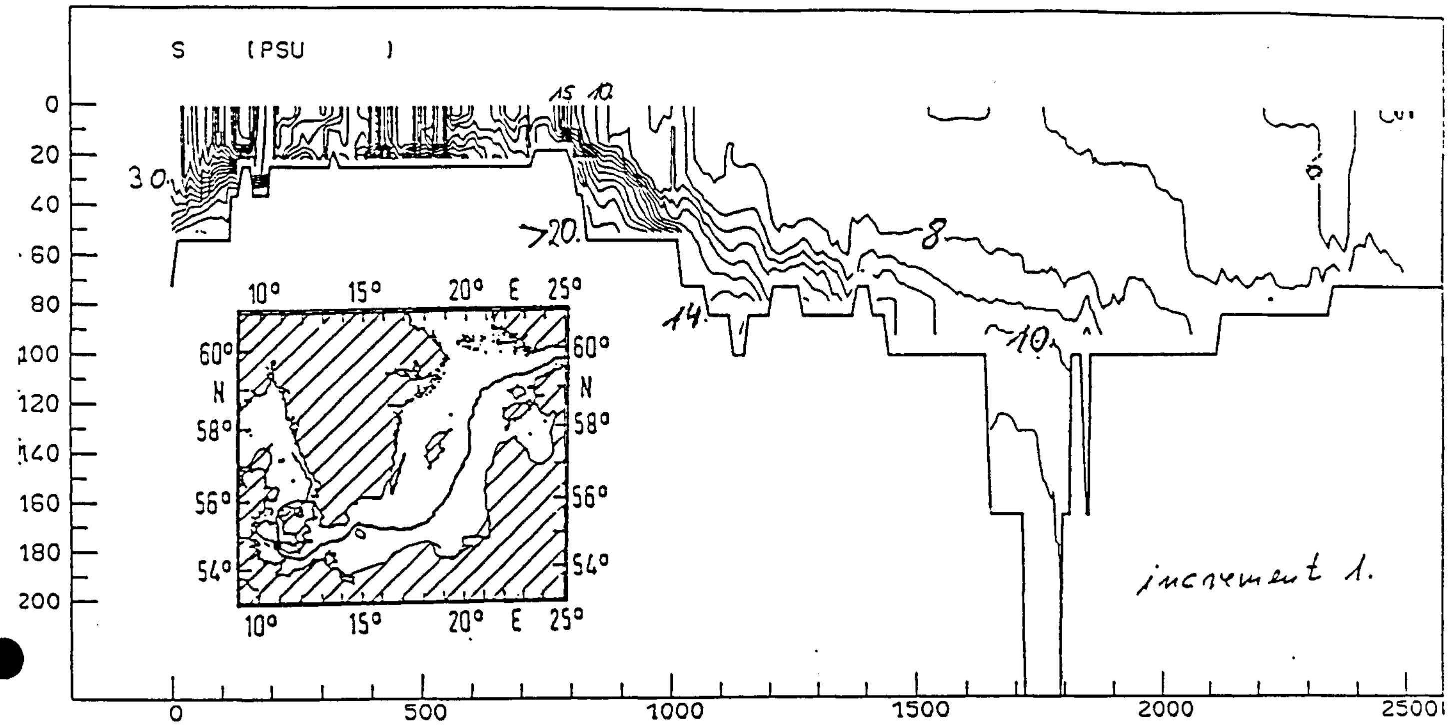

Fig. 5 Longitudinal transect of salinity, Baltic Sea model 10-Dec-1951, Exp. 3.

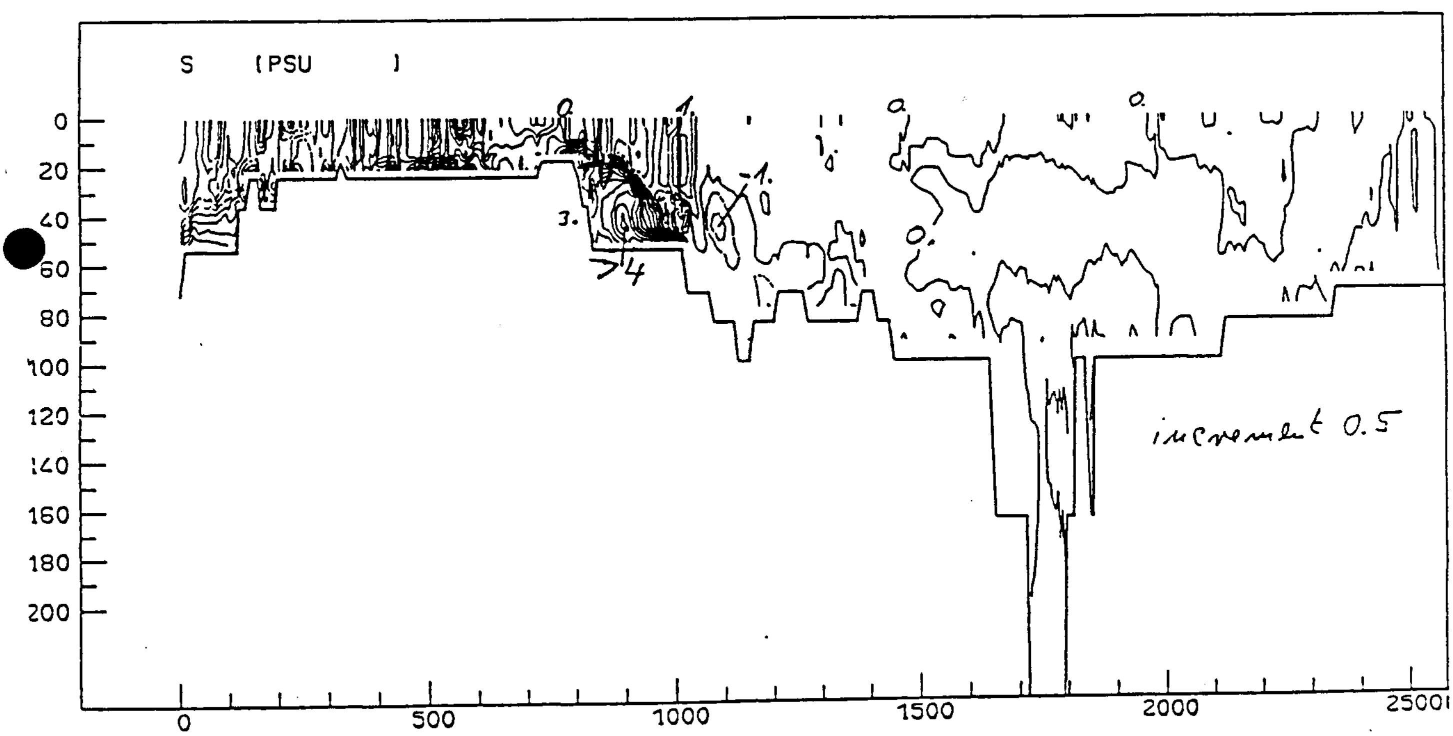

Fig. 6 Difference of longitudinal transects of salinity, Baltic Sea model 10-Dec-1951, Exp. 3 - Exp. 1.

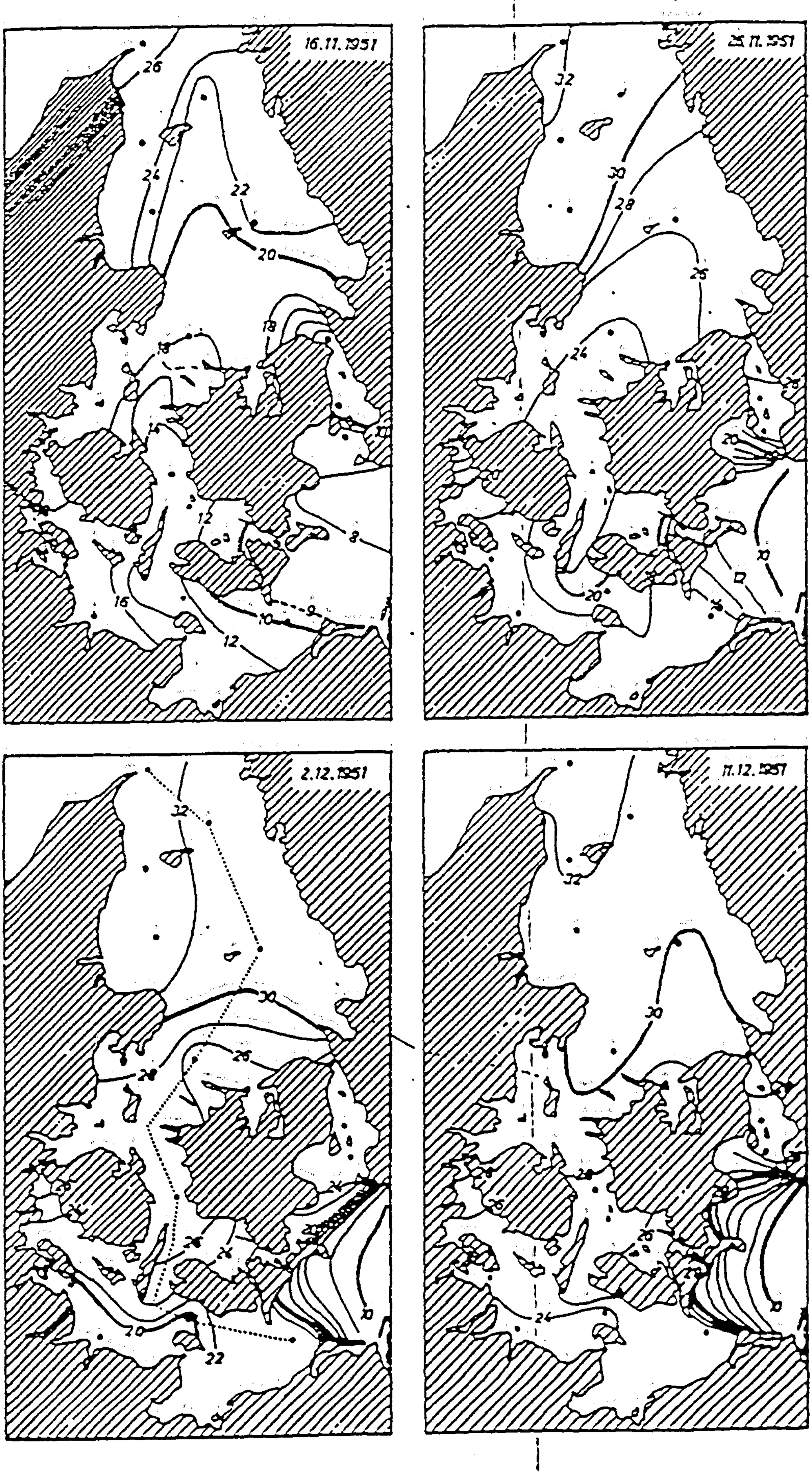

Fig. 7 Evolution in time of the horizontal salinity distribution.
from Wyrtki 1954

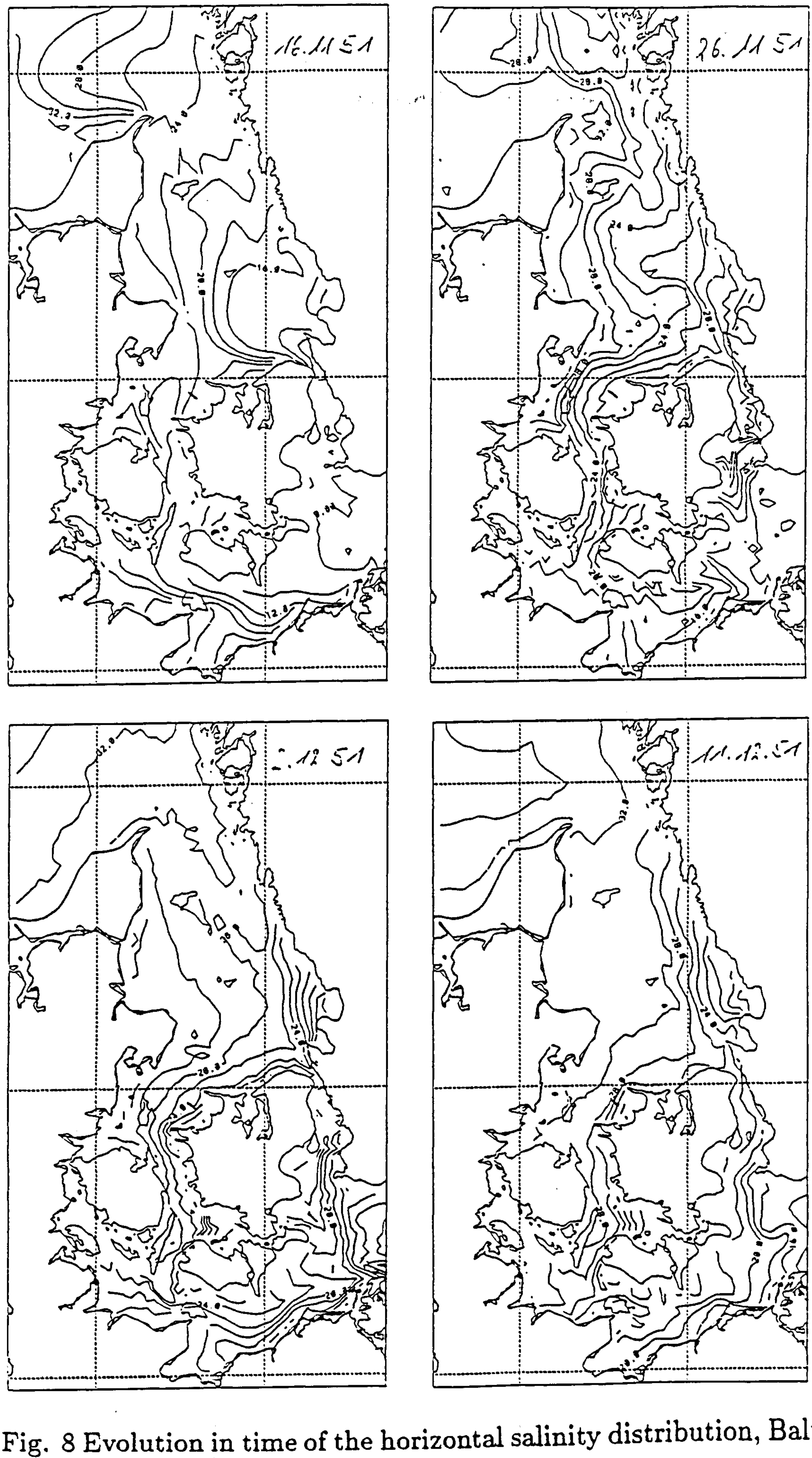

Fig. 8 Evolution in time of the horizontal salinity distribution, Baltic Sea model, Exp 4.

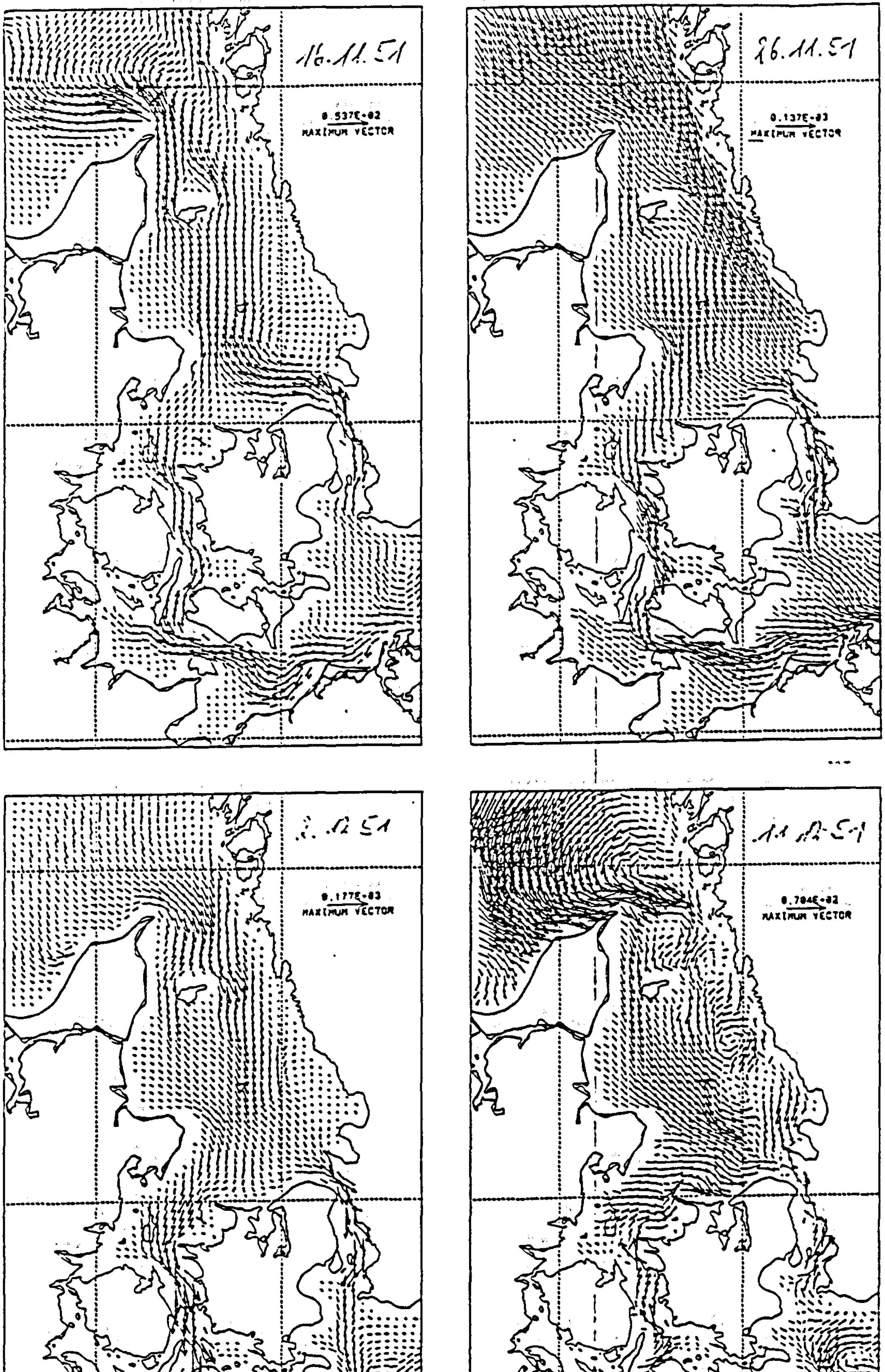

Fig. 9 Evolution in time of the horizontal current field, Baltic Sea model, Exp. 4.

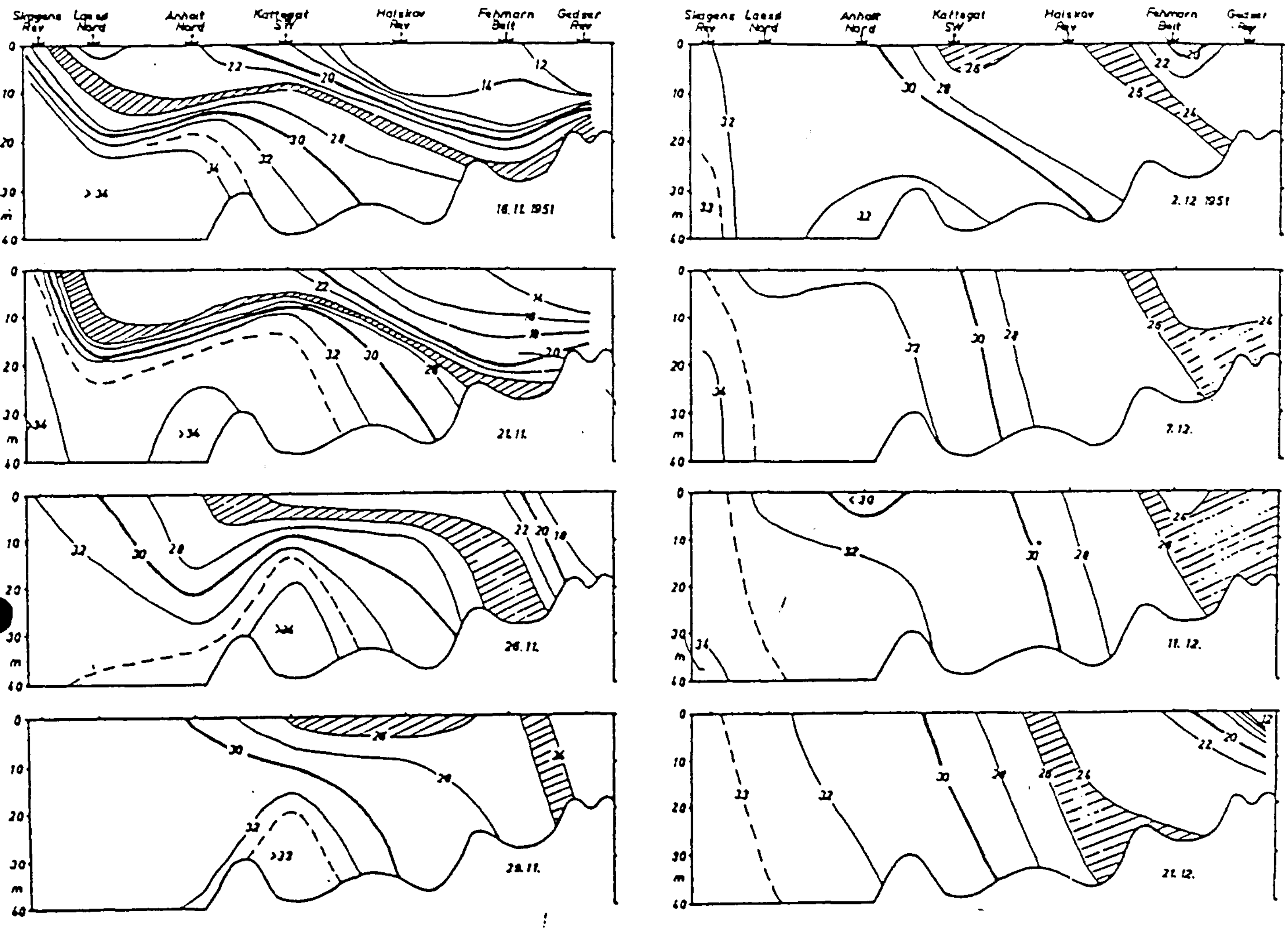

Fig. 10 Evolution in time of the vertical salinity distribution in a section through the Belt Sea.

from Wyrtki 1954

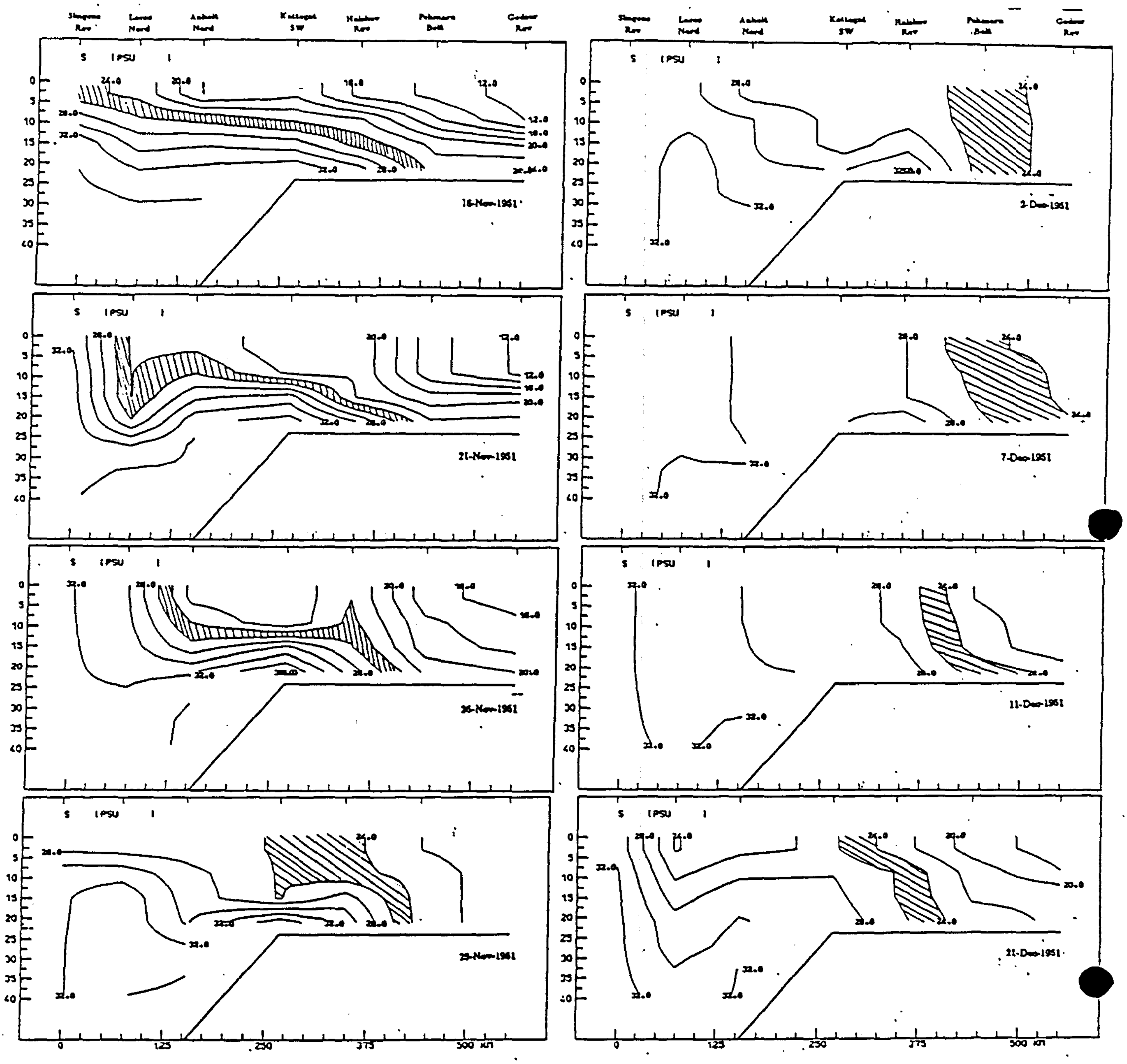

Fig. 11 Evolution in time of the vertical salinity distribution in a section through the Belt Sea, Baltic Sea model, Exp. 4.