On deep saline water flow exchange in the Southern Baltic - month to month variability by 3D model[a]

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Abstract

Based on multi - year averaged fields of the monthly water temperature and salinity, a combination of robust diagnostic and fully prognostic techniques has been applied to evaluate density - driven circulation for the Baltic Sea consistent with the physics of the sigma-coordinate model based on the POM code of Blumberg and Mellor (1987).

The model domain (8° 50' E - 29° 15' E; 53° 50' N - 65° 50') comprises the whole Baltic Sea with the Gulf of Bothnia, the Gulf of Finland and the Gulf of Riga as well as the Danish Straits and Kattegat and Skagerrak, At the open boundary in the Skagerrak simplified boundary conditions (radiation type) are applied. Model resolution, horizontal - ca. 5 km and vertical - 24 levels of sigma - coordinate, allows to analyse basic features of water movements in the Baltic Sea.

Model is forced by climatological forcings, coupled by the a method of "relaxation to climatology" (e. g., Lehmann, 1995). The three-dimensional fields of the seawater temperature T and its salinity S in each month of a year, constructed from the monthly mean (multi - year averaged) charts presented in Bock's (1971) and Lenz's (1971) atlases, were used in the model runs as initial fields of T, S and as climatological forcings.

Simulated termohaline fields were compared with the initil i.e., monthly mean data. Development of the temperature and salinity profiles for each month of a year was monitored at the selected stations. After 28-31 days of simulations model adjusted temperature and salinity profiles were reproduced in relatively good accordance with the monthly mean ones.

The hydrodynamics related to the model adjusted 3D fields of T and S was used to evaluate deep saline water exchange through the Bornholm Channel and the Slupsk Furrow. Results of estimation showed that significant month to month variability of the deep water flows. Yearly mean value of the deep water flow with $S > 9.0$ PSU through the Bornholm Strait was equal to 42758 $m^3 s^{-1}$ with standard deviation equal to 4465 $m^3 s^{-1}$. In the case of the Slupsk Furrow similar estmate yielded 47240 $m^3 s^{-1}$ with standard deviation equal to 12338 $m^3 s^{-1}$. The calculated values of yearly mean estimates of saline water flow are not far from the results of other investigators (models or calculations based on in situ data) .

Introduction

The deep saline water exchange between the deep basins in the Southern Baltic occurs, due to complex bottom topography, mainly through the Bornholm and the Slupsk Channels. Only few estimates based on direct *in situ* measurements of deep water flow through the vertical control sections in that channels are available (Jakobsen 1996, Petren and Walin 1976). Most investigators have used different kind of models (i.e. Köuts and Omstedt 1993, Pedersen 1977, Rydberg 1976, Stigebrandt 1987), including three-dimensional (3D) numerical model (Lehmann and Hinrichsen 2002).

In this study a 3D σ - coordinate numerical model with adapted robust-diagnostic scheme has been applied to evaluate density - driven circulation in the Baltic Sea.The model was forced by climatological forcings only. The hydrodynamics of the Baltic, related to the model adjusted 3D fields of temperature and its salinity was used to evaluate deep saline water volume transport through the selected vertical sections in the Southern Baltic (*Fig. 1*).

The aim of this presentation is to demonstrate the model capability for estimation of deep saline water flow exchange in the Southern Baltic. The focus is put on the mean volume transport across vertical sections in the Bornholm Channel (BC) and in the Slupsk Furrow (RS) (*Fig. 1*).

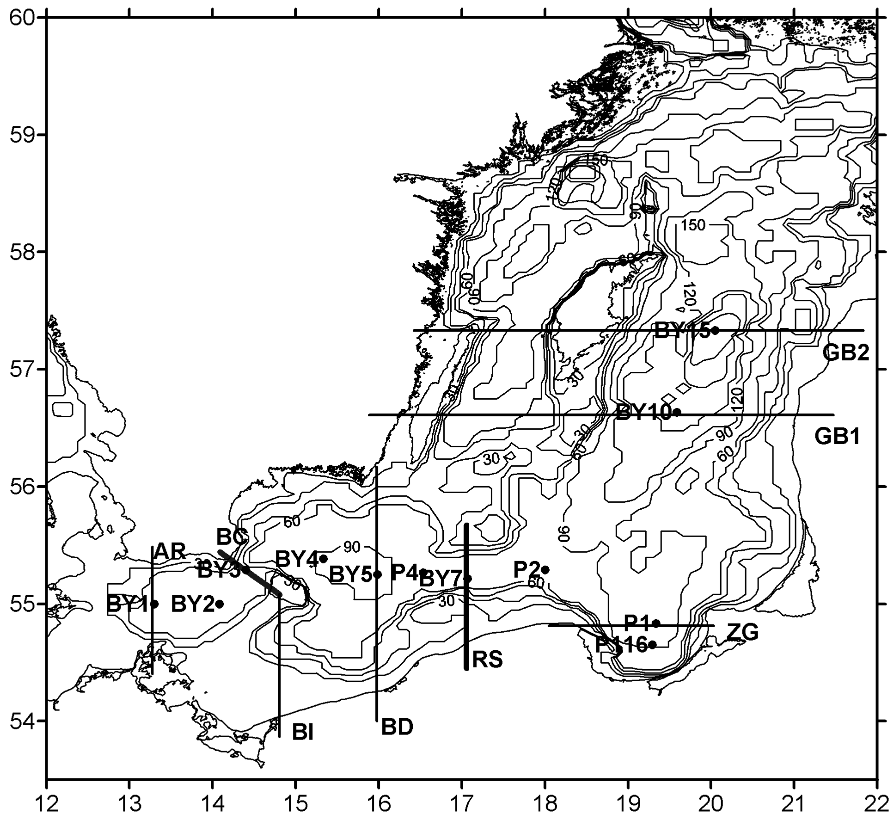

Figure 1 The study area and location of the vertical hydrographic sections and the points used to visulize the results of simulations. The bottom topography was elaborated from data from Seifert and Keyser (1995). The numbers on the isolines indicate the depth in meters

Model description

The model is based on the Princeton Ocean Model code of Blumberg and Mellor (1987), known as POM, adapted to the Baltic Sea (Jankowski 2002). The model domain (8^o 50' E - 29^o 15' E; 53^o 50' N - 65^o 50') comprises the whole Baltic Sea. At the open boundary in the Skagerrak simplified boundary conditions (radiation type) are applied. The model has horizontal resolution of ca. 5 km and 24 σ - levels in vertical. The model bottom topography was elaborated on the basis of data from Seifert and Kayser (1995). The model was forced by climatological forcings only, coupled by a method of "relaxation to climatology" (cf. Lehmann, 1995).

The initial 3-D fields of the seawater temperature and its salinity in each month of a year were constructed from the monthly mean (multi-year averaged) maps taken from Bock's (1971) and Lenz's (1971) atlases and additional available in situ data. The thermohaline fields, initially prepared at selected depths for were interpolated in the vertical onto 24 σ-levels by cubic splines The climatological forcings were calculated in the following way. The two-dimensional fields of the temperature T and salinity S at the sea surface for all 12 months were taken from the monthly mean (multi-year averaged, climatic) surface maps in Bock's (1971) and Lenz's (1971) atlases. Next, the 2-D fields of T and S were linearly interpolated in time with an interval equal to the internal time step.

Model description ... continuation

In numerical simulations the robust diagnostic method adopted from Sarmiento and Bryan (1982) was used. This approach introduces Newton damping terms into the prognostic equations for salinity and temperature:

$$\frac{\partial F}{\partial t} = RHS - \gamma\,(F - F_c) \tag{1}$$

where: F, F_c - the model tracer and the climatic value, γ - relaxation (restoring) factor and RHS - stands for other terms in the tracer equations.
This additional term on the right hand side of tracer equation tends to restore the model solution for tracer towards their climatic values F_c with time scales $T_t = 1/\gamma$. As in Sarmiento and Bryan (1982) we use γ as exponential function of depth:

$$\gamma(z) = 1/t_b + (1/t_s - 1/t_b)\ exp(-z/H_0) \tag{2}$$

Results presented herein have been calculated with the following values of these numerical constants in prognostic equations :

$$\begin{array}{llll} for\ temperature & t_s = 20days & t_b = 200days & H_0 = 200m \\ for\ salinity & t_s = 200days & t_b = 2000days & H_0 = 200m \end{array}$$

Simulation and results

The calculations started with the results of pre-processing run of 20 days' duration. At this stage model was run in pure diagnostic mode with fixed thermohaline fields for January. After that, the simulations were performed in turn for each month of a year. For following month, model was initialised from the final results of the previous one and was run in a prognostic mode with included robust-diagnostic scheme. At this stage model was driven by climatological forcings and by additional source terms in the equations for temperature and salinity.

Development of the temperature and salinity profiles for succesive month was monitored at the selected stations (*Fig. 1*). The performance of the numerical simulations has been quantified by monitoring the root mean square error (*Rmse*) between the calculated on current day and the monthly mean vertical profiles of temperature and salinity. After 28-31 days of simulations model adjusted temperature and salinity profiles were reproduced in relatively good accordance with the monthly mean ones. (*Rmse*), estimated on the last day of model run, are c. 0.5 - 1.5^{o}C and c. 0.3 - 1.0 PSU, depending on the location of the hydrographic station. Examplary values of *Rmse* calculated on first day and last one at stations *BY5, BY7* are shown in (*Fig. 2a, 2b*).

The hydrodynamics related to the model adjusted 3D fields of T and S was used to evaluate deep saline water exchange through the Bornholm Channel and the Slupsk Furrow. Results of estimation showed that significant month to month variability of the deep water flows (*Fig. 3* and *Fig. 4*)).

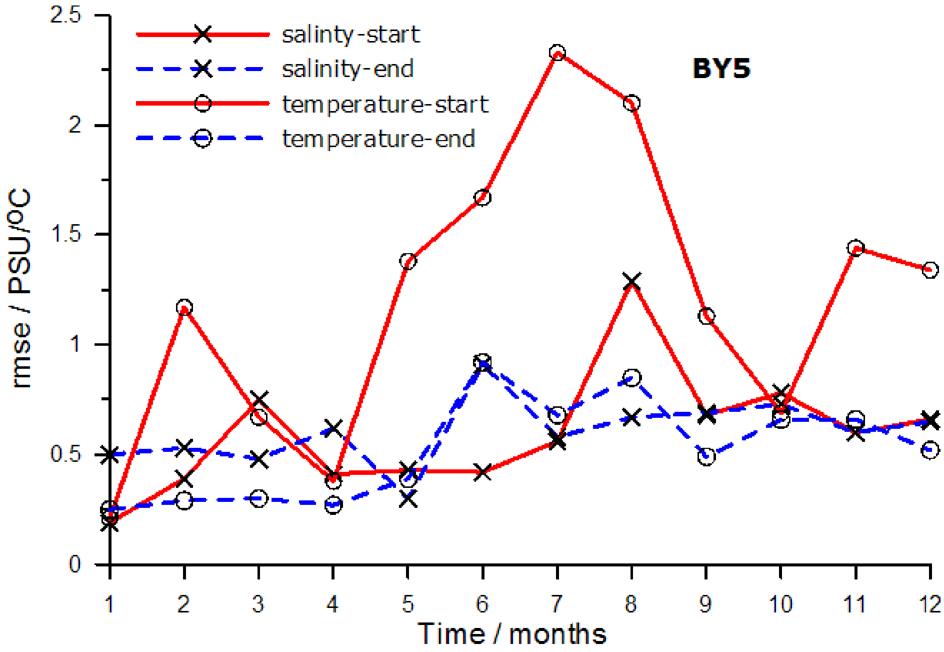

Figure 2a Rmse for the salinity and temperature vertical profiles at the point BY5. For point location - see *Fig. 1*.

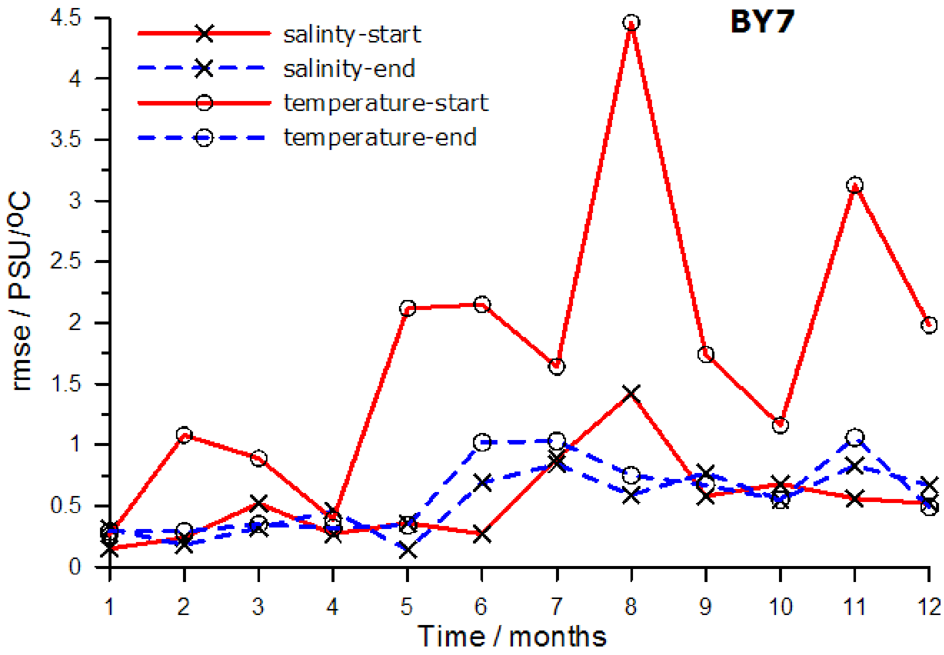

Figure 2b Rmse for the salinity and temperature vertical profiles at the point BY7. For point location - see *Fig. 1.*

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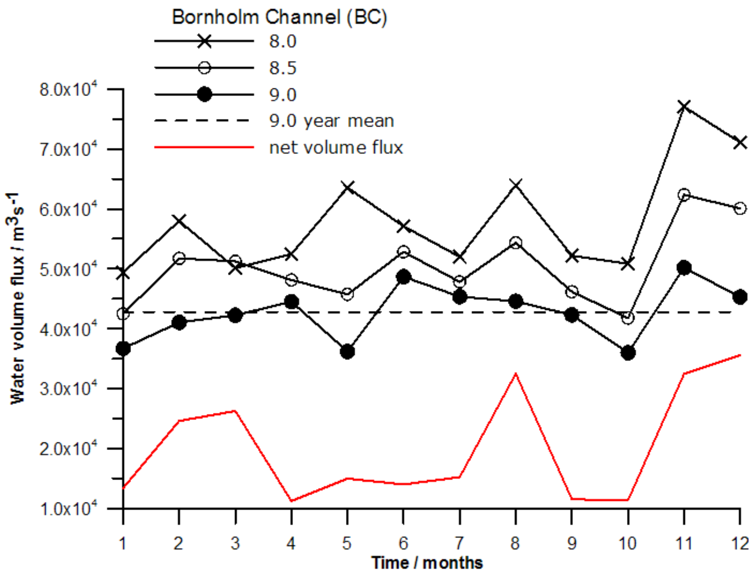

Figure 3 The calculated deep saline water flow across the vertical section in the Bornholm Channel (BC). For location of section - see *Fig. 1*.

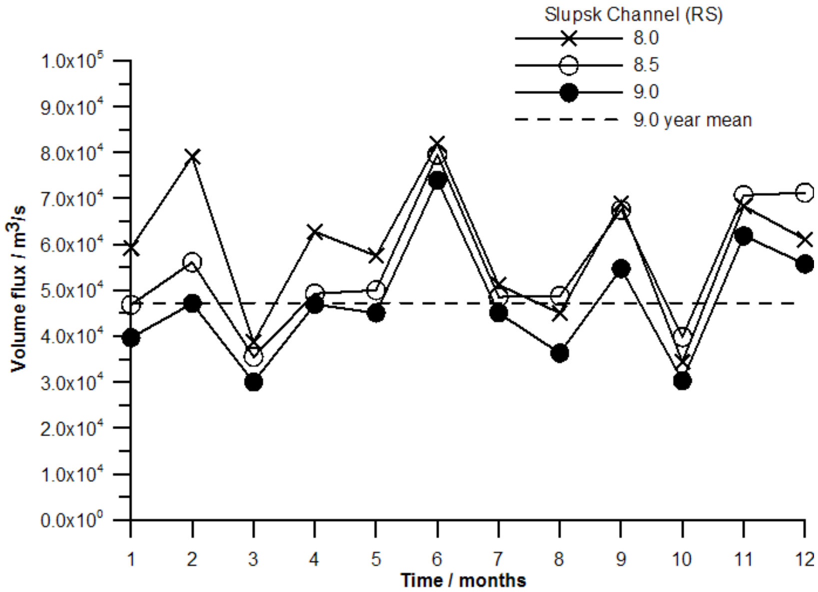

Figure 4 The calculated deep saline water flow across the vertical section in the Slupsk Channel (RS). For location of section - see *Fig. 1*.

Simulation and results ... continuation

Estimated yearly mean value of the deep water flow with $\boldsymbol{S} > 8.0$, 8.5 and 9.0 PSU across vertical section in the Bornholm Channel (*BC*) and in the Slupsk Furrow (*RS*) are presented in *Tab. 1*. The calculated values of yearly mean estimates of saline water flow are not far from the results of other investigators based on models calculations as well as on *in situ* data (see *Tab. 2* for details).

Correctness of model results has been estimated through calculating volume transport component across the selected hydrographic vertical sections. *Figs. 5* and (*Fig. 6*) present results for section *AR* and *BC+BI*. Yearly mean values of cumulated volume transport through the all selected sections are shown in *Tab. 3*.

Table 1 Yearly mean values of volume transport $\boldsymbol{Q}$ of water with salinity > 8.0, 8.5 oraz 9.0 PSU through the vertical sections in the Bornholm Channel (BC) and in the Slupsk Channel (RS). SD - standard deviations. Positive value of transport - to the east . (Location of the sections - see Fig. 1).

S PSU	$\boldsymbol{Q_{net}}$ $\boldsymbol{m^3s^{-1}}$	$\boldsymbol{SD}$ $\boldsymbol{m^3s^{-1}}$	$\boldsymbol{Q_{east}}$ $\boldsymbol{m^3s^{-1}}$	$\boldsymbol{SD}$ $\boldsymbol{m^3s^{-1}}$	$\boldsymbol{Q_{west}}$ $\boldsymbol{m^3s^{-1}}$	$\boldsymbol{SD}$ $\boldsymbol{m^3s^{-1}}$
Bornholm Channel (BC)						
8.0	58156	8616	62449	9428	-4293	5434
8.5	50400	6122	51105	6067	-704	556
9.0	42758	4465	42891	4458	-133	202
Slupsk Channel (RS)						
8.0	59012	14161	83045	19351	-24034	11840
8.5	55326	13181	63600	19317	-8273	8469
9.0	47240	12338	50344	14472	-3103	4608

Table 2

Values of volume transport $\boldsymbol{Q}$ through the vertical sections in the Bornholm Channel (BC) and in the Slupsk Channel(RS) estimated by other authors. (Location of the sections - see Fig. 1). Positive value - transport to the east.

Q $m^3 s^{-1}$	Salinity PSU	Author (source, reference and comments)
		Bornholm Channel (BC)
12200-17400	> 8.25	Petren and Walin (1976)(*in situ*)
11500	> 9.75	Petren and Walin (1976) (*in situ*)
60000-110000		Jakobsen (1996) (*in situ*)
23650	12 - 16	Stigebrandt (1987) (*model*)
25900	11 - 18	Köuts and Omstedt (1993) (*model*)
12150	8 - 10	Lehmann and Hinrichsen (2002) (*model*)
18320	> 10	Lehmann and Hinrichsen (2002) (*model*)
		Slupsk Channel (RS)
50000	> 8.5	Rydberg (1976) (*model*)
23000-54000		Pedersen (1977)(*in model*)
20000-140000		Jakobsen (1996) (*in situ*)
33200	13 - 15	Köuts and Omstedt (1993)(*model*)
8792	8 - 10	Lehmann and Hinrichsen (2002) (*model*)
16260	> 10	Lehmann and Hinrichsen (2002) (*model*)

Table 3 Values of cumulated volume transport $Q[km^3]$ through the selected vertical sections. Positive value of transport - to the east (north). (Location of the sections - see Fig. 1).

Section	Q_{in} $[km^3]$	Q_{out} $[km^3]$	Q_{net} $[km^3]$	Q_{net}/Q_{in} [%]	Q_{net}/Q_{out} [%]
AR	2164.8	-2235.0	-70.8	3.3	-3.2
BC+BI	2824.6	-2908.7	-84.2	3.0	-2.9
BD	5890.6	-6066.9	-176.3	-3.0	2.9
GB2	12399.2	-12010.8	388.4	3.1	-3.2
GB1	9933.4	-9925.4	8.0	0.1	-0.1
ZG	2668.8.0	-2707.1	-19.0	-0.7	0.7

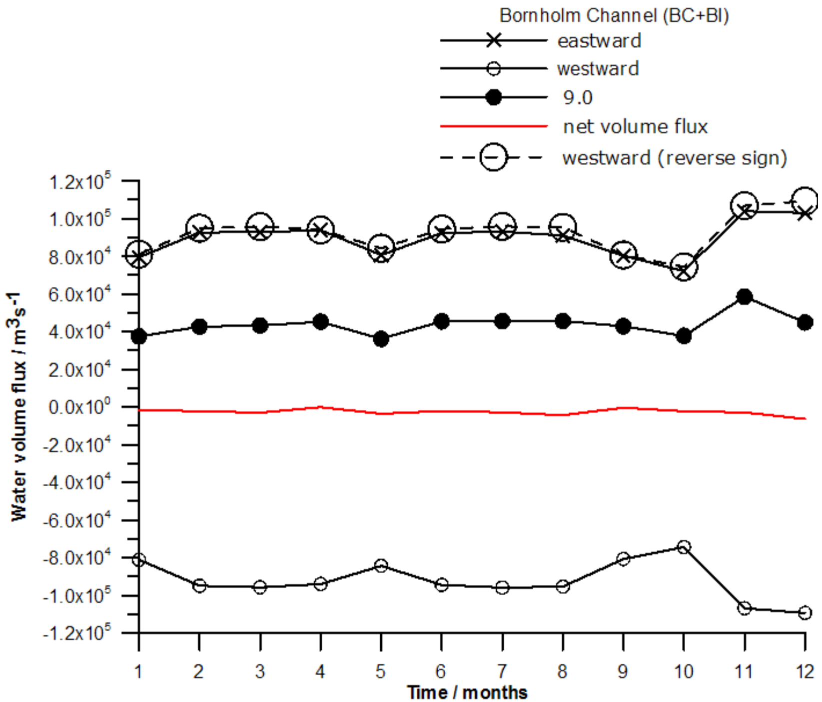

Figure 5 The calculated water flow across the control vertical section in the Bornholm Channel BC+BI). For location of section - see *Fig. 1*.

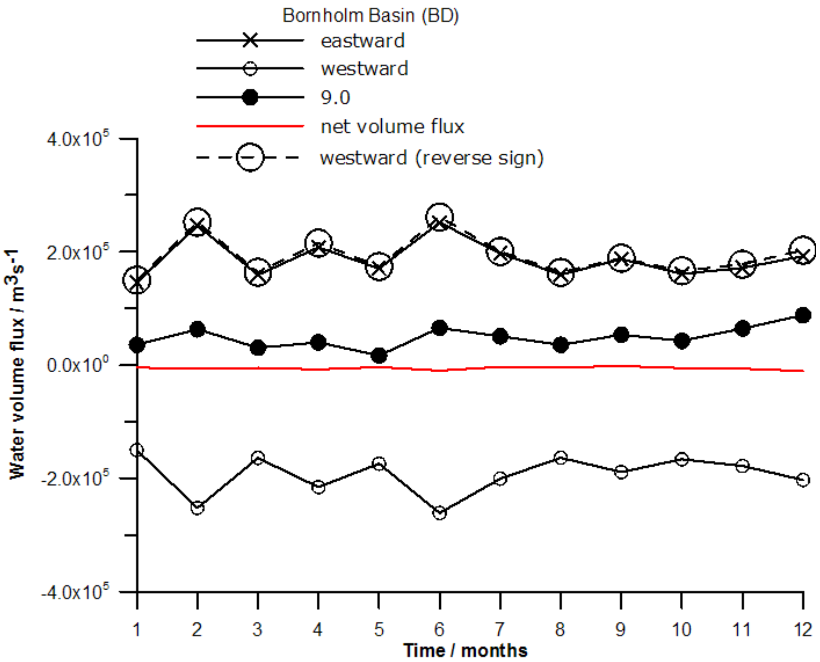

Figure 6 The calculated water flow across the control vertical section in the Bornholm Basin BD). For location of section - see *Fig. 1.*

Comments

3D $\boldsymbol{\sigma}$ - coordinate numerical model with adapted robust-diagnostic scheme has been applied to evaluate density - driven circulation in the Baltic Sea. The model was forced by climatological forcings only.

The model results were used to evaluate deep saline water volume transport across vertical sections in the Bornholm Channel (BC) and in the Slupsk Furrow (RS). Results of estimation showed significant month to month variability of the deep water flows.

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