Variability in the saline water exchange between the Baltic and the Gulf of Gdańsk by the σ-coordinate model*

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Baltic Sea
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Residence time

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Abstract

A three-dimensional baroclinic σ–coordinate model was applied to study the circulation and thermohaline variability in the coastal zone in the south-eastern Baltic Sea. The model is based on the Princeton Ocean Model code of Blumberg & Mellor (1987), known as POM, and has the horizontal resolution of ~ 5 km and 24 σ-levels in the vertical. The hydrodynamic conditions and variability of water and salt exchange between the Gulf of Gdańsk and the Baltic Proper, and the renewal of water masses in the Gulf of Gdańsk due to atmospheric forcing are analyzed. The numerical simulations were performed with real atmospheric forcings as well as with homogeneous (spatially uniform) wind fields over the whole Baltic Sea. The numerical simulations showed that the atmospheric forcing (winds) can play a significant role in shaping the renewal of bottom saline waters in the Gulf of Gdańsk. Two regions of inflow/outflow of saline waters responsible for the salinity regime were located. The overall water exchange between the Gulf and the Baltic Proper as well as the exchange of saline bottom waters appear to be strongly dependent on wind conditions. The net flux of water of salinity > 9 PSU is of the order of 48 000–100 000 $\mathrm{m}^3\ \mathrm{s}^{-1}$. SE, E, S and NE winds were found to exert the greatest influence on salinity conditions in the Gulf of Gdańsk. Estimates of saline (salinity > 9 PSU) water residence time based on the model simulation yielded values from 46 days for SE winds to 153 days for NW winds.

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1. Introduction

Situated in the southern part of the Gdańsk Basin, the Gulf of Gdańsk is one of the Baltic's open gulfs. It has a wide and deep connection with the open sea, which is not without influence on the hydrological regime of its waters (Majewski 1990, Andrulewicz 1996). The numerical models of water movements in the Gulf (e.g. Kowalik & Wróblewski 1971, Jankowski 1983, 1985, 1997, Jędrasik 1997, Kowalewski 1997) produced so far show that the Gulf cannot be treated as a separate basin as far as its water circulation is concerned. The current field in the Gulf is a continuation of such a field in the southern Baltic. This fact makes it more difficult to determine the water and salt exchange between the Gulf and the Baltic Proper and also to estimate the balance of biogenic and chemical deposits carried into and out of the basin.

The problem could be solved if a series of buoys with current meters and other instruments for measuring various hydrological parameters were installed at the open boundary of the Gulf for a longer period of time. However, for technical reasons, such an undertaking would be extremely costly and difficult to implement. Therefore, model-based investigations could be of some use in evaluating the water exchange between the Gulf and the Baltic. The present paper explores this problem, aiming as it does to outline the saline water exchange dynamics between the Gulf of Gdańsk and the Baltic Sea on the basis of a three-dimensional (3-D) baroclinic circulation, σ-coordinate model.

Krauss & Brügge (1991) reported that as a result of easterly winds, Baltic bottom waters are translocated from the Bornholm Basin to the Gdańsk Basin through the Słupsk Channel. These dense, saline and oxygen-rich waters then proceed to other Baltic basins more distant from the Bornholm Deep.

On the basis of numerical model results, Elken (1996) and Jankowski (1997) demonstrated that the Gulf of Gdańsk can serve as a buffer zone for the deep saline waters spreading from the Słupsk Furrow on their way to the Eastern Gotland Basin. Jędrasik (1997) highlighted the significant influence of advection on the water temperature field in the Gulf of Gdańsk and on the exchange of water with the Baltic. It was shown that easterly winds can be regarded as a natural factor bringing about the renewal of Gulf of Gdańsk waters.

For many environmental problems in the coastal area, we need to know the three-dimensional temperature and salinity distributions and circulation patterns, which are frequently dominated by short-term wind-induced events. The inflow of saline and oxygenated waters along the bottom is essential for bottom-living animals in all parts of the Baltic Sea, including the Gdańsk Basin and the Gulf of Gdańsk. The right salinity and oxygen conditions are of great importance for animals inhabiting bottom waters. For example, Baltic cod, for which the Gdańsk Basin is an important spawning ground, need a salinity of > 11 PSU and an oxygen concentration of > 2 ml l^{-1} (Żmudzinski 1994). Oxygen depletion due to consumption in the deep layers causes oxygen deficiencies and the production of hydrogen sulphide (cf. e.g. Trzosińska & Cyberska 1992, Trzosińska & Łysiak-Pastuszak 1996). After a long period of stagnation this situation can change as a result of saline waters flowing in from the North Sea.

The water and mass exchange between the Gulf of Gdańsk and the Baltic Proper can be assumed to be a basic source from which saline, oxygen- and nutrient-rich waters can renew the Gulf's ecosystem. Therefore, a better understanding of this process will provide better predictions in the marine environment. It also seems important to evaluate the anemobaric conditions which may favour the restoration of the Gulf's waters.

2. Material and methods

2.1. Model description

The model domain comprises the whole Baltic with its main basins: the Gulf of Bothnia, the Gulf of Finland, the Gulf of Riga, the Belt Sea, the Kattegat and Skagerrak. At the open boundary in the Skagerrak simplified radiation-type boundary conditions were applied. The bottom topography of the Baltic Sea used in the model is based on data from Seifert & Kayser (1995).

The model is based on the free surface baroclinic (σ-coordinate) model of Blumberg & Mellor (1987). A detailed description of the equations and modifications made in order to adapt the model to the Baltic Sea can be found in Jankowski (2002a, b).

The model code solves the finite-difference analog of the set of momentum and mass transport equations, assuming that the fluid is incompressible and hydrostatic, and using the Boussinesq approximation after its transformation to the σ-coordinate system ($\sigma = \frac{z-\eta}{H+\eta}$, where η is the deviation of the free surface from its equilibrium position ($z = 0$) and H is the equilibrium depth of the water column). A 'C' numerical grid (Mesinger & Arakawa 1976) is applied.

Because the model has a free surface and can thus include atmospheric-induced sea level variations as well as free surface gravity waves, time integrations are split into a two-dimensional (2-D), external mode with a short time-step based on the Courant-Friedrichs-Lewy (CFL) stability conditions and calculated using the (fastest) free surface gravity wave speed, and a three-dimensional (3-D), internal mode with a long time-step based on the CFL condition, and calculated using the internal wave speed. Further details concerning the numerical schemas used in the POM code can be found in (Mellor 1993).

In the calculations presented here, horizontal space steps of $\Delta\lambda = 5.4'$ and $\Delta\phi = 2.7'$ (i.e. a grid size of $\Delta x \simeq \Delta y \simeq 5$ km) were used. In the vertical, 24 σ-levels were applied with the distribution: 0.0, −0.00329, −0.00658, −0.01316, −0.02632, −0.05263, −0.10526, −0.15789, −0.21053, −0.26316, −0.31579, −0.36842, −0.42105, −0.47368, −0.52632, −0.57895, −0.63158, −0.68421 −0.73684, −0.78947, −0.84211, −0.89474, −0.94737, −1.0. The time-steps for the external 2-D and internal 3-D calculations were 10 sec and 10 min, respectively.

With a horizontal resolution of ∼5 km and with 24 σ-levels in the vertical, the model enables variability as well as mesoscale features of the order of 10 km of currents and thermohaline fields in the Baltic to be investigated. To date, the model has been demonstrated as suitable for simulating the major features of the Baltic Sea. These include the general circulation and hydrology of the period of the PIDCAP′95 experiment[1] (Jankowski 2002a) and the hydrodynamic conditions relating to the upwelling events in September 1989 (Jankowski 2002b). For futher details on the POM model the reader is referred to Blumberg & Mellor (1987), Mellor (1993), and to Jankowski (2000, 2002a, b) for details of the Baltic version.

Although model runs were performed for the entire Baltic Sea, the presentation of the simulation results is limited to the south-eastern area (18°00′E–20°12′E; 54°12′N–55°18′N) (cf. Fig. 1), where the the Gulf of Gdańsk is located.

2.2. Initial conditions and atmospheric forcings

The model is forced by wind stress, atmospheric pressure, surface heat fluxes and climatological forcings. The last-mentioned are coupled to the model by means of the so-called method of 'relaxation towards climatology' (cf. Oey & Chen 1992, Lehmann 1995, Svendsen et al. 1996, Jankowski 2000, 2002a, b). Hence, the surface boundary conditions for the transport equations take the form:

$$K_v \frac{\partial T}{\partial z} = \frac{Q_T}{\rho_0 c_{pw}} + Q_{TSR}, \quad \text{and} \tag{1}$$

$$K_v \frac{\partial S}{\partial z} = \frac{Q_S}{\rho_0} + Q_{SSR}, \tag{2}$$

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[1] Pilot Study for Intensive Data Collection and Analysis of Precipitation

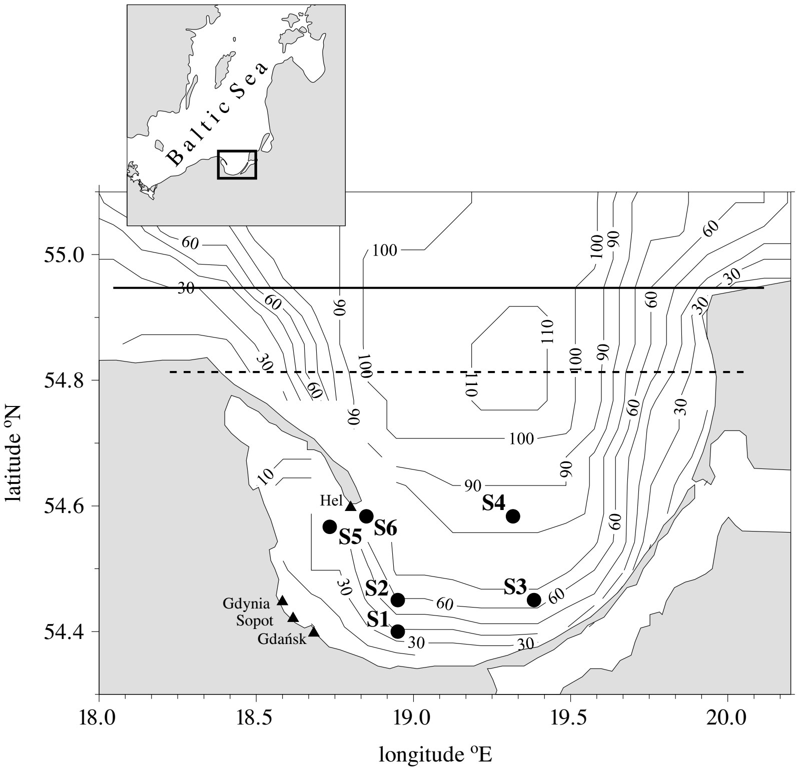

Fig. 1. The study area and location of the vertical hydrographic sections and the selected points used to visualize the results of the model calculations. The solid line indicates the location of the vertical sections to visualize variability in water salinity. The dashed line indicates the location of the open boundary of the Gulf of Gdańsk for calculating the residence time and water exchange between the Gulf of Gdańsk and the Baltic Proper The bottom topography of the south-eastern Baltic was elaborated from data from Seifert & Keyser (1995). The numbers on the isolines indicate the depth in meters

where z is the vertical coordinate (positive upwards), ρ_0 is the water density, c_{pw} is the specific heat capacity of seawater, T, S represent the sea water temperature and salinity, K_V is the vertical eddy diffusivity, and Q_T, Q_S are heat and salinity fluxes.

The terms (Q_{TSR}, Q_{SSR}) in eqs. (1) and (2) express additional climatological heat and salinity fluxes used to drive the model in the case when real fluxes are very small, impossible to estimate from meteorological data, or absent altogether. These additional surface heat and salinity fluxes Q_{TSR}, Q_{SSR} are estimated as follows (Jankowski 2002a, b):

$$Q_{TSR} = C_{TC}(T_c - T_1); \qquad Q_{SSR} = C_{SC}(S_c - S_1), \tag{3}$$

where C_{TC}, C_{SC} are relaxation constants, T_1, S_1 are the respective calculated values of temperature and salinity in the surface layer, and T_c, S_c are the respective climatological values of temperature and salinity at the sea surface.

The values of relaxation constants C_{TC}, C_{SC} were chosen to be equal to $C_{TC} = 2$ m days^{-1} and $C_{SC} = 20$ m days^{-1}, respectively. This means that during weak forcing (or without it) the temperature and salinity in the uppermost 1 m layer return to the climatological values T_c, S_c on time scales of 2 days and 20 days, respectively.

The calculation was initiated from the climatological data for September. The initial 3-D fields of the seawater temperature T and its salinity S in September were constructed from the monthly mean (multi-year averaged) maps taken from Bock's (1971) and Lenz's (1971) atlases and additional *in situ* data from the Regional Oceanographic Database of IO PAS (http://www.iopan.gda.pl) recorded in September for several years.

The climatological forcings for September were calculated in the same way as in Jankowski (2002b). The two-dimensional fields of the temperature T and salinity S at the sea surface for September 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.

The model was forced by winds and atmospheric pressure and surface heat fluxes estimated from the meteorological data taken from BED (2000).

The meteorological data to calculate real atmospheric forcings (atmospheric data: pressure, air temperature, relative humidity) were taken from BED (2000) for the entire period of simulation (from 1 to 30 September 1989). The meteorological data, which were provided every 3 h on a 1° x 1° grid, were mapped onto a numerical model grid by bi-linear interpolation.

In order to estimate the wind stress components (τ_x^s, τ_y^s) and the heat flux at the sea surface (Q_T) the standard way of utilizing the bulk formula commonly used in modelling was applied (cf. e.g. Oey & Chen 1992, Lehmann 1995). For details the reader is referred to Jankowski (2002a, b).

Fig. 2 illustrates the wind conditions – exemplary time series of wind directions (Fig. 2a) and speeds (Fig. 2b) at selected points in the Gulf of Gdańsk (19°20′E; 54°50′N) for the period 1 to 30 September.

From this figure it follows that wind forcing over the coastal area in September 1989 can be roughly characterized by a number of phases. Winds from NW were dominant during the first phase (1 to 7 September), with short interruptions on 1 and 4 September. On 8 September the wind veered E backing NE and continued to blow from that sector for the rest of the second phase until 12 September. On that day the winds backed rapidly

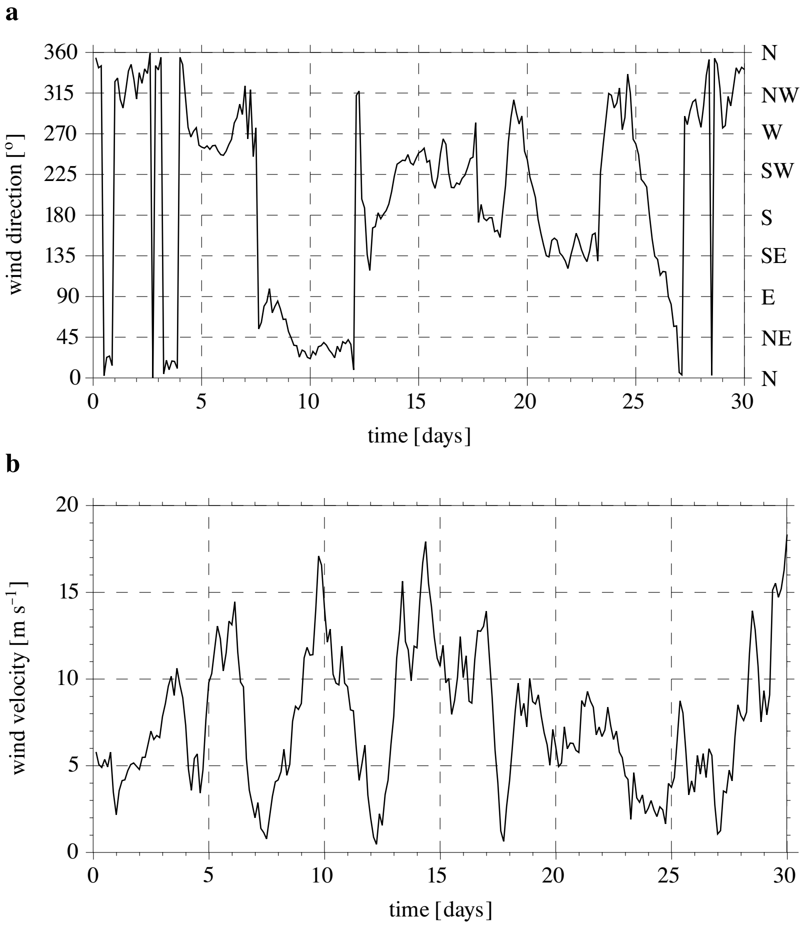

Fig. 2. Time history of wind direction [°] (a) and wind speed [m s^{-1}] (b) during simulation with real atmospheric forcings

to NW (W), after which the wind direction fluctuated from S to W for 1–2 days followed by winds from SE (from 21 to 23 September). On 24 September the wind rapidly changed direction to N , NW and SW until the end of the month, with an interuption to NE on 27 September. The wind speed fluctuated with a period of 2–3 days and an amplitude ranging from 3 to 7 m s^{-1}.

Besides the real meteorological forcing, spatially uniform winds from 8 directions were also considered. The winds from 8 directions: SE, S, SW, W, NW, N, NE and E were of constant speed (the wind stress was assumed to be 0.1 N m^{-2}) over the whole Baltic area. An example of wind stress time history during numerical simulations for the case of a W wind is presented in Fig. 3.

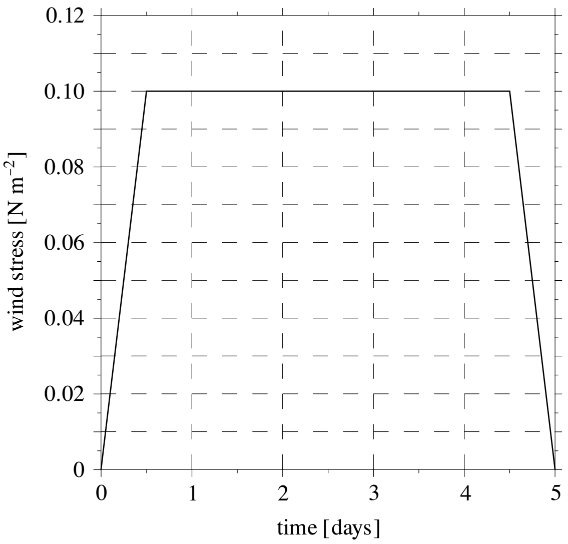

Fig. 3. Time history of wind stress in experiments with homogenous wind fields

2.3. Methodology and strategies of computations

The model simulations were performed in two stages. In both stages the river runoff rates (assumed as yearly means) of the main rivers of the Baltic Sea catchment area were taken into consideration.

The first stage, a pre-processing run of 20 days' duration, was used to initialize the model computations. At this stage the model started from the three-dimensional initial distribution of temperature and salinity and was forced only by the climatological forcings, without external atmospheric forcings i.e. without wind stress, atmospheric pressure or surface heat fluxes. The initial fields of sea level η, current velocity vector component u, v, w and the mean-depth current components U, V were set equal to 0. The climatological forcings were coupled to the model by means of the 'relaxation towards climatology' method and at this stage the boundary conditions (1) and (2) for transport equations took the simplified form:

$$K_v \frac{\partial T}{\partial z} = Q_{TSR} = C_{TC}(T_c - T_1), \tag{4}$$

$$K_v \frac{\partial S}{\partial z} = Q_{SSR} = C_{SC}(S_c - S_1). \tag{5}$$

An adaptation of the model dynamics to initial fields and climatology was achieved by a forward integration of the model equations over a period of 20 days once a quasi-stationary state had been reached.

The second stage was started from the previous stage's final results. and consisted of a fully prognostic run. Besides climatological forcings the model was forced by real atmospheric forcings (atmospheric pressure, winds and heat fluxes) for a period of 30 days (1 to 30 September 1989). At this stage the transport equations for heat and salt were solved with the surface boundary condition (1) and (2) in full form. In the simulations presented here, the salinity flux Q_S at the sea surface was assumed negligible and was set equal to 0. In the case of the model wind fields (uniform in space) the second stage simulations were performed as in the first stage, except that now, the climatological forcings and the constant wind stress were applied to the whole sea. Thus, the transport equations for heat and salt were solved with the the simplified form of the surface boundary condition (4) and (5).

3. Model results and discussion

Two variants of atmospheric forcing were considered – real atmospheric forcing for the period from 1 to 30 September 1989, and the model one, with winds of spatially uniform wind stress over the whole Baltic basin. The latter was considered in order to understand better the role of wind forcings as the separate forcing component (factor).

3.1. Real atmospheric forcing

The model simulation was run for a period of 30 days with real atmospheric forcings for September 1989. The calculations started with the results of the first stage, i.e. from the 'climatic state' of the sea's hydrology obtained after 20 days of calculations without atmospheric forcings (see section 2.3 for details of the computation strategy).

In order to test the reliability of the model, the model results were compared with measurements.

The vertical distribution of temperature and salinity was chosen as the best way of visualizing the results of the model simulation and to test the model's capability of reproducing the thermohaline variability due to real forcings.

The model results were compared with the *in situ* measurements (vertical soundings of temperature and salinity at a number of hydrographic stations in the Gulf of Gdańsk) collected during the cruise of r/v 'Oceanograf' in September 1989[2]. Their distribution in the Gulf of Gdańsk is shown in Fig. 1. The hydrographic stations chosen for the model verification represent thermohaline variability in relation to different bathymetric conditions in the Gulf.

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[2] The data were obtained from the Institute of Oceanography of the University of Gdańsk as a result of a bilateral cooperation agreement and were made available by Dr. J. Jędrasik.

For the purpose of visualization, the model results were interpolated by cubic spline (Forsythe et al. 1977) from σ-levels onto 'z' – levels with a space step of 2 m.

Fig. 4 depicts exemplary vertical profiles of the modelled sea water temperature and salinity in some regions of the Gulf. Besides the model results, the figure also shows the *in situ* measured temperature and salinity profiles.

In order to evaluate the quantitative model results versus *in situ* observations standard statistical criteria were calculated: (i) the correlation coefficient (cor), (ii) the average error (ae), (iii) the average absolute error (aae), (iv) the root mean squared error ($rmse$) and (v) the model efficiency coefficient (ef), frequently used in ecological modelling (cf. e.g. Mayer & Butler 1993):

$$ef = 1 - \frac{\sum_{i=1}^{N} (Y_i^m - Y_i^p)^2}{\sum_{i=1}^{N} (Y_i^p - \overline{Y}^p)^2}, \tag{6}$$

where N – number of measurement levels in the vertical profile, Y_i^m, Y_i^p – the ith of N modelled and *in situ* measured temperature or salinity at the ith-level, and $\overline{Y}^m$, $\overline{Y}^p$ are the modelled and measured averages of temperature or salinity, respectively.

As is known the correlation coefficient cor measures the tendency of the modelled and observed values to vary together linearly or similarly. The root mean squared error, average error, and average absolute error are all measures of the magnitude of the discrepancies between predicted and observed values. The modelling efficiency coefficient ef (6) shows how well a model predicts relative to the average of the observations. Values of it less than zero indicate that the measurement average would be a better predictor than the model results. If its value is around unity, this indicates a close match between measured and model results. A value close to zero indicates that the model predicts individual observations no better than the average of the observations.

The estimates of ae, aae, cor, $rmse$ and ef for the temperature and salinity profiles at selected points S1–S6 (cf. Fig. 4) are presented in Table 1. Comparison of the computed and measured temperature and salinity vertical profiles shows (cf. Fig. 4) that the model reproduces the vertical structure of seawater temperature and salinity in relatively good agreement with the *in situ* observations. The results depicted in Fig. 4 and estimates of statistical criteria presented in Table 1 show that the degree of agreement between observations and computed data depends on the regional scale of bottom structures (location of observation point). This is clearly visible in the case of point S6.

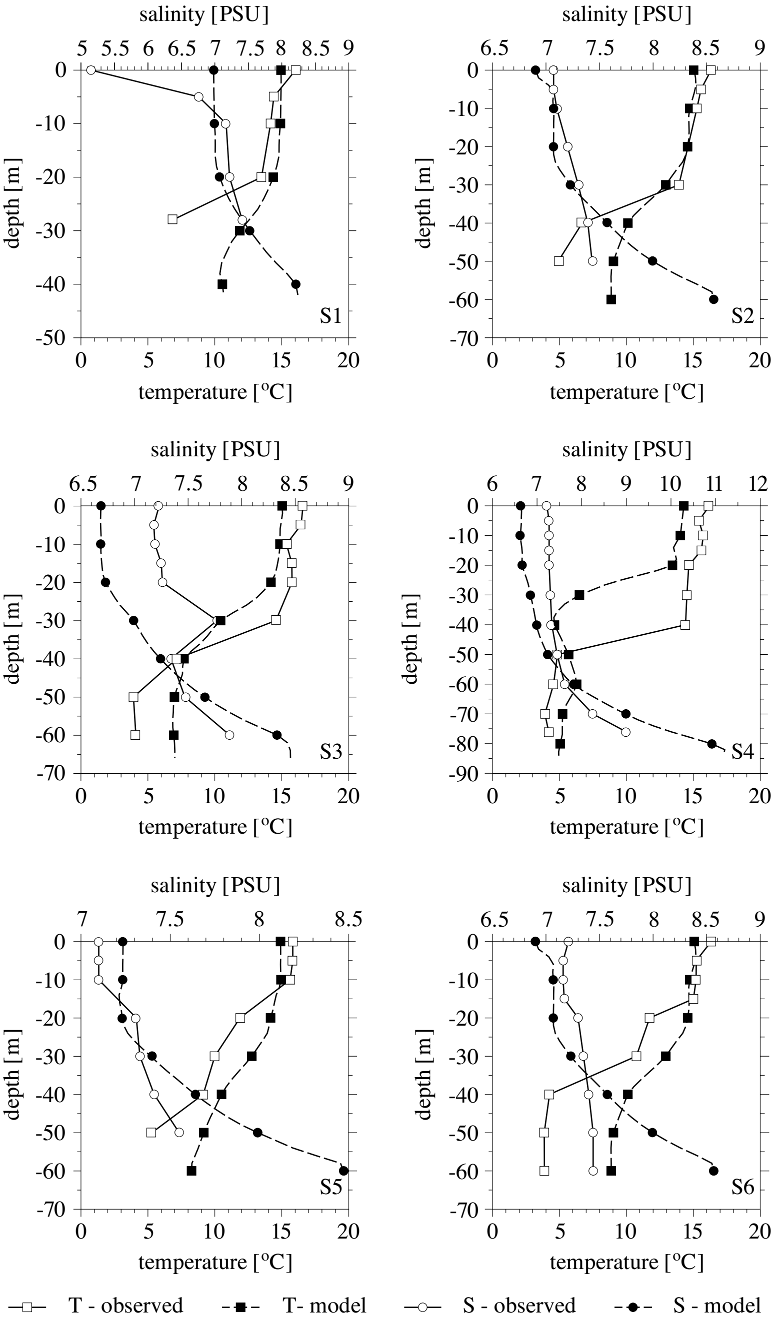

Fig. 4. Modelled and *in situ* measured vertical distributions of temperature and salinity at selected hydrographic stations S1–S6 in the Gulf of Gdańsk. For details of their locations – see Fig. 1. *In situ* measurements from the cruise on 18–19 September 1989 of r/v 'Oceanograf' (see text for details)

Table 1. Values of statistical criteria calculated for the verification of modelled temperature and salinity profiles at selected points in the Gulf of Gdańsk (*cov* – the correlation coefficient, *ae* – the average error, *aae* – the average absolute error, *rmse* – the root mean squared error, *ef* – the model efficiency coefficient (eq. (6))

	Salinity					Temperature				
Point	*aae*	*ae*	*cor*	*ef*	*rmse*	*aae*	*ae*	*cor*	*ef*	*rmse*
S1	0.17	0.046	0.90	–1.92	0.24	1.54	0.61	0.98	0.75	2.13
S2	0.46	–0.32	0.79	–3.07	0.51	1.86	–0.43	0.95	0.82	2.19
S3	0.48	0.35	0.50	–0.021	0.83	2.26	1.82	0.98	–0.19	3.48
S4	0.54	–0.19	0.99	–0.21	0.59	2.80	–1.91	0.73	0.40	4.05
S5	0.17	0.15	0.88	–0.64	0.21	1.83	1.11	0.95	0.68	2.13
S6	0.31	0.10	0.82	–14.60	0.45	2.58	2.10	0.98	0.56	3.34

In the next figure (Fig. 5) the calculated basin-averaged salinity is presented for the case of realistic atmospheric forcings relating to September 1989 (see Figs. 2a, b for wind conditions). Fluctuations are in the range of +/–0.4 PSU and are well correlated with the variability in wind directions (Fig. 2a). Its temporal variations correspond to fluctuations of wind speed (Fig. 2b).

The volume transport of saline water through the hydrographic vertical section along the open boundary of the Gulf of Gdańsk has been computed (see Fig. 1 – for its location). Fig. 6 depicts the net flux in $\mathrm{m}^3\ \mathrm{s}^{-1}$ of water with salinity > 9 PSU calculated for the real anemobaric situation. Negative values indicate volume transport into the Gulf. The model data calculated for September 1989 are well synchronized with the timing and duration of variations in speed, and, especially, changes in wind direction (cf. Figs. 2a, b).

The overall water exchange between the Gulf and the Baltic Proper as well as the exchange of saline bottom waters appear to depend strongly on wind conditions. The net flux of water with salinity > 9 PSU was of the order of 48 000–100 000 $\mathrm{m}^3\ \mathrm{s}^{-1}$ for the September 1989 simulation (Fig. 6).

Fig. 7 depicts the salinity distribution on selected days: 6, 13 and 16 September. These relate to a specific situation – the outflow (6 and 16) or inflow of deep saline water (cf. Fig. 6) and, obviously, to abrupt changes in wind direction (cf. Fig. 2a). The isohaline layout shows a strong halocline in the depth range 45–65 m with its bottom boundary at the 9.0 PSU isohaline. Below it, the fluctuations of the isohalines depend strictly on inflow/outflow conditions. It is easy to see that the more remarkable variations are close to the western and eastern boundaries of the section. The isoline distribution

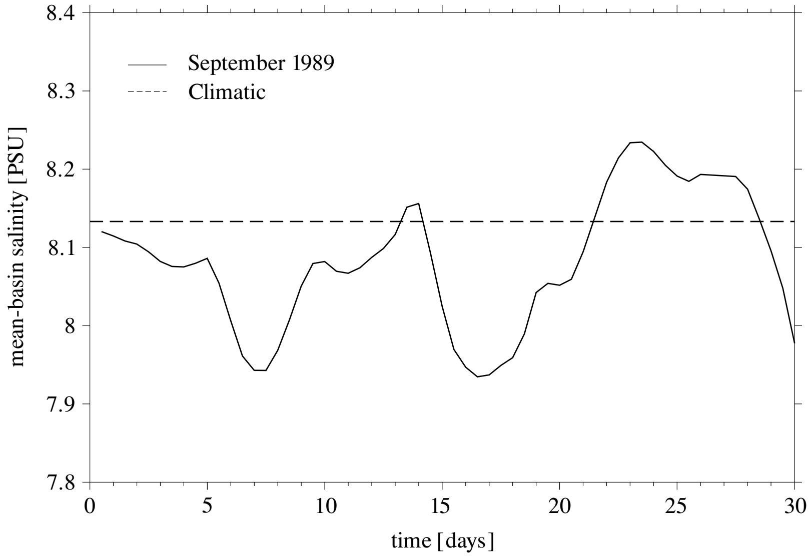

Fig. 5. Mean-basin salinity [PSU] in the Gulf of Gdańsk calculated with real atmospheric forcings

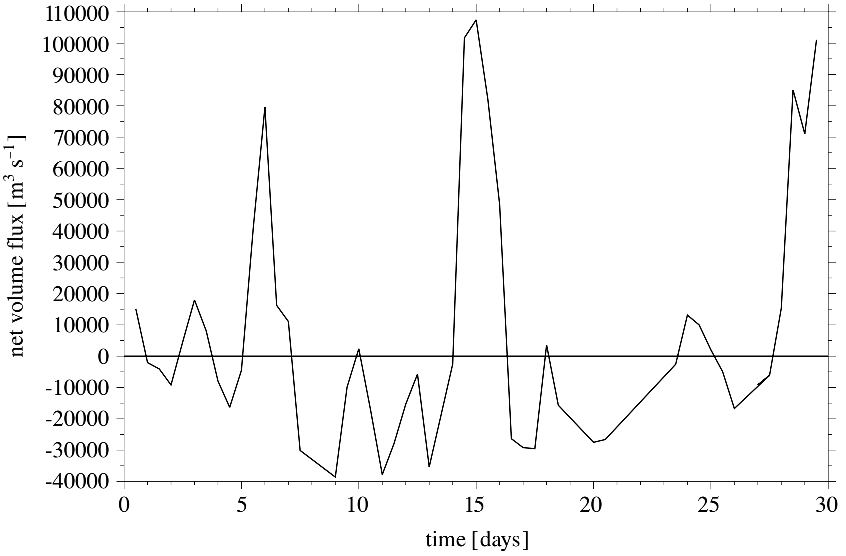

Fig. 6. Net volume flux [m^3 s^{-1}] of water of salinity > 9 PSU through the open boundary of the Gulf, calculated with real atmospheric forcings. Positive values – outflow towards the open sea; negative values – inflow into the Gulf of Gdansk. See Fig. 1 for location of boundary

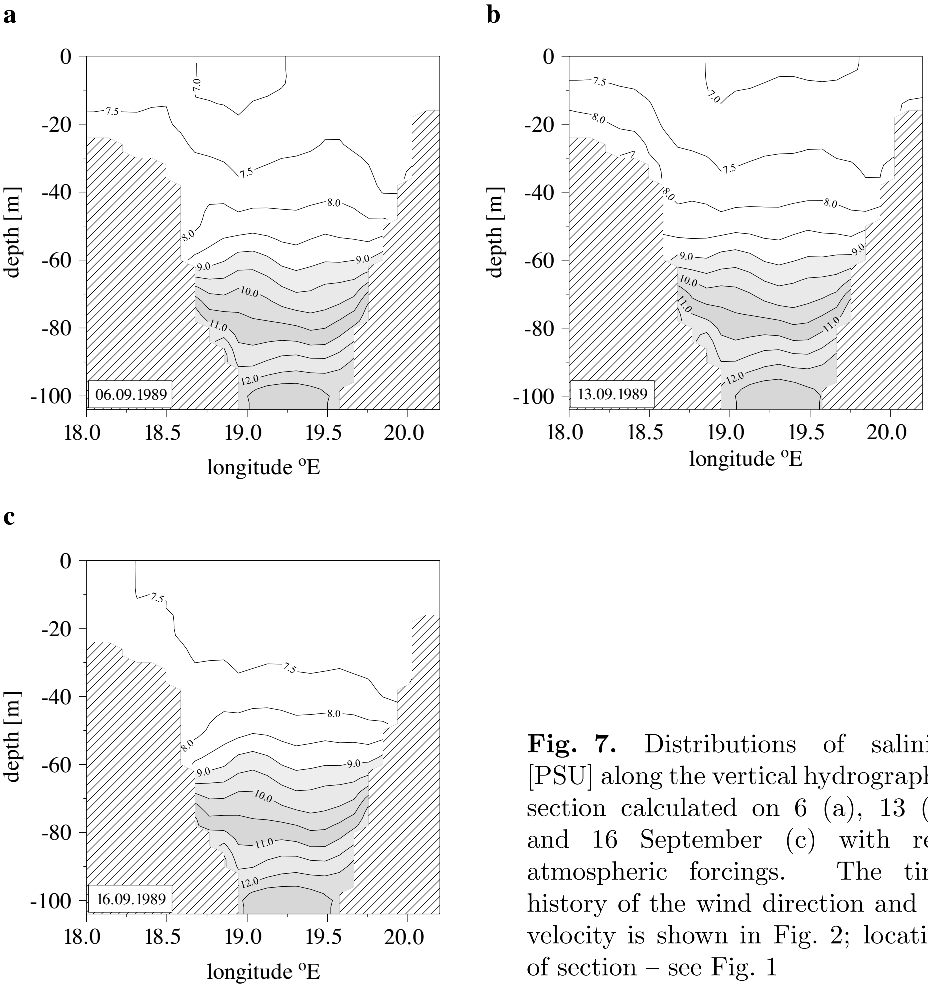

Fig. 7. Distributions of salinity [PSU] along the vertical hydrographic section calculated on 6 (a), 13 (b) and 16 September (c) with real atmospheric forcings. The time history of the wind direction and its velocity is shown in Fig. 2; location of section – see Fig. 1

indicates the existence of coastal jets along both boundaries. These findings may be more clearly visible in the horizontal salinity distribution.

To complete the spatial picture of the salinity regime in the Gulf of Gdańsk and to support the findings to date, the calculated fields of salinity distribution at 65 m depth on 6, 13 and 16 September as well as for the ‘climatic’ (without wind) case as shown in Fig. 8. It may be seen from the figures that saline water (salinity >9 PSU) enters the Gulf of Gdańsk in two areas, which can be assumed to be a source of deep saline waters. One, located at the north-western edge of the Gulf, can be regarded as a source of direct waters from the Słupsk Furrow (i.e. the Gulf of Gdańsk (Basin) can be regarded as a buffer zone/area (Elken 1996)), which enter the Gulf along the Hel Peninsula, under the influence of bottom relief variations. The other source of deep saline waters lies in the south-eastern part of the

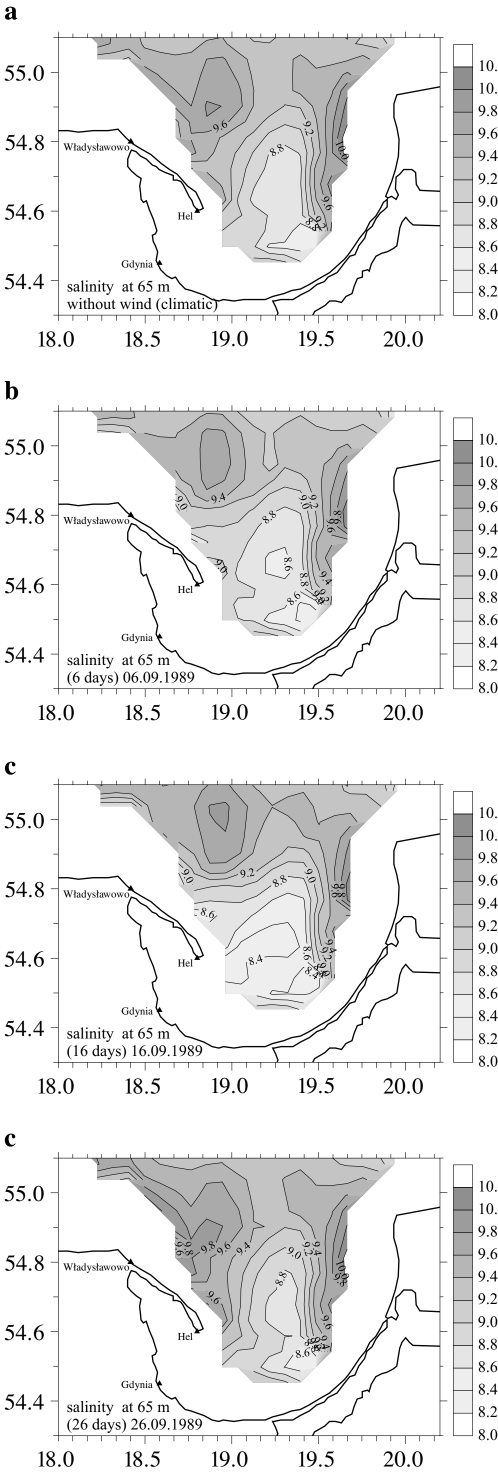

Fig. 8. Simulated seawater salinity [PSU] at 65 m depth – climatic (a), calculated without wind and on 6 (b), 13 (c) and 16 September (d), calculated with real atmospheric forcings

Gulf. This one supplies saline waters from the east, i.e. from the deeper north-eastern part of the Gdańsk Basin (Eastern Gotland Basin), i.e. not directly from the Słupsk Channel. These waters can be assumed to be 'old, resident' waters in the Gdańsk Deep, which had spread into the Gulf under favourable inflow (anemobaric) conditions. Such conditions can be observed during the periods of W and SW winds (cf. Fig. 2a). When winds blow from the SE and E, the inflow of saline waters directly from the Słupsk Furrow seems to be more significant.

3.2. Model atmospheric forcing

In order to achieve a better understanding the role of wind forcings as a separate forcing factor in shaping the salinity regime in the Gulf of Gdańsk, simulations with winds from 8 directions (E, N, W, S, SE, SW, NE and NW) and of a constant wind stress over the Baltic were considered. The model runs were performed over a period of 5 days starting from the 'climatic' state as in the case of real atmospheric forcings. An example of temporal

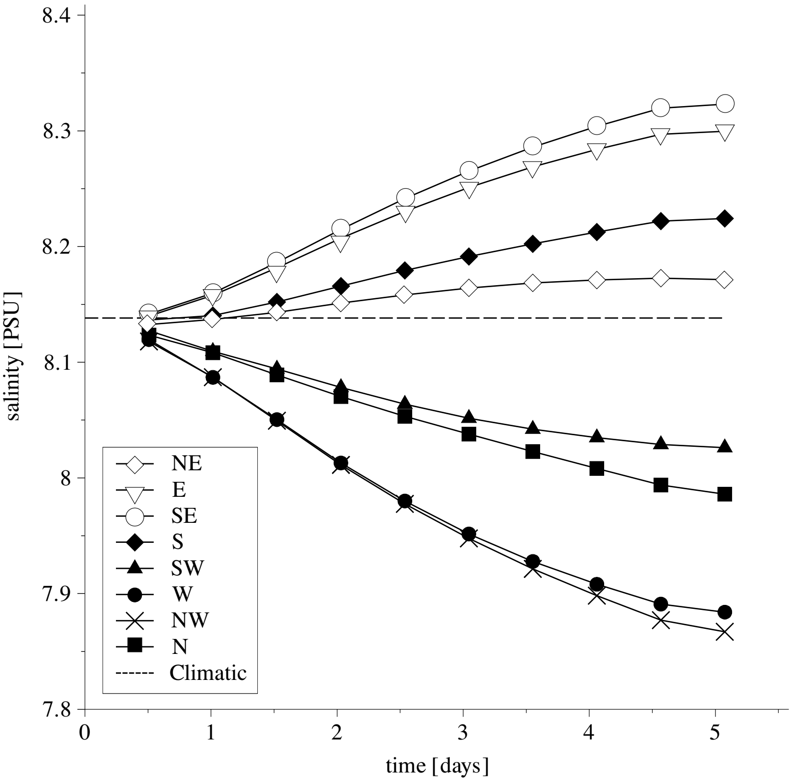

Fig. 9. Mean-basin salinity [PSU] in the Gulf of Gdańsk estimated in experiments with homogeneous wind fields

variations in wind stress during the numerical simulations for the case of a W wind is presented in Fig. 3. The results of the numerical simulations are presented in the same manner as for real atmospheric forcings.

Fig. 9 depicts time series of the basin–mean salinities in the Gulf calculated for winds blowing from all 8 directions (S, W, E, N, SE, SW, NE and NW). From this figure it can be seen that the wind from sectors S, SE, E and NE are more likely to increase the salinity in the area. Winds from the other directions have the opposite effect, causing a drop in the overall salinity regime.

As in the case of real atmosperic forcings, the net flux (transport) through the vertical hydrographic section located at the open boundary of the Gulf of Gdańsk has been estimated from the model results. (location of section – see Fig. 1). Fig. 10 illustrates the net flux in m^3 s^{-1} of water

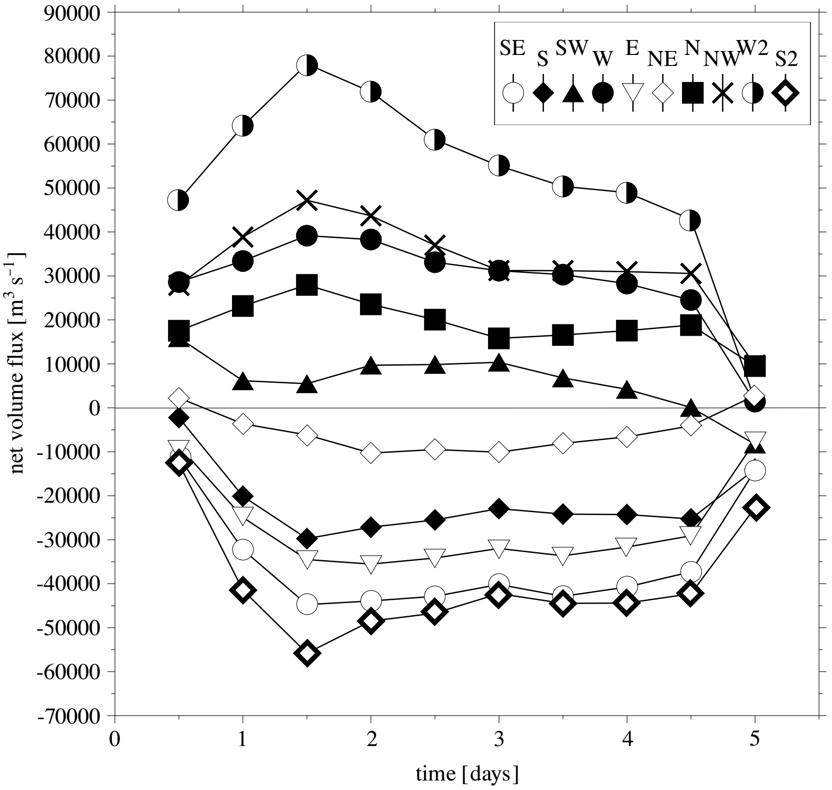

Fig. 10. Net volume flux [m^3 s^{-1}] of water of salinity > 9 PSU through the open boundary of the Gulf estimated in experiments with a homogeneous wind with a stress equal to 0.1 N m^{-2} and, additionally, 0.2 N m^{-2} for S and W winds (curves S2 and W2). Positive values – outflow towards the open sea; negative values – inflow into the Gulf of Gdansk. See Fig. 1 for location of boundary

of salinity > 9 PSU calculated for the case of a homogeneous anemobaric situation (uniform wind stress). Negative values indicate transport into the Gulf. It is seen that in the case of uniform winds, the net saline water volume range is +/–50 000 $\mathrm{m}^3\ \mathrm{s}^{-1}$. The results of additional simulations for strong S and W winds, with a wind stress equal to 0.2 N m^{-2}, were added (Fig. 10, curves W2 and S2). As expected, the maximum transport of saline water almost doubled.

From the above figure it follows that SE, E, NE and S winds are more favourable to the inflow of saline bottom waters into the Gulf. Comparison

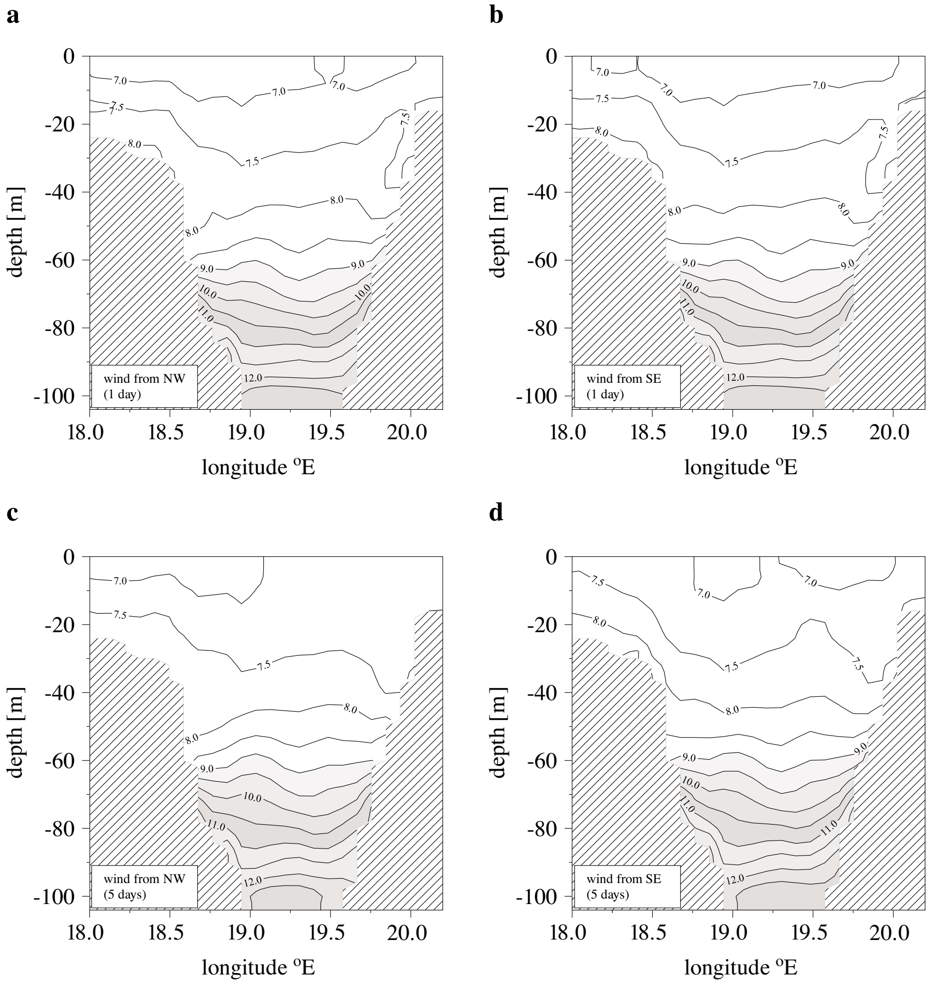

Fig. 11. Distributions of salinity [PSU] along the vertical hydrographic section, after 1 and 5 days of NW (a, c) and SE (b, d), spatially uniform winds. The time history of wind stress is shown in Fig. 3; location of section – see Fig. 1

with Fig. 9 shows that the inflow of saline waters into the Gulf is greatest when winds are from the SE, whereas the opposite situation, the largest outflow of saline waters from the Gulf, occurs when winds are from the NW.

Fig. 11 presents the distribution of salinity along the vertical hydrographic section at the entrance to the Gulf of Gdańsk (see Fig. 1 for location of section). Figs. 11 a–d depict the salinity distribution after a period of 1 and 5 days of SE and NW winds, respectively. These wind directions are related to the highest rise and fall in mean-basin salinity shown in Fig. 9, i.e. when they are related to the best/worst inflow/outflow event (cf. Figs. 9 and 10). As mentioned above, in the case of real atmospheric forcing, there is a strong halocline in the depth range 45–65 m with its lower boundary lying along isohaline 9.0 PSU. Below it, the variations in isohalines depends strictly on inflow/outflow conditions (cf. Fig. 10).

The same conclusions can be drawn regarding the behaviour of the salinity distribution under homgeneous winds as for real atmospheric conditions. Clearly, the more remarkable variations are close to the western and eastern edges of the section. From the layout of the isolines it follows that there are coastal jets along both sides of the vertical section.

The salinity distribution fields at 65 m depth for SE and NW winds after 1 and 5 days of model calculations, respectively, presented in Fig. 12, complete the spatial salinity picture in the deep layer of the Gulf. As for real atmospheric conditions, it can be seen from Fig. 12 that saline water (salinity > 9 PSU) enters the Gulf of Gdańsk in two regions. Two sources of saline waters are located in the same regions of the Gulf of Gdańsk. From a comparison of the horizontal distribution of salinity at 65 m depth after 1 and 5 days, respectively, it follows that winds from SE favour the inflow of saline waters in both regions of the Gulf.

3.3. Residence time[3]

A knowledge of water exchange processes is necessary in order to understand physical, chemical and biological processes in a sea basin, and the mixing time may be particularly important when estimating chemical or biological fluxes or in ecological budget calculations.

In aquatic systems, where most of the living biomass and masses of nutrients, contaminants, dissolved gases and suspended particles are carried in a fluid medium, it is essential to understand the hydrodynamic processes

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[3] Residence time estimation was suggested by Prof. G. E. Millward from the Department of Environmental Sciences, University of Plymouth, Drake Circus, Plymouth, PL48AA, United Kingdom, during the ECSA34 Symposium, 25–29 September, 2002, Gdańsk.

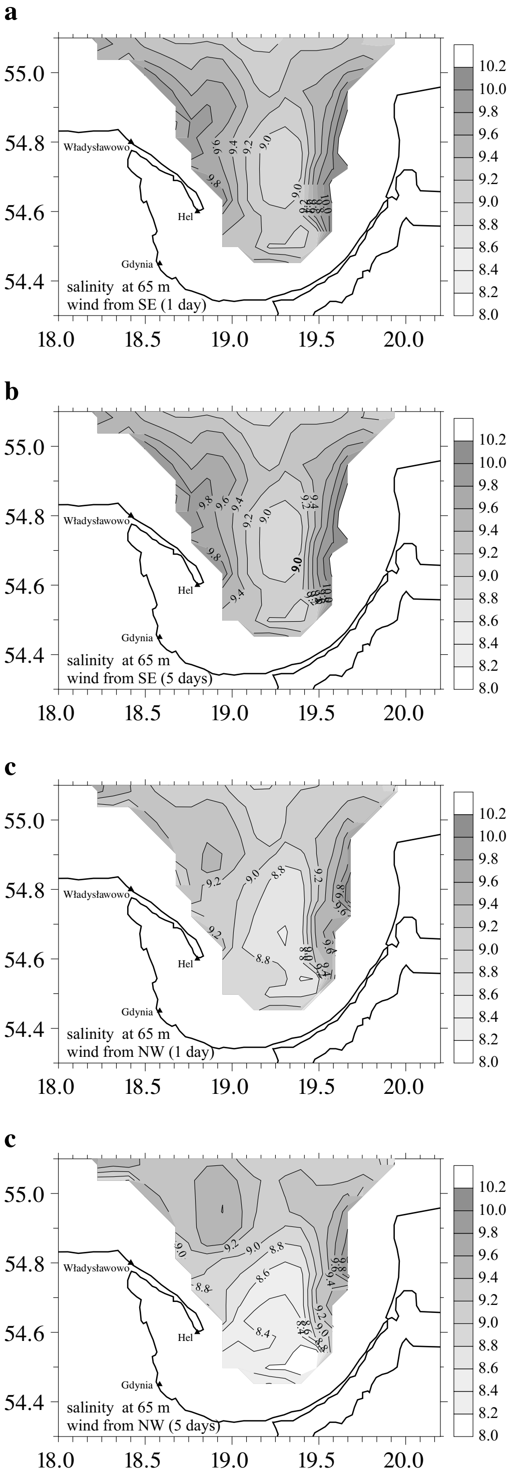

Fig. 12. Simulated seawater salinity [PSU] at 65 m depth after 1 and 5 days of calculations with homogeneous SE (a, b) and NW (c, d) winds

that transport water and its constituents. A first-order description of transport can be expressed as 'residence time' or 'flushing time', which may serve as measures of water mass retention in the basin. It is assumed that residence time is such an important attribute that it should be the basis for comparative analyses of ecosystem-scale nutrient budgets (cf. e.g. Bolin & Rhode 1973, Dick & Schönfeld 1996, Monsen et al. 2002, Rasmussen & Josefson 2002). The residence (or flushing) time τ_{Fl} used to characterize the water exchange of a certain sea area can be defined as the ratio of the water volume of a sea basin V_0 to the flux through the boundaries of the area F_b (cf. Dick & Schönfeld 1996, Monsen et al. 2002, Rasmussen & Josefson 2002):

$$\tau_{Fl} = \frac{V_0}{F_b}. \tag{7}$$

For the purposes of this study, the concept of residence time is used to round off the above discussion of the results of wind-induced water exchange between the Gulf of Gdańsk and the Baltic. From the point of view of a biologist or an ecologist, the estimated residence time may serve as a mixing time scale in biogeochemical processes for calculating mass balances in the Gulf of Gdańsk.

In our calculations the boundary of the Gulf of Gdańsk was located along the dashed line in Fig. 1. The mean volume of the Gulf of Gdańsk $V_0 = V_{zg}$, estimated from the model results, was equal to 264.9 km^3.

Five (5) inflow/outflow rates were considered as the flux through the open boundary of the Gulf: F_{FS} – the net flux of saline water of salinity > 9 PSU, F_{Fout} – the flux of the total outflow rate of water, F_{Fin} – the flux of the total inflow rate of water, F_{FSout} – the flux of the outflow rate of saline water of salinity > 9 PSU, and F_{FSin} – the flux of the inflow rate of saline water of salinity > 9 PSU.

The residence times were estimated only for the case of homogeneous wind conditions. The calculated residence times (in days) for the saline water (salinity > 9 PSU) are displayed in Table 2.

Analysis of Table 2 shows that saline water residence times τ_{FSin} based on model simulation results take values from 46 days for a SE wind to 153 days for a NW wind, respectively. It is worth noting that the estimated residence times τ_{Fout} and τ_{Fin}, i.e. the mixing time scales for the total outflow and total inflow fluxes, yielded almost the same results. This finding confirms that during simulations with uniform winds the stationary regime

Table 2. Mean residence time estimates [days] (eq. (7)) based on the results of calculations with homogeneous wind from eight directions. Negative values indicate estimates relating to influxes into the Gulf of Gdańsk. For further explanations – see text

Wind	S_0	τ_{FS}	τ_{Fout}	τ_{Fin}	τ_{FSout}	τ_{FSin}
direction	[PSU]	[days]				
1	2	3	4	5	6	7
SE	9.0	–72.2	12.9	–13.0	130.0	–46.4
E	9.0	–91.6	12.9	–13.0	118.5	–51.6
NE	9.0	–379.8	15.8	–15.7	93.5	–74.4
N	9.0	158.0	19.6	–19.5	66.2	–117.4
NW	9.0	85.8	17.6	–17.5	53.9	–152.7
S	9.0	–120.7	15.1	–15.4	110.8	–57.6
SW	9.0	432.0	16.2	–16.4	73.6	–90.9
W	9.0	93.3	15.8	–15.8	54.9	–137.0

of water exchange between the Gulf of Gdańsk and the Baltic Proper approaches 2–3 days. Thus, it makes our estimations of residence times using the 5-days runs more reliable. Only one estimate of residence time for the Gulf of Gdańsk was found (Witek et al. 2000). The average residence time of the Gulf, based on the annual averaged salinity and water exchange for the period from 1993 to 1998, was estimated to be approximately 80 days.

4. Conclusions

The 3-D circulation baroclinic model of the Baltic Sea, based on the Princeton Ocean Model code of Mellor (1993), was applied to study the circulation, water exchange and renewal of saline water masses in the Gulf of Gdańsk. Real meteorological forcing for September 1989 as well as winds from 8 directions with stress, uniform in space over the sea, were used.

Model simulations allowed us to discover some characteristic features of the water and salt exchange between the Gulf and Gdańsk and the Baltic:

- The renewal of saline water in the Gulf of Gdańsk is a combined effect of wind and density-driven flow of bottom water.
- Whereas the thermohaline flow is slow (but persistent), winds can produce sufficiently strong enough currents in the bottom layers and can thus be very efficient in transporting saline waters into the basin.
- The renewal of deep saline water in the Gulf of Gdańsk is more likely when winds are from the SE.

- Two sources of saline waters have been found – one is related to the direct inflow from the Słupsk Furrow along the Hel Peninsula, the other is located in the southeastern (eastern part) of the Gulf. The latter is assumed to be related to the inflow of saline water from the other, deeper region of the Gdańsk Basin, so this water can be treated as 'old', not so oxygen-rich saline water.

Although the calculations were performed only for the climatic thermohaline conditions for September and the real atmospheric conditions in September 1989, the results produced some new, general findings that may be useful for a better understanding of the water exchange dynamics and origin or sources of saline waters in the Gulf of Gdańsk. The results of some of these investigations will be discussed in future papers.

However, more detailed investigations of model current fields are needed as well as new calculations for other seasons and real atmospheric conditions. Of course, more results of *in situ* measurements are indispensable for improving the model and making its results more reliable.

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