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# REPRODUCTION VOLUME OF BALTIC COD IN THE BORNHOLM BASIN ESTIMATED FROM SINGLE POINT MEASUREMENTS

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## Abstract

Estimates of the reproduction volume of Baltic cod defined as the total volume of water with salinity above 11 psu, oxygen concentration above 2 ml/l and temperature above 1.5 °C are presented for the Bornholm Basin based on quasi-synoptic hydrographic surveys. The primary data set consisted of hydrographic observations recorded during 14 cruises in the period from 1991 to 1996 covering a regular grid of 36 stations with a spacing of appr. 10 nm. This data set was supplemented by including two additional surveys from 1989 with 21 stations. A statistical method the objective analysis was applied to map the horizontal distribution of the thickness of the spawning layer. Subsequently, the reproduction volume was calculated by basin wide integration. Highly significant correlations ($r^2 \geq 0.89$, $p < 0.001$) between single point observations of the thickness of the spawning layer and the overall reproduction volume in the Bornholm Basin was found for 4 stations located in the central part of the surveyed area. Linear regression models for single stations and the basin wide reproduction volume were established representing different hydrographic scenarios from stagnation to inflow periods. The results are discussed with respect to a backward extension of the time series using historical single point observations.

## Introduction

Oxygen content and salinity have been shown to be the major environmental factors affecting Baltic cod egg fertilization rate and survival (e.g. Westin & Nissling 1991, Wieland et al. 1994). The vertical extension of suitable levels of oxygen concentration and salinity distribution below the halocline restricts the volume of water for successful cod reproduction (Plikshs et al. 1993, Wieland, 1995), whereby temperature may have an additional effect in years with severe winters (Wieland & Zuzarte 1991). Lower critical limits for successful egg development as derived from experimental studies and field observations are a temperature of 1.5 °C, a salinity of 11 psu salinity and an oxygen concentration of 2 ml/l (Westin & Nissling 1991, Wieland et al. 1994).

Due to the irregularity of inflows of well oxygenated saline water masses from the North Sea, the oxygen content and the salinity in the deep layers of the basins of the Baltic shows a high variability. After a stagnation period in the 80's lasting about 10 years, the hydrographic conditions in the Bornholm Basin improved. Since the beginning of the 90's a series of weak to moderate inflow events have been observed of which the 1993 inflow was the strongest (Matthäus & Lass 1995). Estimates of the reproduction volume of Baltic cod presented so far were based on a limited number of hydrographic stations extrapolating the depth range with conditions suitable for succesful egg development from a few single point measurements to the entire area (Plikshs et al. 1993). This approach assumes a homogeneous horizontal distribution of temperature, salinity and oxygen concentration and does not consider any mesoscale variability within the spawning area.

In this paper a statistical method is used to estimate the reproduction volume of Baltic cod based on a series of hydrographic surveys covering the Bornholm Basin with a spatial resolution of appr. 10 nm. Linear relationships are presented to calculate the reproduction volume from single point observations of the vertical extension of the thickness of the spawning layer. Applications for periods in which hydrographic measurements are limited to single stations are presented using the ICES data base for subarea M25.

## Material and Methods

The hydrographic data set consists of measurements of 16 cruises carried out in the Bornholm Basin (ICES-Subdivision M25) between May 1989 and April 1996 (Tab. 1). Temperature, salinity and oxygen concentration were recorded with a ME OTS 1500 probe. Water samples were taken repeatedly to calibrate the sensor readings. The station grid represents the Bornholm Basin enclosed by the 60 m isobath (Fig. 1). Two cruises conducted in 1989 covered 21 stations while during all other surveys 36 standard stations were performed with a mean horizontal resolution of about 10 nm. The survey data were used to calculate the thickness of the spawning layer for Baltic cod, i.e. the vertical extension of the water body which is assumed to be suitable for successful egg development (salinity > 11 psu, oxygen > 2 ml/l, temperature > 1.5 °C). Horizontal fields of the thickness of the spawning layer were constructed by objective analysis (Bretherton et al. 1976).

The technique of objective analysis is based on a standard statistical approach - the Gauss-Markov Theorem- which gives an expression for the least square error linear estimate of the variables. The objective analysis is an optimal interpolation technique in that sense that among other linear estimators this one on average has the minimal least square error. It also yields an estimate of the residual uncertainties in the interpolated values. The method presented here has the advantage that it can make use of statistical results (spatial covariance function of measurements) and assumptions concerning measurement noise and small scale errors inferred from the observed data. Thus, at every single point (x,y) an estimate can be given, which depends lineary on the total number of measurements, i.e. a weighted sum of all observations (Bretherton et al. 1976). Due to the fact that the optimal estimator is linear, the objective analysis technique will provide a smoothed version of the original measurements with a tendency to underestimate the true field because of the specific assumptions involved in our treatment of measurement noise and small scale signals unresolved by the observation array. Error maps only depend on the statistics of the field, the noise level and the locations of the observation points, and not the measurements themselves. Hence, error maps can be calculated a priori for different array designs without reference to any particular data set.

As most of the experiments between 1989 and 1996 were designed to produce synoptic maps of the spawning layer, an accurate mapping technique was required. Applying the technique of objective analysis, which has been widely used in recent years (e.g. Bretherton et al. 1976, Sarmiento 1982, Hinrichsen & Lehmann 1994) an unit array configuration was provided based on the standard station grid. Based on 36 locations observed during quasi-synoptic surveys, a two-dimensional horizontally regular spaced grid was constructed where each grid point is representative for the thickness of the spawning layer centered around it. The study area was gridded with a approximately constant spacing of $d\lambda = 2'$ and $d\varphi = 1'$, which corresponds to a horizontal resolution of appr. 1 nm or 2 km, respectively. It was assumed that the error variance due to measurement errors and small scale noise amounts to 15 % of the total variance of the fields.
The reproduction volume of Baltic cod in the entire study area was calculated for the different surveys by simple horizontal integration of the fields of the thickness of the spawning layer,

whereby only the area for which the expected root mean square (r.m.s.) error in the interpolation amounted less than 20 % was considered. The 20% r.m.s error isoline was chosen because of it is closely related to the 60 m isobath which corresponds to the limit of the cod egg distribution (Wieland 1995). The array adjusted to water depths > 60 m covers an area of approximately 9800 $km^2$.
For each of the 36 stations the thickness of the spawning layer was cross correlated with the total reproduction volume obtained for the 14 observation dates in the period 1991 to 1996 evaluated by linear regression analysis. In order to take into account reproduction volumes representing the extremely bad environmental conditions observed during the stagnation period in the late 80's, data from two additional surveys (1989: based on a 21 station grid; see Fig. 1) were included into the analysis. The reproduction volumes for 1989 were estimated with respect to the unit array configuration based on the standard grid (36 stations).

**Results**

Regression models
The process of estimating the cod reproduction volume according to discrete values of the spawning layer thickness can be easily aided by use of a simple linear regression model. Figure 2 shows the horizontal distribution of the $r^2$ values for the cross correlation between spawning layer thickness of a single station and corresponding cod reproduction volume based on the spatial coverage of 36 stations. Most of the locations yield high correlation of single point observations of the spawning layer thickness with horizontally integrated quantities of its water volumes. For the northern part of the Bornholm Basin the overall structure of the correlations does not change dramatically. It is apparent that highest values for $r^2$ occurred in the central deep part of the basin, whereas the correlations yield the tendency to decrease with decreasing water depth. Additionally, relative high correlations were found for the Bornholm Gat region, i.e. the north western part of the study area. Generally, for the southern part of the Bornholm Basin with water depths < 80 m weaker correlations were found.
Linear regression models for four locations in the central Bornholm Basin which yielded correlations with $r^2 \geq 0.89$ (including the data from 1989 based on the reduced station grid) are shown in figure 3. For the observation dates covered in the period 1989 to 1996 (Tab. 1) the reproduction volume as estimated by basin wide integration ranged from 8 ( June 1989) to 229 $km^3$ (April 1994). The corresponding maximum values for the thickness of the spawning layer varied considerably between the four stations. The highest value of 42 m was recorded in the center of the study area followed by 33 m observed at a station located appr. 10 nm further to the east. Close to the entrance to the Stolpe trench and about 12 nm southeast from the central station the maxima of the thickness of the spawning layer amounted only 21 and 27 m, respectively. However, for all of these stations close correlation between the reproduction volume and the thickness of the spawning layer were found. Figure 4 compares the reproduction volume obtained by basin wide integration and the estimates obtained with the linear regression model for 55°17.5'N and 16°00'E. The results from both methods correspond well throughout the full range of observations.

Cod reproduction volume 1958-1996
Information on the thickness of the spawning layer can be obtained from the ICES data base (subdivision M25) for the period prior to 1995. According to the relations obtained for single locations, the spawning layer thickness can be converted to reproduction volume. Figure 5 presents a time series of the reproduction volume from 1958 to 1996 based on data collected at 55° 17.5'N, 16° 00' E. This station was the most frequently observed location (total number of observations: 466) during the last decades whereby all single point measurements were considered which were less than < 10 km apart from the nominal geographical position which the HELCOM Monitoring station BY5 (15°15'N, 16°00'E). The time series shows a strong variability for the years 1958 to 1982 with extremely bad hydrographic conditions present in 1971 and 1975. After a stagnation period in the 80's, the environmental parameters in the

Bornholm Basin had improved. Since the beginning of the 90's a couple of weak to moderate inflow events were observed for which the 1993 inflow was the strongest. However, in 1994 the improvement of the reproduction volume did not persist throughout the year. Most favourable conditions for successful egg development observed in spring 1994 were followed by a strong decrease of the reproduction volume until summer 1995.

## Discussion

In order to establish a relationship between cod egg survival and the volume of water with suitable conditions of successful egg development, hydrographic parameters were recorded at a quasi-stationary grid within the Bornholm Basin in the period 1989 to 1996. The successful study of such a complex area requires that quasi-synoptic data sets and near-synoptic methods can be used. The objective analyis method was applied to describe the temporal evolution of the cod reproduction volume during this time period. This theory is powerful and practical as well and provides an optimal linear minimum mean square error estimate for the observations.

Linear regressions revealed significant correlations between the spawning layer thickness observed at locations in the deep part of the Bornholm Basin (> 80 m) and its corresponding basin wide integrated quantity (reproduction volume). The closest correlations were found for stations located in line with the general path of inflowing high saline and oxygen rich water which is through the Bornholm Gat downstream towards the eastern central Bornholm Basin (Lehmann 1994). Shallower regions are less representative due to a variability in the thickness of the spawning layer affected by both the influence of more frequent but weaker (less saline) inflow events which are generally not detectable in the shallower water regions and the tendency of the halocline to interact with the bottom layer. Furthermore, a bias is introduced if the hydrographic measurements were performed when an inflow event is under progress and hence the improvement of the spawning conditions has not been completed in the entire area. This can lead to uncertainties in the estimates obtained for winter periods as most of the major inflows have been observed between November 1 and January 31 with durations between 5 and 29 days (Matthäus & Franck 1992).

The strong increase of the reproduction volume in 1993 is associated with the Major Baltic inflow in January 1993. This inflow transported 125 $km^3$ of highly saline and well oxygenated water into the Baltic Sea (Matthäus & Lass 1995). In the beginning of 1994 a further improvement of the hydrographic conditions were recorded due to a weak inflow in winter 1993/94. Although the reproduction volume declined in summer, in both years favourable environmental conditions prevailed during the cod spawning period which was observed from May to August with peak spawning in the end of June (Wieland & Horbowa 1996).


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Tab. 1: Hydrographic surveys in the Bornholm Basin

| Survey period | Research vessel |
|---|---|
| 1989, May 25 - 27 | RV Alkor |
| 1989, June 24 - 26 | RV Alkor |
| 1991, July 6 - 8 | RV Alkor |
| 1991, August 10 - 12 | RV Poseidon |
| 1992, July 7 - 9 | RV Poseidon |
| 1993, April 21 - 23 | RV Alkor |
| 1993, May 22 - 26 | RV Alkor |
| 1993, July 6 - 8 | RV Alkor |
| 1994, April 28 - 30 | RV Alkor |
| 1994, May 30 - June 4 | RV Alkor |
| 1994, July 7 - 11 | RV Alkor |
| 1995, April 8 - 12 | RV Alkor |
| 1995, May 12 - 17 | RV Alkor / RV A.v. Humboldt |
| 1995, July 17 - 23 | RV Alkor |
| 1995, September 8 - 10 | RV Alkor |
| 1996, April 14 - 16 | RV Alkor |

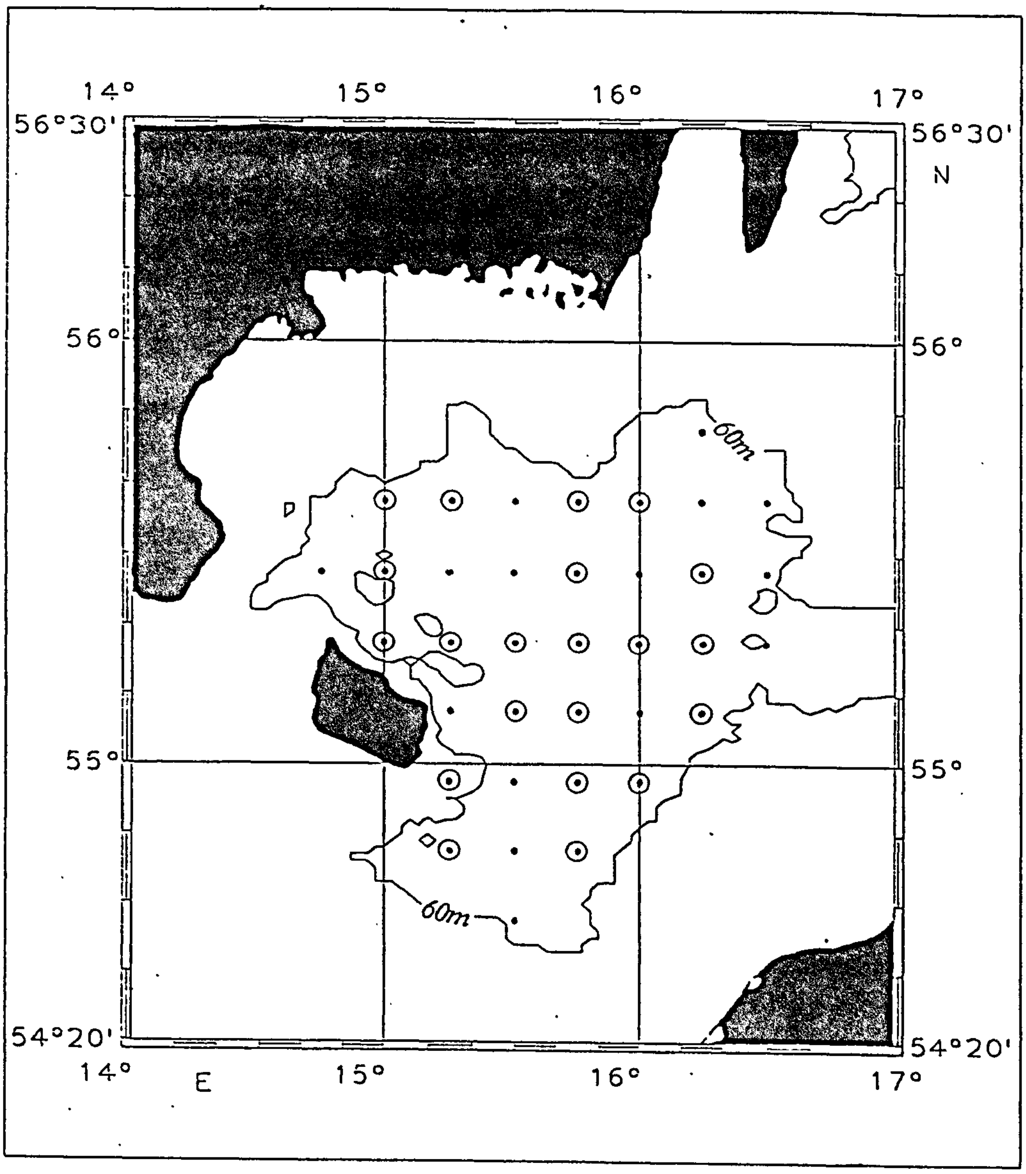


Fig. 1: Hydrographic standard station grid in the Bornholm Basin; dots: 36 stations (1991-1996), circles: 21 stations (May and June 1989)

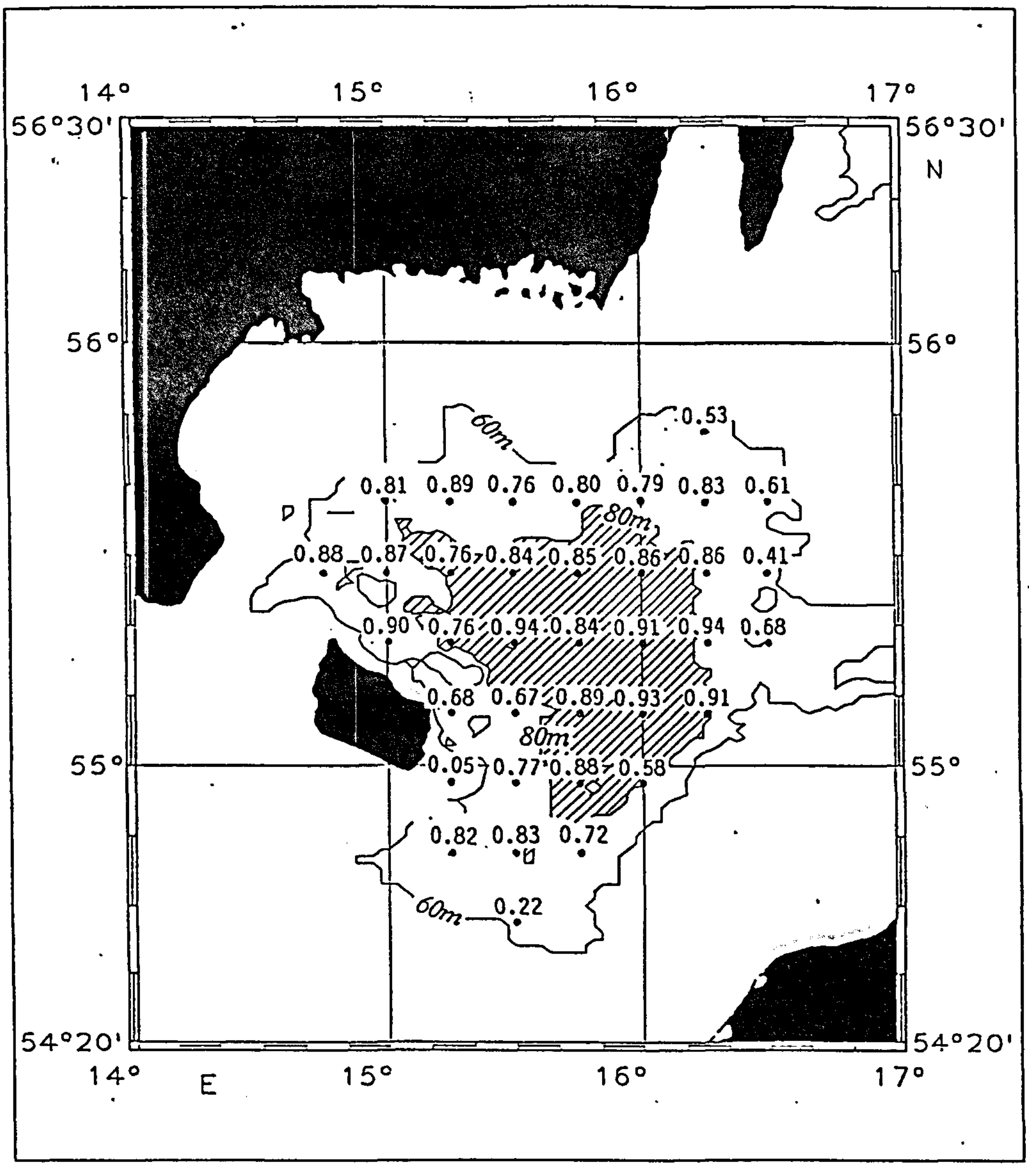


Fig. 2: $R^2$ values for the cross correlation between the thickness of the spawning layer and reproduction volume of cod based on a 36 standard station grid (1991-1996) in the Bornholm Basin, depths > 80 m shaded

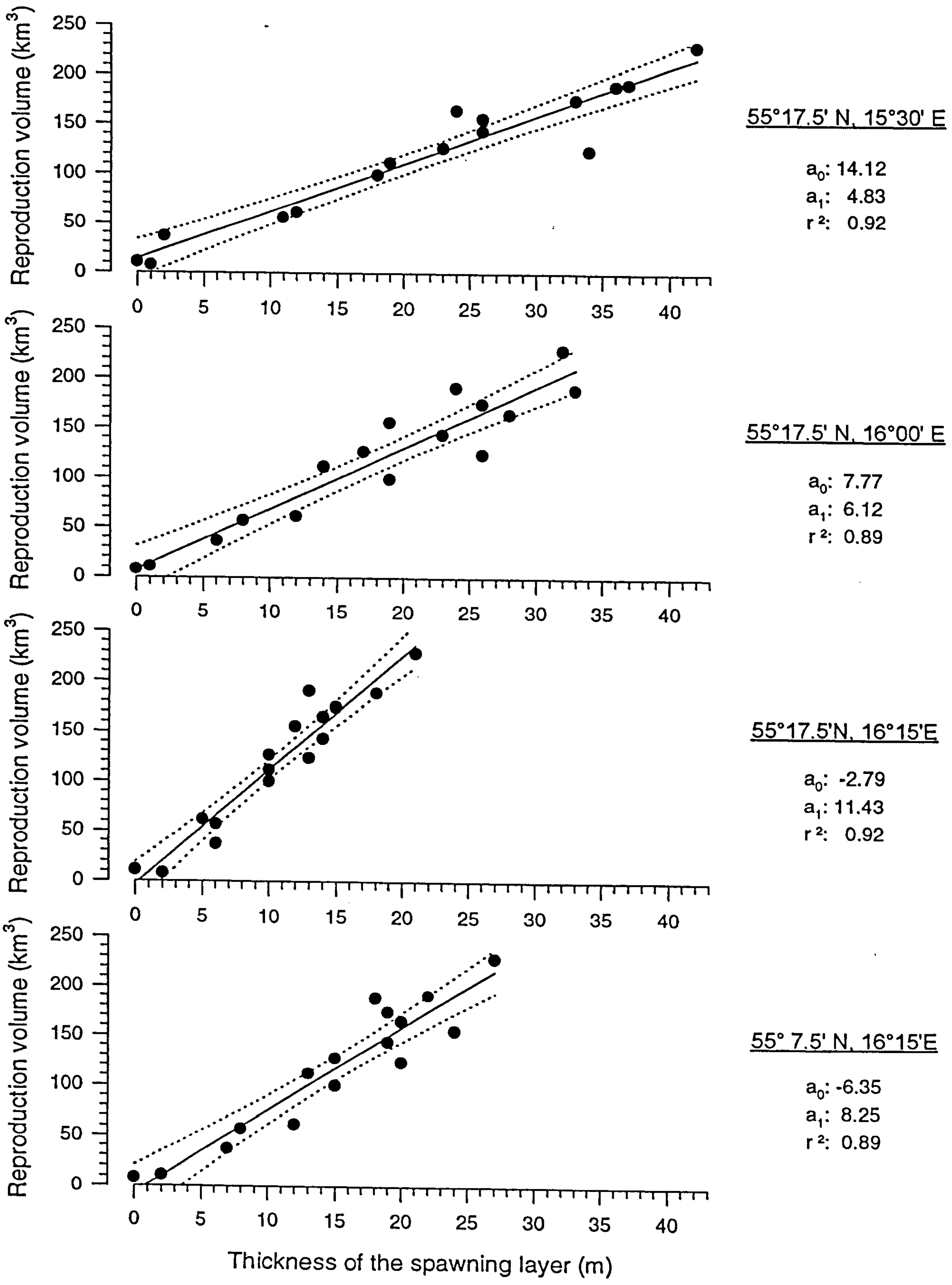


Fig. 3: Regression models for the correlation of the thickness of the spawning layer at 4 stations with the basin wide reproduction volume. Dotted line refers to 95 % confidence limits.

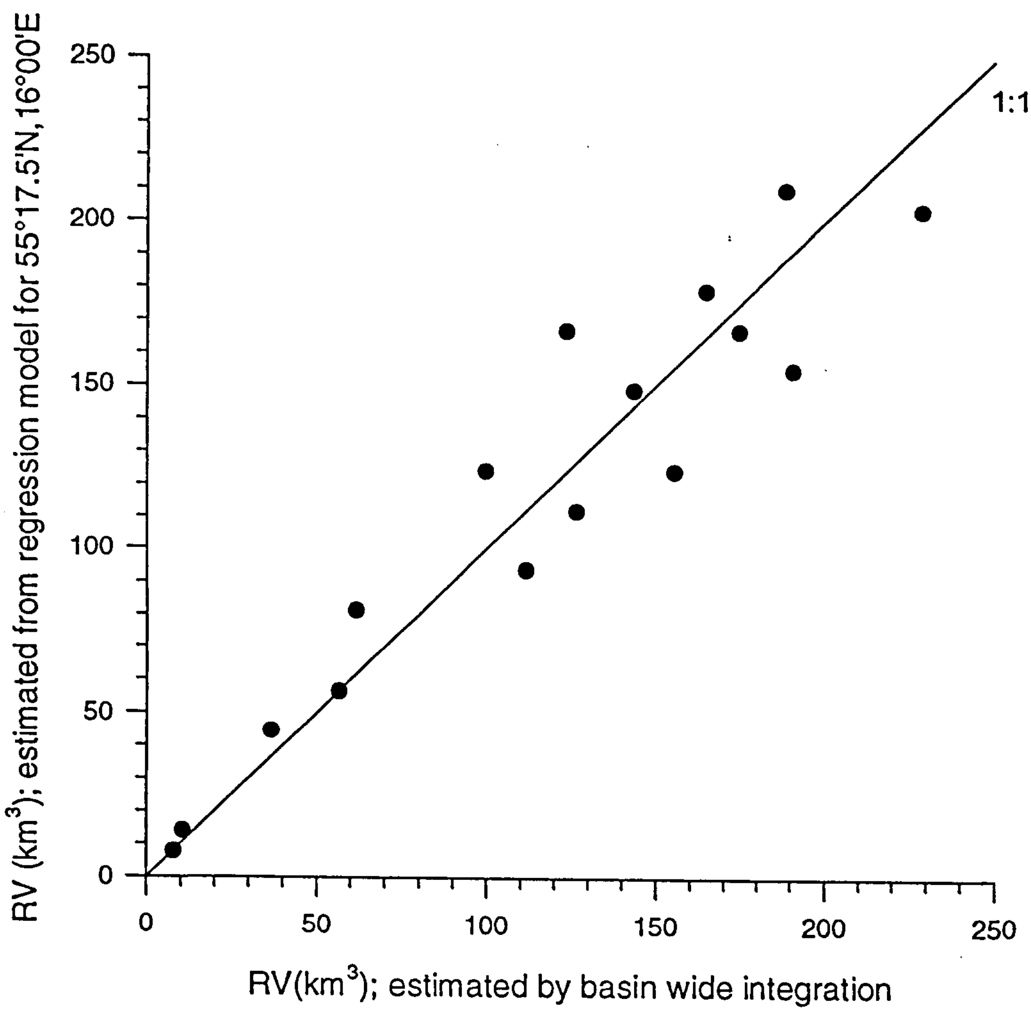


Fig. 4: Comparsion of the reproduction volume (RV) estimated by basin wide integration with the corresponding values obtained from the regession model for one selected station in the central Bornholm Basin (55°17.5'N, 16°00'E)

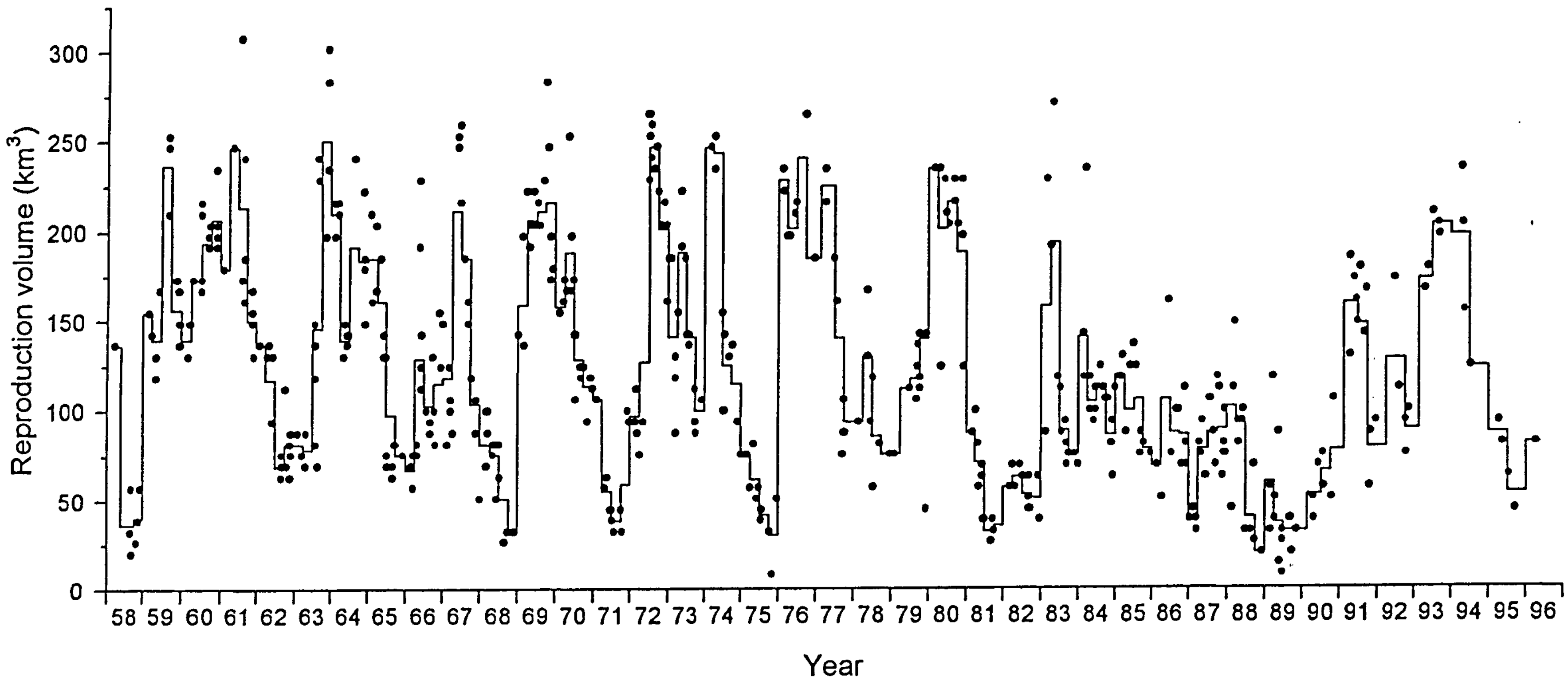


Fig. 5: Reproduction volume of cod in the Bornholm Basin 1958 - 1996 based on single point measurements at 55°17.5'N and 16°00'E. Solid line refers to mean values by quarter.