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Bundesforschungsanstalt Bibliothek für Fischerei, Hamburg

CM 1993/C48
Session V

NUMERICAL SIMULATION OF THE RECENT (1993) MAJOR BALTIC INFLOW

E.Kleine

Bundesamt für Seeschiffahrt und Hydrographie
Postfach 30 12 20
D-20305 Hamburg

1. Introduction

The Baltic Sea is a relatively shallow brackish water sea that is connected to the global ocean system by a narrow and shallow passage. Bathymetrically, it is extensively structured and consists of a series of basins aligned one behind the other seperated by sills. The oceanographic conditions in the Baltic Sea are controlled by this arrangement. The water body in each basin has its own characteristic thermohaline structure and is divided into surface and deep water by the permanent haline discontinuity layer. Additionally, seasonal thermal stratification occurs in the surface water which in the autumn and winter is well mixed as far down as the halocline. On the other hand, the deep water is largely excluded from the vertical exchange and tends to stagnate. Even the strongest winds are unable to cause mixing of the deep water.

The exchange of water between the North Sea and the Baltic represents the only effective way in which the deep water can be renewed. The narrow and shallow passages between the Kattegat and the Arkona Basin, i.e. the Little Belt, Great Belt and the Sound, form the link with the North Sea and thus with the ocean. Although the exchange of water between the North Sea and the Baltic is a continuous process, the movement of the water back and forth in the passages generally means that only the water in the Belt Sea is renewed which lies beyond the Baltic proper whose boundaries are regarded as being the Darss Sill (0.8 km^2 cross section; 18 m sill depth) and Drogden Sill (0.1 km^2 cross section; 7 m sill depth) (cf. Fig. 1).

An exchange of deep water in the Baltic proper only occurs when the amount of inflowing water is large, highly saline and heavy enough to displace the old bottom water. To transport such highly saline water (from the Kattegat) across the sills into the Baltic Sea, the water must be moved over a far greater distance than occurs during the normal oscillation of the Skagerrak and Belt Sea fronts (Wattenberg [1941]). Such extraordinary inflows - known as major Baltic inflows - occur only when forced by special meteorological events. This explains why major Baltic inflows only occur in the autumn and winter when stormy weather causes strong movements in the water.

Major inflows are only triggered by a combination of factors (Wyrtki [1954]; Dickson [1973]; Börngen et al. [1990]; Lass, Schwabe [1990]). Intensive research into the various prerequisites and their interaction is now being carried out (Matthäus, Franck [1992]), especially as the frequency and intensity of major inflows has fallen considerably since 1976 and between the start of 1983 and the end of 1992 no major inflow occurred at all (Franck, Matthäus [1992]). Not until January 1993, after 16 years of stagnation in the deep water of the east Gotland Basin, did a major Baltic inflow again occur.

2. The recent major Baltic inflow

Between the end of 1992 and the 5th of January 1993 easterly winds caused an outflow from the Baltic Sea. During this phase, Baltic Sea surface water was transported far into the Belt Sea towards the Kattegat.

There followed a period, lasting until the 26th of January, of strong, westerly winds across the North Sea and Baltic Sea that culminated in three hurricanes across the transition area. With the onset of the west wind on the 6th of January, the flow reversed direction from outflow to inflow.

This inflow continued, with short interruptions, until the 28th of January when a period of outflow started that lasted until the 19th of February except for a short inflow around the 5th of February.

3. Modelling

The Bundesamt für Seeschiffahrt und Hydrographie in Hamburg (BSH, Federal Maritime and Hydrographic Agency) operates a numerical model of the North Sea and Baltic Sea. It is an operational model that continuously forecasts water levels and currents (Müller-Navarra & Mittelstaedt [1988], Dick & Soetje [1990]). Each short-term forecast applies to the following 24 hours. The time series of these forecasts is continuously prolonged without subsequent correction or assimilation, and thus simulates medium and long-term behaviour. The (prognostic) model simulates the evolution of the water level, current, salinity and temperature (Kleine [1994]).

Boundary layer currents in shallow surface waters influenced by bottom topography, wind, atmospheric pressure, heat flux, inflow and run-off, Earth gravitation (oscillations) and Earth rotation (Coriolis effect) are modelled. With hydrostatic pressure approximation, the fundamental system of differential equations of geohydrodynamics is obtained, consisting of mass and momentum balance equations (for horizontal currents). It is supplemented by budget equations for heat and salt from which density is calculated.

The model is forced by data from the numerical weather prognoses by the Deutscher Wetterdienst (DWD, German Weather Service). The results provided by the model are not manipulated in any way and, since the present (baroclinic) version was initialised, the model has operated without interruption or re-initialisation. The results are continuously checked mainly using on-line water level data and satellite pictures of the surface temperatures. The model is gradually being improved using the experiences gained in the process.

The atmosphere dynamics as simulated by the DWD for January 1993 also triggered a major Baltic inflow in the numerical model of the BSH. The model results are first (section 4.) compared with measurements and then they are used to interpret the course of the major Baltic inflow (section 5.).

4. Comparison between observations and model results

The model results were generated solely by the atmospheric forcing of the DWD's model. Thus, a comparison between observations and model data of the atmosphere dynamics is indicated. Consider, for example, the reference point at Arkona (Fig. 1). In Fig. 2, the wind speeds calculated by the DWD model were compared with wind speeds measured there. The figure clearly shows that the wind velocity's easterly component - essentially responsible for the transport of water through the entrance to the Baltic Sea - is on average larger in nature than in the model. An extreme deviation occurs in the night of the 14th to the 15th January when the wind calculated by the meteorological model decreases, while very high wind speeds up to 40 m/s occurred in reality. The reason for this was that the forecasting model did not take account of a small, strong depression.

As to the assessment of the output of the model, consider the gauge at Saßnitz (Fig. 1). A comparison of water level data is given in Fig. 3. About 80 % of computed water levels lie within an interval of ± 20 cm around the measured water level. The extreme deviations (14 and from 22 to 26 January) are due to differences in forcing (see Fig. 2) in the model and in reality.

For another comparison, the evolution of the distribution of salinity is considered. During the inflow, by the Institute für Ostseeforschung Warnemünde (IOW, Baltic Sea Research Institute), transects across the Darss Sill into the Arkona Basin (Fig. 1) were recorded using shipborne CTD probes. Out of them, two transects together with the corresponding model results are displayed in Fig. 4. The displacement of the water masses from Fehmarn Belt to Arkona Basin between the start and the end of the main phase of the inflow is adequately described by the model. The nearly homogeneously mixed water body between Fehmarn Belt and Darss Sill is shifted eastwards, with the heavy, highly saline water sinking into the Arkona Basin and filling it (Matthäus [1993]).

However, there are deviations. In the Arkona Basin, (Fig. 4) the salinity in the bottom layer in the model is too low. That is because the climatological stratification with which the model was initialised in September 1992 vanished following due to inappropriate model design.

5. Interpretation of the model results concerning the major Baltic inflow

The major Baltic inflow is an extreme event and so it is worth discussing the behaviour of the model and its results. In the model, the major Baltic inflow can be identified not only by its momentary behaviour, but also by its exceptional character in the long-term recording, a segment of which is shown in Fig. 5.

The model output reveals the following:

- The process of emptying and filling of the Baltic Sea is demonstrated clearly in Fig. 5a, which shows that the water level at Landsort is a good guide to the amount of water in the Baltic Sea. The figure presents the volume of the Baltic Sea defined by the dividing line at 55° 35'N (see Fig. 1) and the water level at Landsort. The scale of the vertical axis is chosen in such a way that an increase in water level of Δh corresponds to an increase in volume of $\Delta V = h * 380.620\ km^2$ (in the model the area of the Baltic Sea is 380.620 km^2).

- The amount of water passing through the above transects at 55° 35' N is about 312 km^3 as Fig. 5b shows. This value agrees well with the conventionally estimated influx volume (Matthäus [1993]). Fig. 5b compares the integrated net volume flux (transported volume) passing through the above transects with the volume content of the entire Baltic Sea. In this figure, the curve for "transported volume" is shifted so that the integration starts at the beginning of the inflow process on the 6th of January. The increasing difference between both curves is due to the river run-off in the model.

- The difference in water levels (Fig. 5c) between the 'Southern Kattegat' and 'Western Baltic' check points is responsible for the inflow and outflow through the Baltic Sea entrances.

- Inflow and outflow alternate over a period of several days. There are, however, several events with very strong inflow lasting a week and more (Fig. 5d).

- In general, both Baltic Sea entrances - the Darss and Drogden Sills - reveal simultaneous inflow or outflow (Fig. 5d). This is especially true of periods with a pronounced flow of water in the one or other direction. However, the ratio of the volume fluxes at Darss Sill and the Sound varies greatly. Fig. 5d shows the calculated volume fluxes across Darss Sill and the Drogden Sill (position of transects as in Fig. 1) and the ratio of these volume fluxes (volume flux across Darss Sill divided by the volume flux across Drogden Sill). Positive flux indicates inflow, negative flux indicates outflow. A simple statistical analysis of the ratio yields the following results:

- for 80% of the time during the period from 1st of December 1992 to 28th of February 1993, the direction of the net volume flux was the same (positive values, either into or out of the Baltic Sea).
- during situations with positive values, the mean value (median) of the ratio was 2.5.

- A major Baltic inflow (as defined by a threshold of salinity at Darss Sill) occurs during the only period with very strong inflow lasting more than 3 weeks from 6th to 28th of January 1993.

- Over these 3 weeks, the inflow occurs intermittently and consists of about 10 single events. Each inflow is forced by a passing depression. The time between two maximum inflow events is about 2 days. This is the time it takes in the winter for weather events to form.

- When the meteorological forcing decreases, the Baltic Sea begins to sweep back westwards. Before outflow occurs, however, the next "push" follows. This occurs with a frequency of about 2 days. Intermittent forcing gradually drives the water from the Belt Sea and Kattegat into the Baltic Sea. It must be pushed far enough to sink into the depths of the Arkona basin. Only when several "pushes" succeed one another does the necessary total mass and total displacement occur that is required for a major in flow.

- That every weather event is accompanied by a significant inflow is only possible because easterly winds had previously caused outflow from the Baltic Sea which as a result was relatively empty. Obviously, inflowing water masses would have met greater resistance if the Baltic Sea had been full.

6. Conclusions

The major Baltic inflow in Januar 1993 was also triggered in the operational numerical model of the BSH. The model results correspond in main points with what is already known from measurements and what has been elaborated from numerous investigations of inflows. The integral properties of the inflow and outflow process are well described. The model - in its operational version - can therefore be used to monitor the water exchange between North Sea and Baltic Sea and to predict the trend of the Baltic water level as an indicator for an imminent major inflow.

In particular, the operational model demonstrates the main features of the major inflow event in January. The barotropic exchange of water at Darss Sill and the propagation of highly saline water in the surface layer are also reproduced well.

The operational model simulated the recent major inflow well because the whole North Sea and Baltic Sea area was treated as one unit forced by atmospheric circulation. The model's worth lies in the fact that results are produced immediately. It thus proved a useful tool for investigating the basic causes, particularly atmospheric forcing, of inflows of highly saline water.

The model - originally designed to simulate the surface current and the water level - still insufficiently describes details of the evolution of temperature and salinity. There are shortcomings in the bottom layer salinity and stratification. The weaknesses of the present model are the poor vertical resolution and the uncertainties in the modelling of the horizontal and vertical transfer of impulse, temperature and salt.

Acknowledgement

The author is grateful to Dr Wolfgang Matthäus (Warnemünde) for a series of fruitful discussions on the subject and providing observational data concerning the recent major inflow. Acknowledgement is given to the German Weather Service for making available the numerical weather prognoses and wind data for Arkona.

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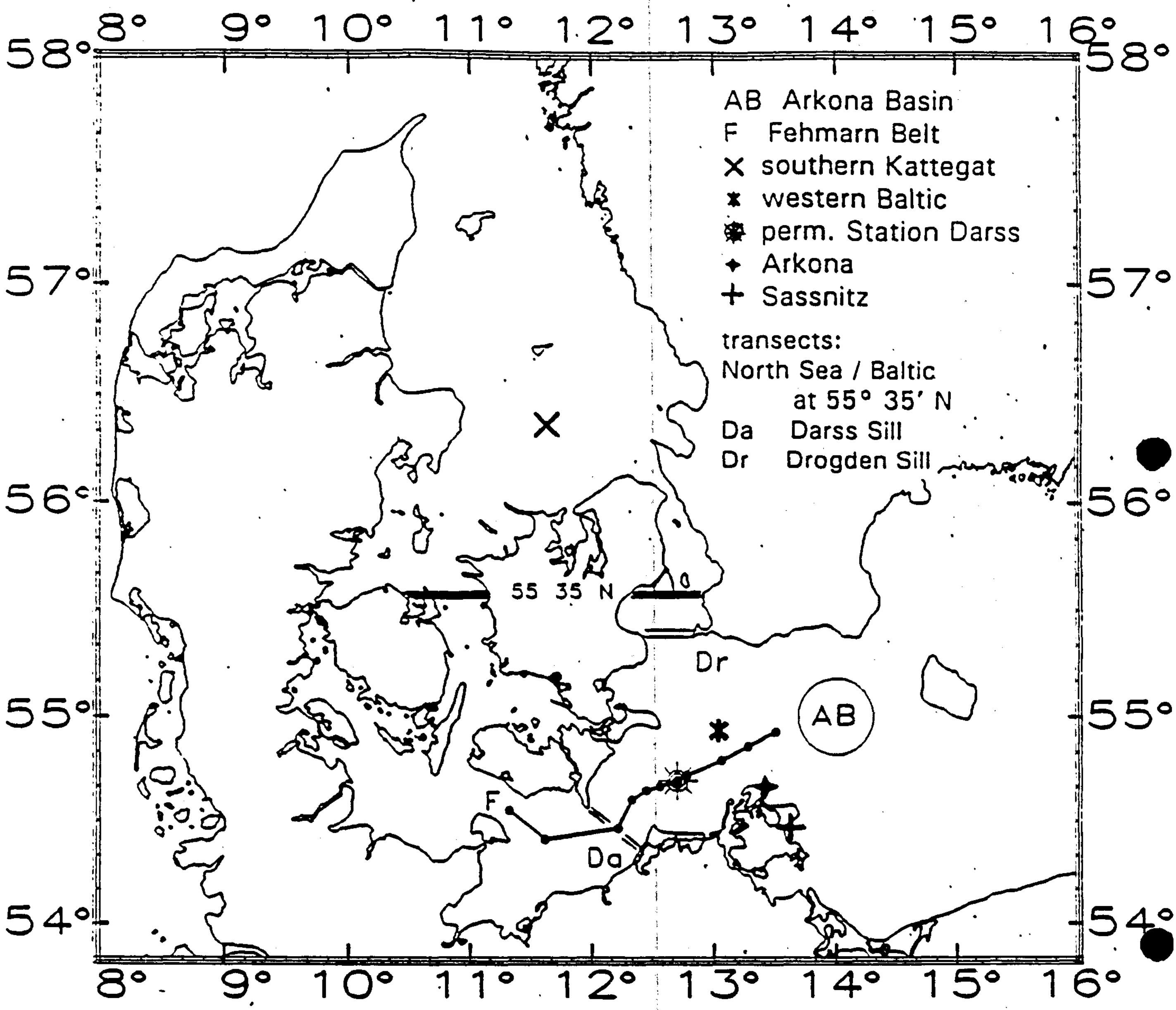
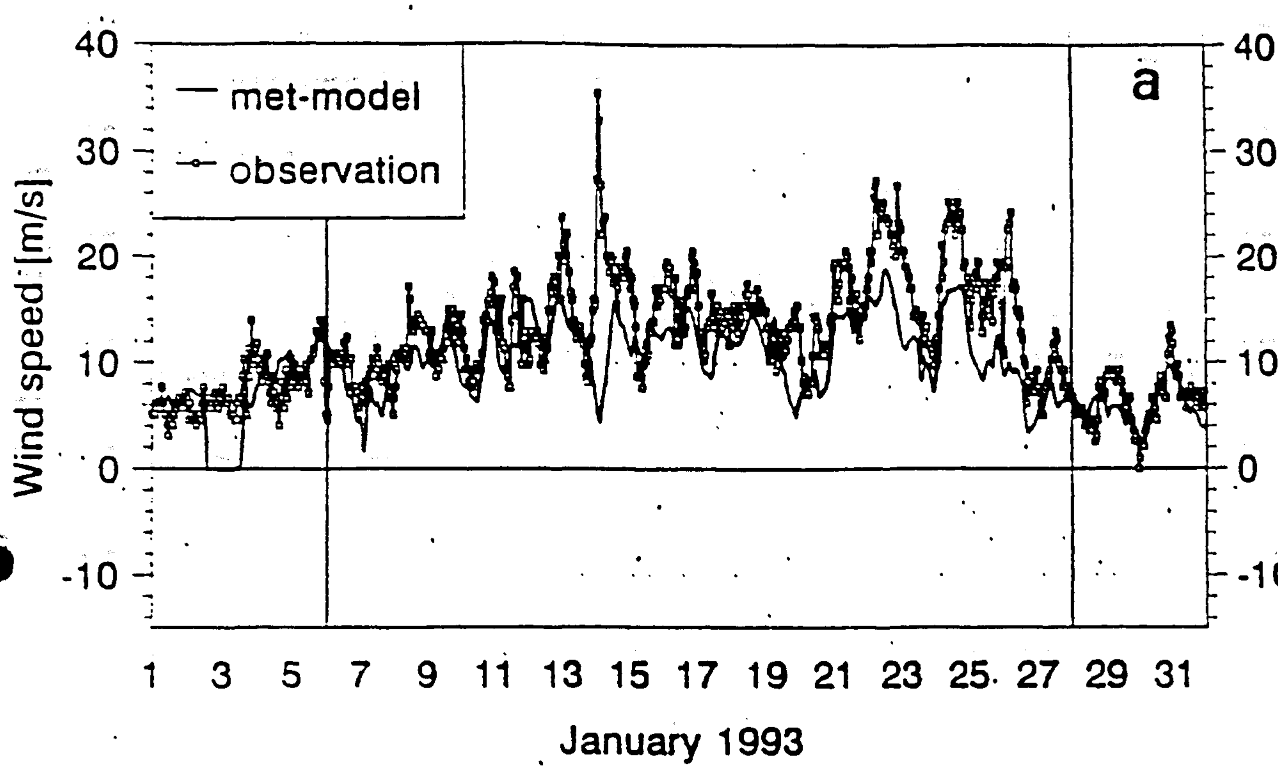


Fig. 1
Map of the transition area between the North Sea and Baltic Sea including the stations and transects mentioned in this paper.



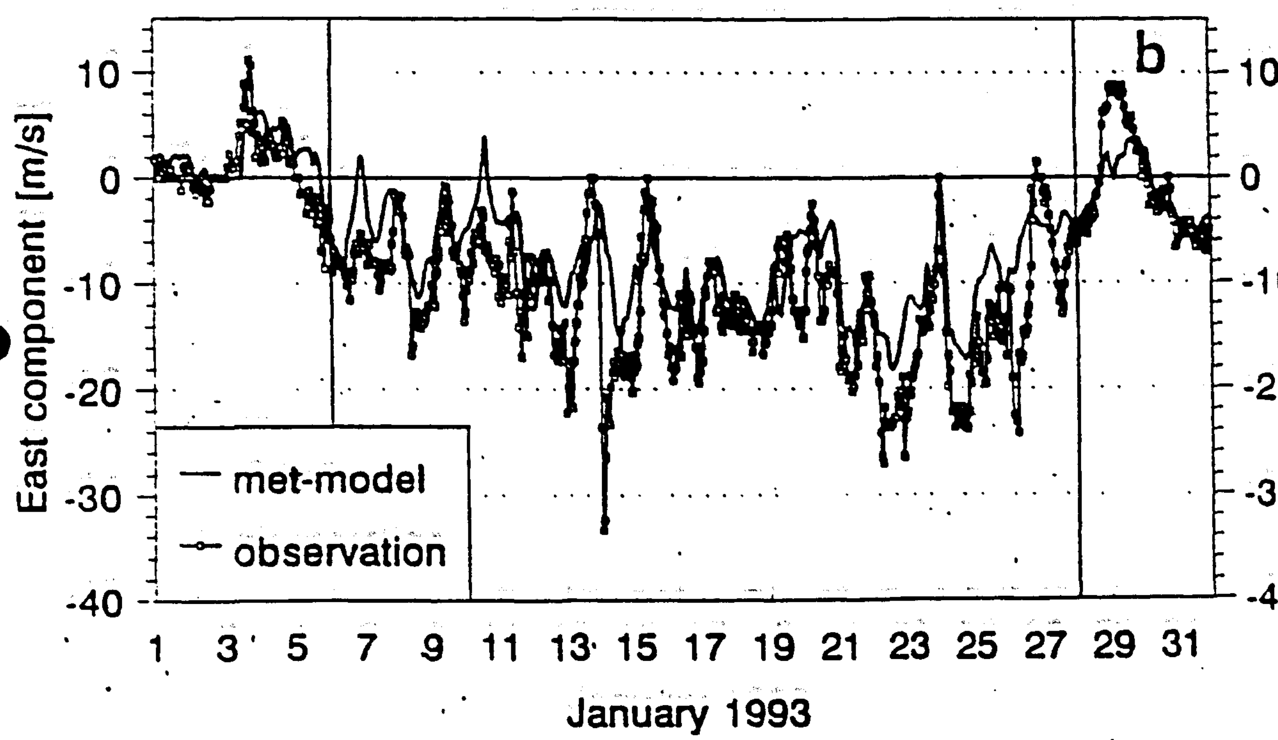


Fig. 2

Comparison between the observed and modelled wind speed input into the BSH-model

(a) and the East component, positive values denoting westward winds,
(b) at station Arkona, hourly averages.

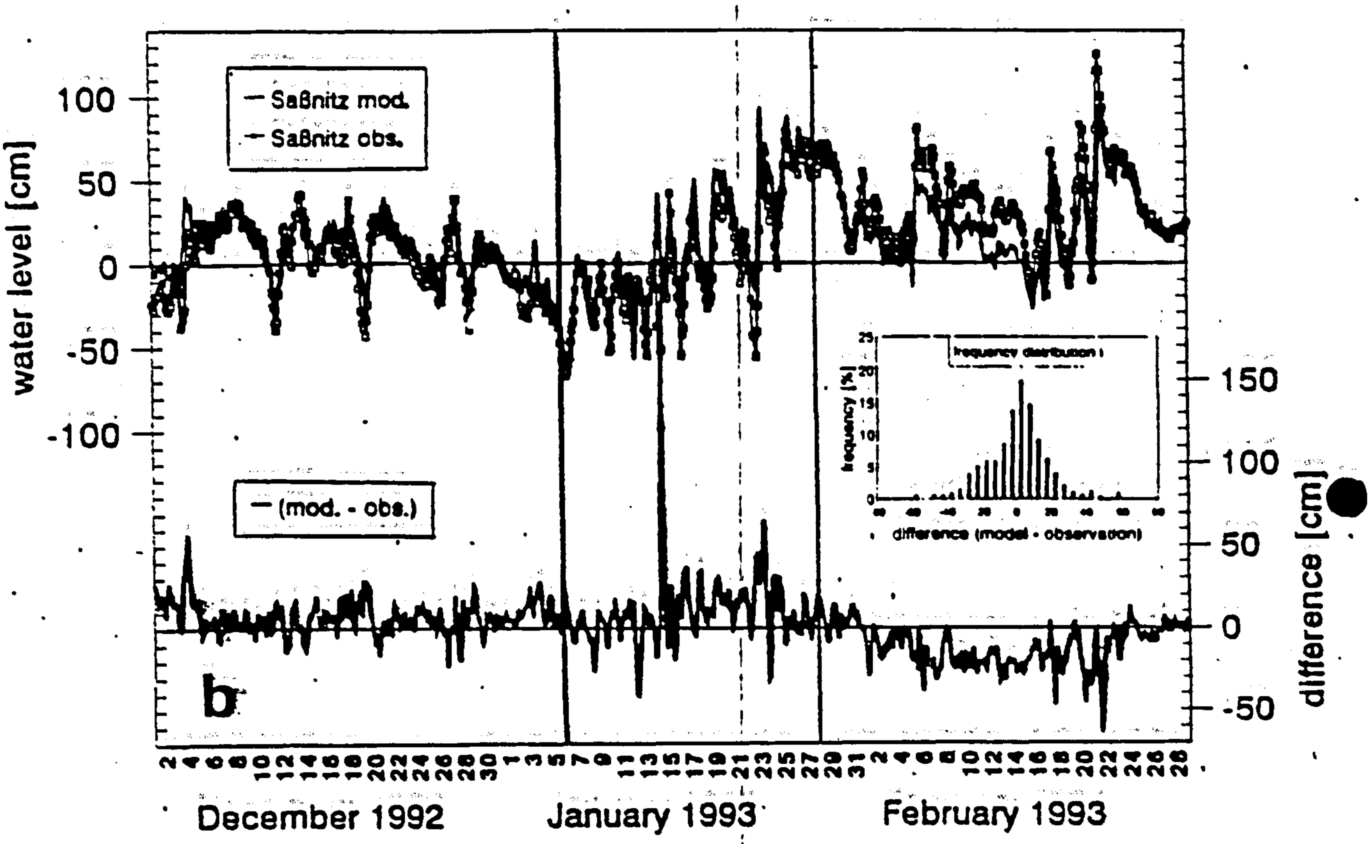


Fig. 3
Comparison between the observed and modelled water level at tide gauge Saßnitz (3-hourly averages).

upper curves: modelled (full line) together with observed water level (line with circles)
lower curve: difference between modelled and observed water level values.

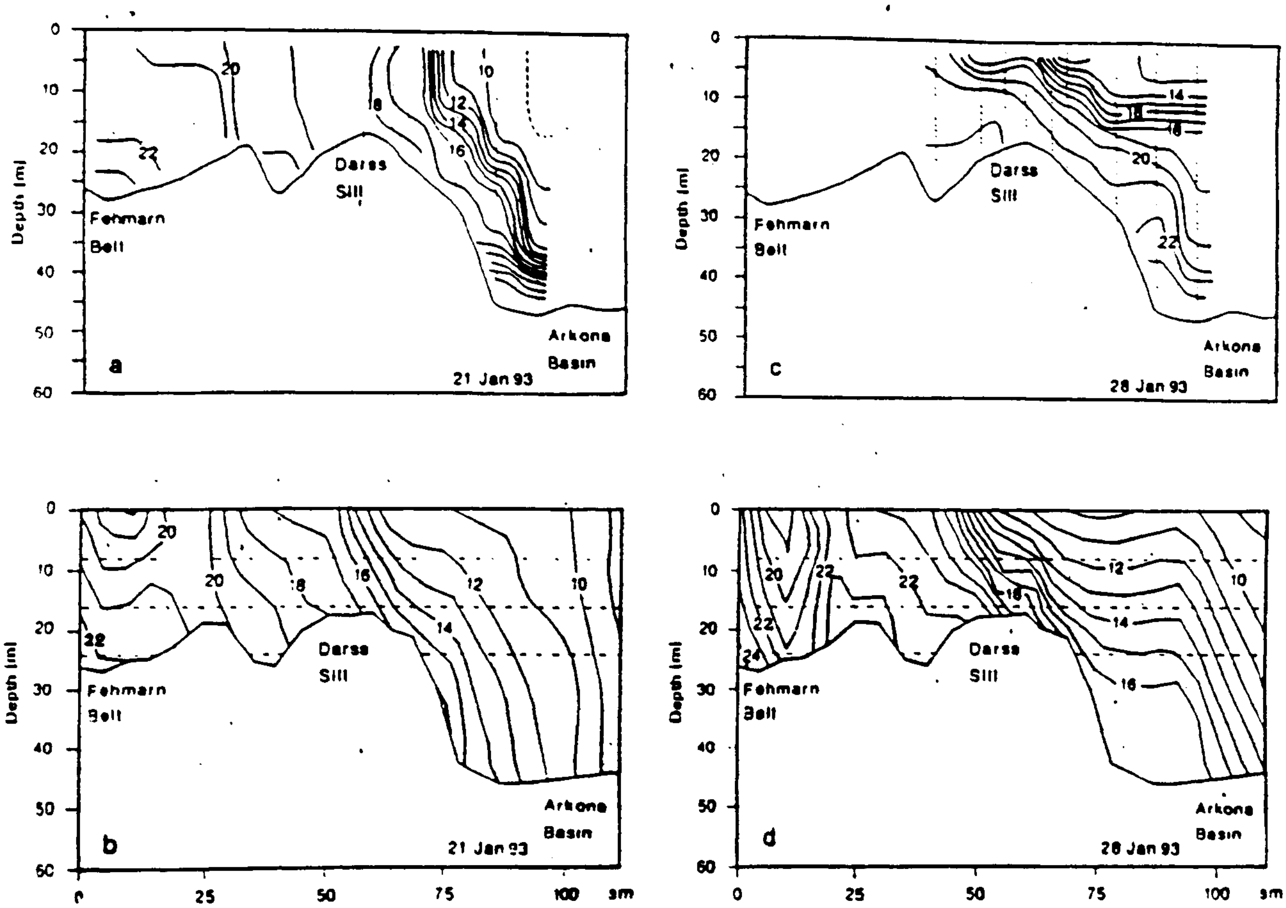


Fig. 4
Comparison between the observed and modelled salinity distribution along the transect Fehmarn Belt to Arkona Basin during the main inflow period

left side: Salinity section observed (a) and modelled (b) on 21 Jan.,1993
right side: Salinity section observed (c) and modelled (d) on 28 Jan.,1993

Fig. 5
Model results (3-hourly averages) for the period 01 Dec., 1992 until 28 Feb., 1993, including the inflow period from 06 Jan. until 28 Jan., 1993

(a) Water level at Landsort (thin line) together with volume of the Baltic Sea (thick line). The scale of the volume is adapted to the scale of the water level with aid of the Baltic Sea's model surface area.

(b) Volume of the Baltic Sea (thick line) together with the integrated net volume flux (thin line) passing through the transect at 55° 35' N (see Fig. 1)

(c) Water level at the two check points, position see Fig.1
upper curves:
Water level at "southern Kattegat" (thin line) together with "western Baltic" (thick line)
lower curve:
Water level difference between check points "southern Kattegat" and "western Baltic"

(d) Net volume flux across Darss Sill and Drogden Sill, for position of transects see Fig. 1
upper curves:
calculated net volume flux across Darss Sill (thin line) together with net volume flux across Drogden Sill (thick line). Positive flux indicates inflow into the Baltic Sea.
lower curve:
ratio (net volume flux Darss) / (net volume flux Drogden). Positive values indicate fluxes in the same direction across both sills, negative values fluxes in opposite direction.