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GENERATION OF MESOSCALE CYCLONIC EDDIES IN THE BALTIC SEA WITH INFLOW EVENTS

Abstract

A sigma-coordinate ocean model, by Blumberg and Mellor (POM), is applied to study the formation processes of mesoscale cyclones observed in the Baltic Sea, following the inflow events. The initial conditions simulate a situation when the Arkona and Bornholm Basins (or Arkona Basin solely) are already filled with the inflow water of the North Sea origin, while the rest of the sea still contains the old water of pre-inflow stratification. The model runs with constant and time dependent northerly/easterly wind, changing the buoyancy forcing, grid geometry and bottom topography, display the following. Entering the East Gotland Basin from the Słupsk Furrow, the bottom intrusion of saline inflow water splits in two: one goes northeast towards the Gotland Deep and the second moves southeast towards the Gulf of Gdańsk. An intensive mesoscale cyclonic eddy carrying the inflow water is generated just east of the Słupsk Furrow with the inflow pulse. A number of smaller cyclones, with boluses of the inflow water, form in the intermediate layer along the saline intrusion pathway to the Gotland Deep. A similar cyclonic eddy is generated in the Bornholm Basin with the inflow pulse from the Arkona Basin. Following Spall and Price [19], the cyclones are expected to form by the geostrophic adjustment of high potential vorticity inflow water column to a low potential vorticity environment. Some evidence for the PV outflow/inflow hypothesis is obtained in a numerical experiment, with a virtual dam restricting water exchange between the Bornholm and Gotland Basins to the limits of the Słupsk Furrow.

1. Introduction

Inflows of highly saline water from the North Sea are known to be the only way to ventilate deep layers of the Baltic Sea. Zhurbas and Paka [23, 24] report data of closely spaced CTD profiling, which was carried out in the East Gotland Basin in April 1993 just 3 months after a major inflow event in January 1993 [6, 11]. Some tens of miles south-south-west of the Gotland

Deep, they found a concave up and down salinity/density disturbance of the permanent halocline which was interpreted as a mesoscale cyclonic eddy (see Figs. 1, 2). The cyclone contained a "bolus" of highly saline water with salinity as high as 11.47 psu. Since the maximum salinity in the Gotland Deep immediately before the 1993 inflow event was no higher than 11.0 psu [6], the cyclone undoubtedly transferred highly saline water of the inflow origin. Horizontal size of thermohaline disturbance associated with the eddy was estimated at 10-12 km. Since this estimate was based on a single transect available, it should be considered as a lower limit, so that the real size of the disturbance might be slightly larger.

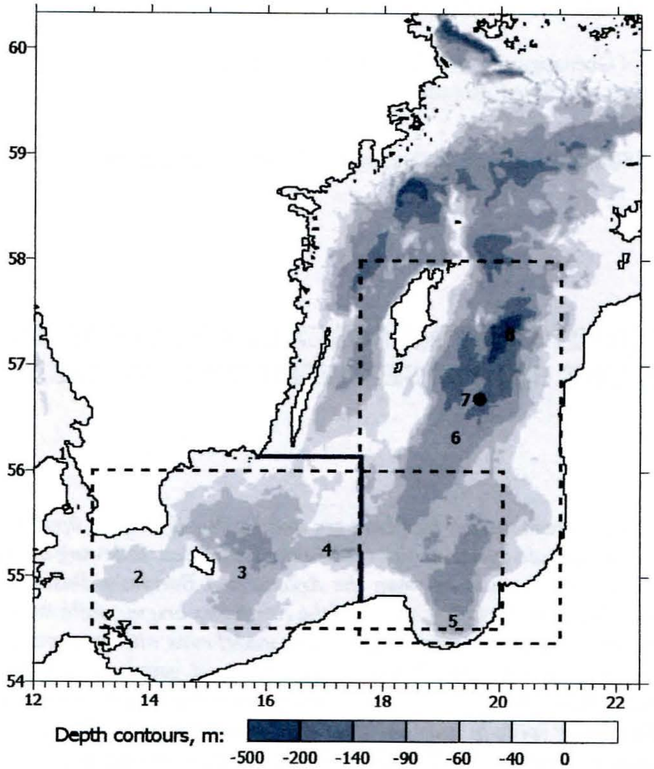

Fig. 1. The Baltic Sea topography.
1 - Sound, 2 - Arkona Basin, 3 - Bornholm Basin, 4 - Słupsk Furrow, 5 - Gulf of Gdańsk, 6 - East Gotland Basin, 7 - position of mesoscale cyclonic eddy observed in April 1993 [23, 24], 8 - Gotland Deep. Dashed rectangles show the fine resolution area of the model domain. Bold gray line is the virtual dam restricting water exchange between the Bornholm and Gotland Basins to the limits of Słupsk Furrow

The objective of this paper is to study the process of mesoscale cyclone formation in the Baltic Sea by way of numerical experiments with a finite-difference ocean circulation model. The philosophy of the numerical experiments is as follows. We will apply the realistic bottom topography of the basin together with idealized wind forcing and initial conditions provided that the idealization accumulates main features of real thermohaline field observed by the inflow event. Doing this, we expect that the model will reproduce mesoscale cyclonic eddies similar to the observed one. As far as mesoscale cyclones are reproduced, we will change the initial conditions, wind forcing, bottom topography, and other model parameters, in order to understand which features of the process are important for cyclonic eddy formation.

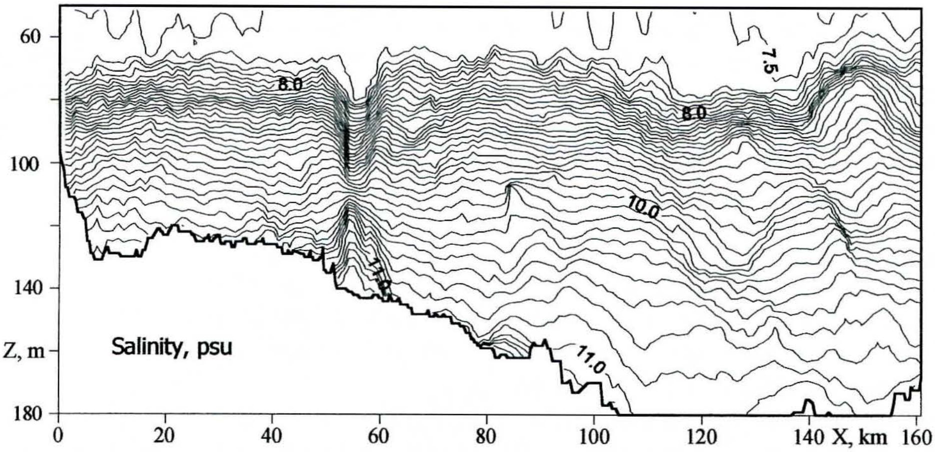

Fig. 2. Salinity versus distance and depths for a closely spaced CTD section in the East Gotland Basin measured in April 1993 after the inflow event (reproduced from [24]). Well pronounced squeezing of isohalines at distance $X = 50 - 60$ km is interpreted as a deep water cyclonic eddy. The position of the eddy is shown in Fig. 1

2. Model Description and Setup

2.1. The model

Several numerical studies of the Baltic Sea circulation have been made during the last decades. Wind driven circulation was studied by Simons [18] and Kielmann [8]. Welander [22], Walin [21], and Stigebrandt [20] analyzed thermohaline circulation in the Baltic basins. Diagnostic computations were performed by Sarkisyan et al. [14].

Since the nineties, the most popular tool to study the Baltic Sea circulation numerically has been a fixed layer ocean circulation model developed at the Princeton University by Bryan [4], Semtner [17] and Cox [5]. This model was implemented to elucidate different aspects of Baltic Sea circulation by Krauss and Brügge [9], Lehmann [10], Seifert and Fennel [15], Elken [7], and Raudsepp and Elken [13].

In this study we used another ocean circulation model developed at the Princeton University by Blumberg and Mellor [1, 2] known under abbreviation of POM. The POM is a primitive equation, free surface, hydrostatic, σ-coordinate model, which uses time splitting with an explicit computational scheme for the barotropic mode and an implicit one for the baroclinic mode. The vertical diffusivities are calculated by means of a well-founded second-moment turbulence closure sub-model, developed by Mellor and Yamada [12] imbedded into POM. Our choice for the benefit of POM was mainly determined by the fact that we have already had experience, using this model to study some aspects of the Baltic Sea circulation [25].

2.2. Grid resolution, regional implementation, initial conditions and wind forcing

All model runs have been performed in the whole Baltic Sea closed in the west at 12°E and at the narrowest section of the Sound. The reason for making calculations in the whole Baltic Sea, while we are interested in mesoscale variability just in a part of it to the south of 58°N, was to achieve proper treatment of barotropic wind forcing which is a key mechanism to drive currents in the water column.

In order to resolve mesoscale eddies as small as 10-15 km in diameter, a horizontal grid cell size of about $\delta x = 1$ km is desirable. Since we cannot afford such a fine resolution in the whole Baltic Sea in view of computer facilities available, a model grid with variable grid spacing has been applied. Namely, there was a fine resolution area with grid cell size $\delta\lambda = 1'$ and $\delta\varphi = 0.5'$ along x and y axes, respectively (i.e., about 1 km in both directions), a moderate resolution area ($\delta\lambda \leq 4'$ and $\delta\varphi \leq 2'$ or about 4 km in both directions), and a coarse resolution area ($\delta\lambda \leq 8'$ and $\delta\varphi \leq 4'$ or about 8 km in both directions). The fine resolution area is an area where mesoscale cyclonic eddies are expected to form (see Fig. 2). The gulfs of Riga, Finland, and Bothnia fall into the coarse resolution area while the moderate resolution was applied to the rest of the sea. In addition, a few runs were performed, with lower horizontal resolution, in the fine resolution area ($\delta x = 2$ and 4 km) for comparison. The model grid was created using a digitized bottom topography of the Baltic with $2' \times 1'$ resolution [16].

In the basic case, the vertical sigma-coordinate grid cell size was chosen at $\delta\sigma = 0.1$ (i.e., 10% of the total water column thickness, H, which is the sum of the sea depth and the surface elevation), and some runs were done at $\delta\sigma = 0.0625$ and 0.04 for comparison.

The lateral viscosity and diffusivity are calculated using the Smagorinsky formula proportional to δx and to the total deformation rate; the proportional coefficient was chosen to be 0.1 for most cases and 0.05 in some cases for comparison.

In order to model the propagation of highly saline water in the East Gotland Basin, following an inflow event, we used an idealized initial distribution of thermohaline fields which describes main features of the real distribution observed in February-March 1993 by the major inflow event of January 1993. The winter season temperature field is known to be of a minor importance for the inflow dynamics, so we took, for simplicity, a constant value $T = 10°C$ for the whole model domain. We suggested that the Arkona Basin, at depths greater than 35 m, is initially filled with high saline inflow water of 22 psu and the Bornholm Basin and western part of the Słupsk Furrow, under 45 m depth, has the salinity of 18 psu. The above values of salinity correspond roughly to those observed in March 1993 after the January 1993 major inflow event [6]. The upper layer salinity was taken at 7.5 psu in the whole area. For the salinity in the East Gotland and Gdańsk Basins, we took a horizontally uniform distribution with a constant value of 7.5 psu in the upper 60 m layer and a square root parabola growth of salinity with depth in permanent halocline, to get a value of 11.0 psu at 200 m depth. These values of salinity correspond well to the real values of salinity observed in the Gotland Deep before the major inflow event of January 1993 [6] (cf. Fig. 2).

In accordance with Krauss and Brügge [9], northerly and easterly winds are necessary in order to transport the inflow water from the Bornholm Basin to the East Gotland Basin via the Słupsk Furrow. That is why first of all we will analyze the response of thermohaline stratification and currents in the East Gotland Basin to northerly and easterly wind forcing. Most of the model runs were performed with horizontally homogeneous wind stress of $\tau = 2\,\text{g}\,\text{cm}^{-1}\text{s}^{-2}$ which corresponds to the wind speed of about 10 m s^{-1}.

3. Results

3.1. Northerly wind

Figure 3 presents the bottom layer salinity and the currents in bottom, intermediate, and surface layers, in an area east of the Słupsk Furrow, for the northerly wind acting over a period $t = 10$ days. The intermediate layer is the sigma coordinate layer at $\sigma = -0.55$; physically, it refers to the upper layer of the permanent halocline in deep parts of the East Gotland Basin where the sea depth exceeds 110 m. Since only isohalines with $S \geq 11$ psu are drawn while the initial salinity in the East Gotland and Gdańsk Basins does not exceed 11 psu, the salinity plume in Fig. 3 and following figures depicts a tongue of bottom intrusion of the salty inflow water. We do not show the salinity of intermediate and surface layer in Figs. 3, 4, 6-8 because it is less than 11 psu everywhere, which means that these layers are above the saline intrusion.

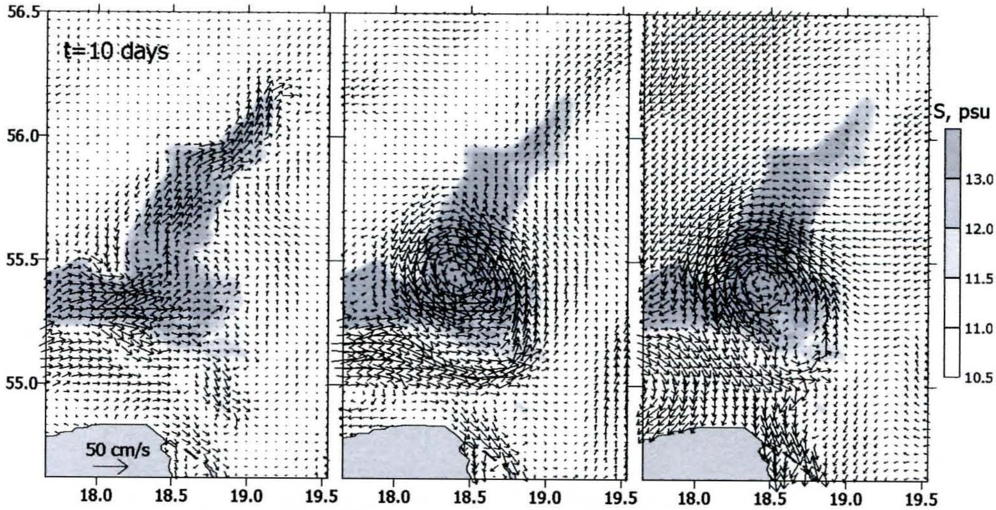

Fig. 3. Bottom layer salinity (all panels) and currents in bottom, intermediate, and surface layers (the left, middle, and right panels, respectively) in an area east of the Słupsk Furrow for the northerly wind acting over a period $t = 10$ days. Vectors of currents are drawn for every fourth grid node

Leaving the Słupsk Furrow, the tongue of saline intrusions splits in two, one goes northeast towards the Gotland Deep and the second moves southeast towards the Gulf of Gdańsk. A strong cyclonic eddy is generated just east of the Słupsk Furrow when the first portion of the inflow water enters the East Gotland Basin. Note that the cyclone is not generated in the bottom layer but above it.

Fig. 4 is the same as Fig. 3 but for $t = 26$ days when the salty intrusion has been advanced north as far as 57°36′N filling up the Gotland Deep with the maximum depth of 250 m at 57°20′N. A number of cyclonic eddies is observed in the water column along the salty intrusion pathway to the Gotland Deep. It can be easily discovered that a large cyclone, between 55°20′N and 56°00′N, is the same eddy as in Fig. 3. A smaller but very intensive cyclone at 56°17′N is discovered to be generated from a meander of the large cyclone. The origin of two less intensive cyclones between that of 56°17′N and the Gotland Deep (at 56°40′N and 57°00′N, respectively), cannot be traced by the sequence of salinity and current maps; they have been formed in the course of salty intrusion propagation along a sloping trough with no apparent motives. In contrast to the two intensive cyclones to the south of 56°30′N, which are well pronounced at the sea surface, the relatively weak cyclones at 56°40′N and 57°00′N do not display any clear signatures at the surface but some jet-like intensification of westward current over the northern periphery of the eddies. It is important to note that the further northward propagation of the salty intrusion, after passing the deepest section of the Gotland Deep, is accompanied with anticyclonic rotation in the intermediate layer.

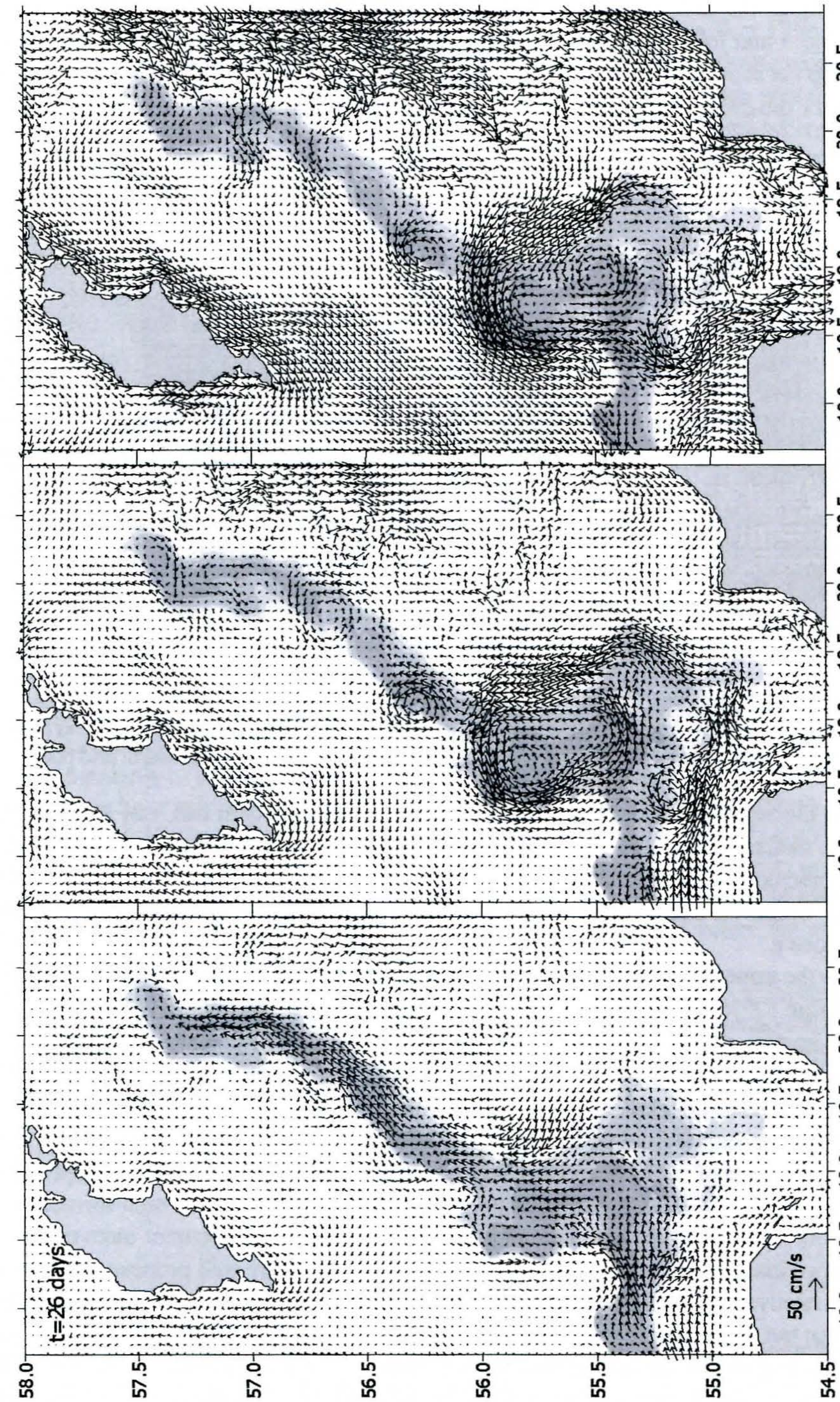

Fig. 4. The same as Fig. 3 but for t = 26 days

Fig. 5 presents salinity versus distance and depth for zonal sections across cyclonic eddies (a, b, and d) and the anticyclonic eddy in the northern periphery of the Gotland Deep (c).

In the large cyclone, isohalines (isopycnals) have well pronounced domed shape and the inner part of the dome is filled with the inflow water. The maximum thickness of water column with salinity above 11 psu in the center of the dome is about 50 m. The maximum rotational velocity of $V_{rot} \approx 0.50$ m s^{-1} is observed at a level $z = 55$ m and at a distance of $R_{eddy} = 22$ km from the eddy center so that the period of eddy rotation can be estimated at $2\pi R_{eddy}/V_{rot} \approx 3.2$ days.

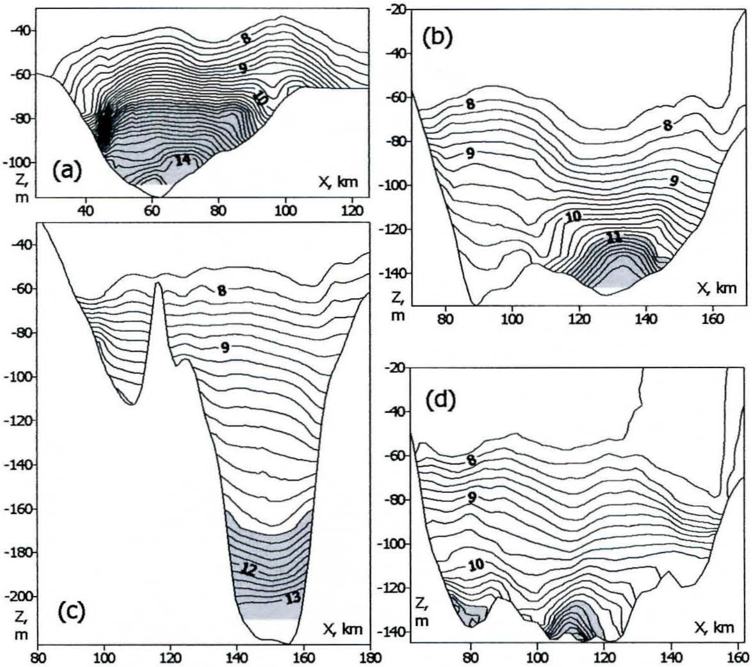

Fig. 5. Salinity versus distance and depth for zonal transects at 55°49′N, 56°40′N, and 57°25′N at $t = 26$ days (a, b, c, respectively; cf. Fig. 4), and 56°33′N at $t = 38$ days (d, cf. Fig. 6, the right panel) of the northerly wind

In small cyclones, formed along the salty intrusion pathway to the Gotland Deep (Fig. 5, b, d) the shape of salinity isolines resembles well that of the observations (cf. Fig. 2). The maximum rotational velocity is observed at $z \approx 100$ m; estimates of the maximum velocity and radius for these eddies are $V_{rot} = 20$ cm/s, $R_{eddy} = 14$ km (Fig. 5b) and $V_{rot} = 15$ cm/s, $R_{eddy} = 7$ km (Fig. 5d).

3.2. Easterly wind

As in the case of northerly winds, the easterly wind condition generates a cyclonic eddy with a bolus of salty inflow water just east of the Slupsk Furrow (Fig. 6, the left panel). When the cyclone has moved east for about 80 km, a new, second cyclone is formed at the same place. It is also seen that the propagation of salty intrusion towards the Gotland Deep is accompanied by weaker cyclonic eddies in the intermediate layer. Since the cyclones above the salty intrusion are formed under both the northerly and easterly wind conditions, we may expect that a variable wind of northern or eastern compass points, followed by inflow events, will produce the same effect.

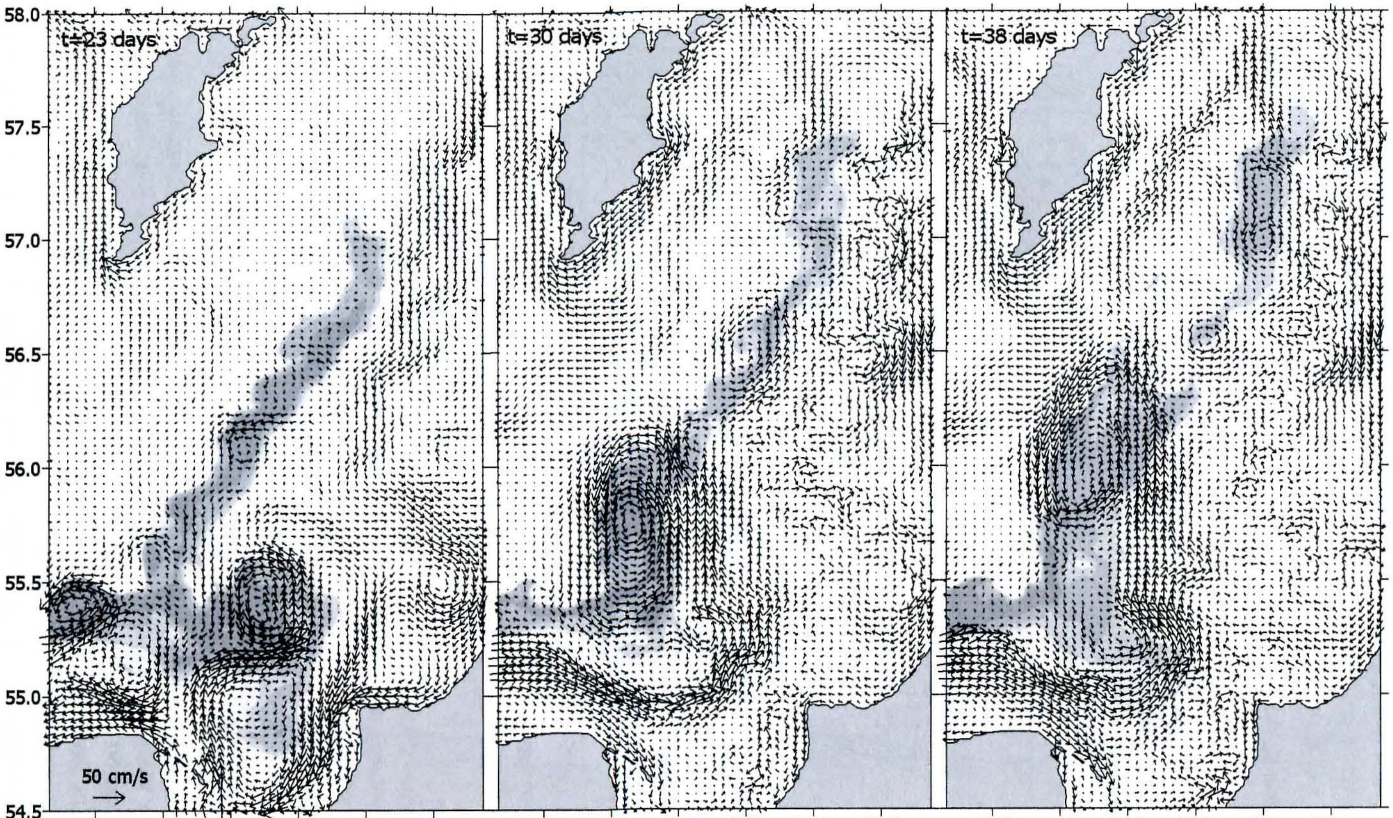

Fig. 6. Bottom layer salinity and intermediate layer currents for $t = 23$ days of the easterly wind (left panel), $t = 30$ days of the northerly wind with reduced baroclinic forcing (middle panel), and $t = 38$ days of the northerly wind for a model run with increased horizontal grid cell size $\delta x = 2$ km and decreased vertical grid cell size $\delta\sigma = 0.04$ (right panel)

3.3. Reduced baroclinic forcing

The numerical experiments described above were performed with very strong baroclinic forcing which is peculiar to the major inflows only. To learn if the cyclones are formed after moderate inflow pulses, a northerly wind experiment, with reduced baroclinic forcing, was initiated with a bottom layer salinity of 15 psu and 18 psu in the Bornholm and Arkona Basins, respectively (Fig. 6, the middle panel). The model run shows that both the cyclone, just east of the Słupsk Furrow and smaller cyclones along the salty intrusion pathway to the Gotland Deep, can be formed even after moderate inflow pulses.

3.4. Variable wind forcing

To study the effect of variable wind forcing on cyclone formation, an experiment was initiated in which the northerly wind acting for a period $t = 0-8$ days, altered for the southerly wind, acting for a period $t = 9-13$ days and finally restored at $t \geq 14$ days. The experiment showed that the southerly wind burst interrupted the salty water supply but did not destroy the cyclone that had been formed just east of the Słupsk Furrow. Once the northerly wind was restored, a new inflow pulse caused the formation of a new cyclone at the same place (see Fig.7, the left panel). In a while, the old and new cyclones merged in one. In the meantime, weak cyclones were observed in the intermediate layer along the salty intrusion pathway to the Gotland Deep.

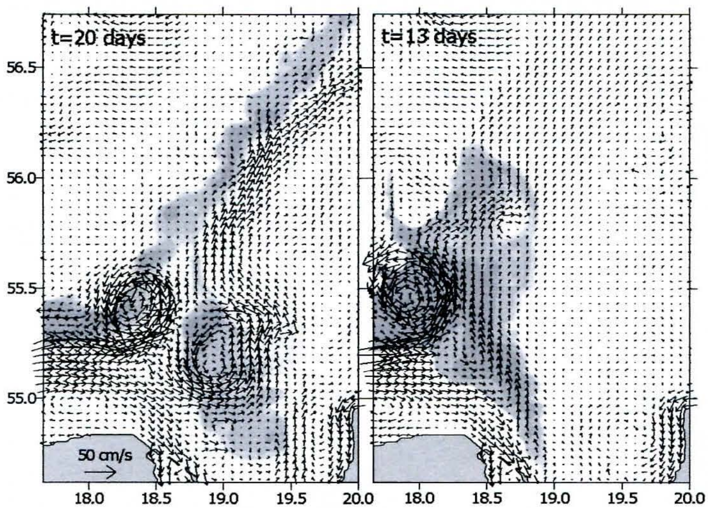

Fig. 7. The same as Fig. 6 but for t = 20 days of variable, north-south-north wind (left panel), and t = 13 days of the northerly wind for the flat bottom experiment (right panel)

3.5. Flat bottom experiment

To learn if the increase in sea depth between the Słupsk Furrow and the East Gotland Basin is critical for generation of the cyclone just east of the furrow, an experiment with a flat bottom was initiated. Namely, when the sea depth is less than 60 m, the real topography of the Baltic Sea is applied and the constant sea depth of 100 m is taken when the sea depth exceeds 60 m. Since the depth of the Słupsk Sill exceeds 60 m, the experiment implies that the depth of both the furrow and basins connected to it, is 100 m. A model run, with such an artificial configuration, displays that the cyclonic eddy with a bolus of inflow water, is still formed just east of the furrow (Fig. 7, the right panel).

3.6. Changing the grid cell size

A number of numerical experiments were initiated to learn the sensitivity of cyclone formation to the grid cell size. Three values of both horizontal grid cell size and vertical sigma coordinate grid cell size were applied, namely, $\delta x = 1$, 2, and 4 km, and $\delta\sigma = 0.1$, 0.0625, and 0.04. The large cyclone, just east of the Słupsk Furrow, was reproduced well in all experiments. Small cyclones along the salty intrusion pathway to the Gotland Deep were formed in all experiments as well but the time and position for a small cyclone to bear and die did not coincide for different experiments. An example of cyclones, formed at reduced horizontal resolution ($\delta x = 2$ km) and enhanced vertical resolution ($\delta\sigma = 0.04$), is given in Fig. 6, the right panel (see also Fig. 5d).

3.7. An experiment with a dam

It follows from Figs. 2 and 3 that the eastward flow throughout the whole water column is settled in the Słupsk Furrow under the northerly wind (and under the easterly wind as well), while the balancing, westward flow takes place in the upper layer outside the furrow. If we construct a virtual dam, restricting the water exchange between the Bornholm and East Gotland Basins to the limits of the Słupsk Furrow (see Fig. 1), there will be no possibility for balancing flow outside the furrow. The flow in the furrow is expected to turn to a two-layer one (i.e., the upper layer moves to the west while the lower layer moves to the east) and such changes in the flow structure may affect the possibility to form cyclonic eddies.

Fig. 8 shows the same as Fig. 3 but for an experiment with the dam. Due to the dam, the flow in the furrow does acquire the two-layer structure and the intensity and size of cyclonic eddies does reduce considerably (cf. Fig. 3).

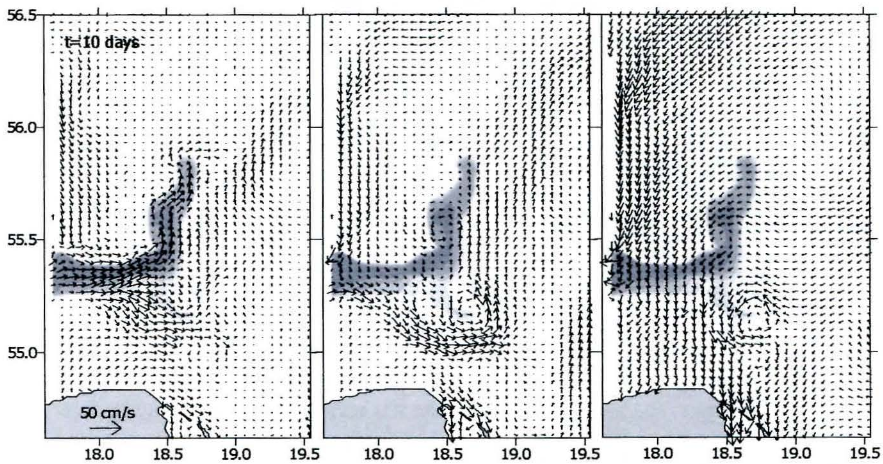

Fig. 8. The same as Fig. 3 but for the experiment with a virtual dam restricting water exchange between the Bornholm and East Gotland Basins to the limits of the Słupsk Furrow

3.8. Cyclone formation in the Bornholm Basin

The results presented above deal with cyclonic eddy formation in the East Gotland Basin following the salty water inflow from the Bornholm Basin through the Słupsk Furrow. Similar effects can be expected in the Bornholm Basin with the inflow from the Arkona Basin. To simulate the process numerically, a version of the model with grid steps $\delta x = 1$ km and $\delta\sigma =$

0.0625 in the high resolution area covered the Arkona and Bornholm Basins as well as the Slupsk Furrow was developed (see Fig. 1). The bottom layer salinity was 22 psu in the Arkona Basin, whilst horizontally homogeneous salinity, with the value of 18 psu at 100 m depth, which is typical to the Bornholm Basin, was applied to the rest of the model domain.

After a period of $t = 4$ days of the northerly wind, a well pronounced cyclonic eddy of 20 km diameter was formed in the intermediate and surface layers just northeast of a strait between the Bornholm Island and Swedish coast (see Fig. 9). Note that in the bottom layer under the cyclone, the vorticity changed sign for the anticyclonic one.

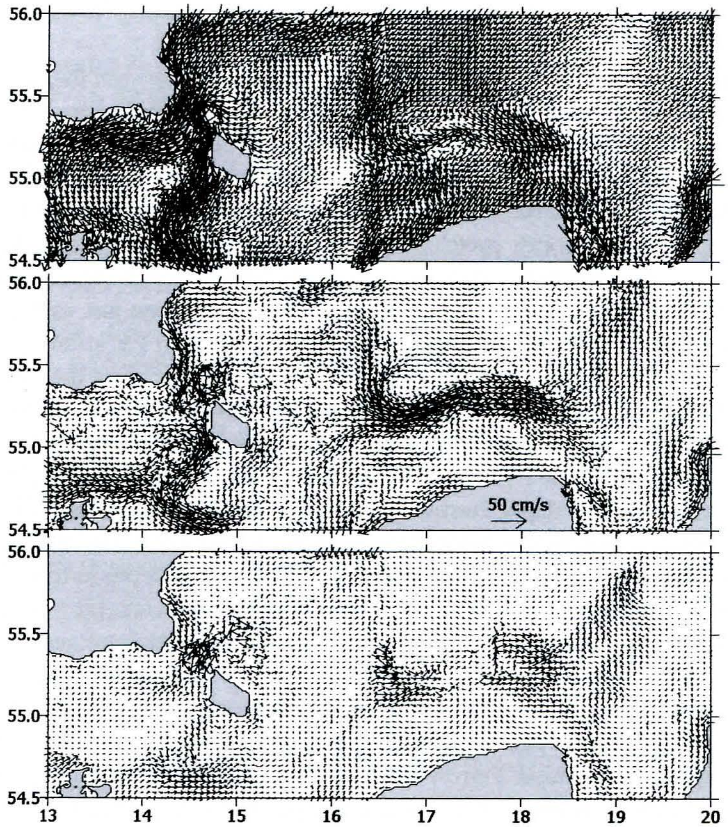

Fig. 9. Experiment on cyclonic eddy formation in the Bornholm Basin: Currents in the surface, intermediate, and bottom layers (top, middle, and bottom panels, respectively) for the northerly wind acting over a period of $t = 4$ days

In addition, Fig. 9 displays well the unidirectional eastward flow throughout the whole water column formed in the Słupsk Furrow under the northerly wind.

4. Discussion

A clue to understanding processes responsible for generation of mesoscale cyclones in the Baltic Sea following inflow events, can be found in a paper by Spall and Price [19] who studied the cause for the continuous formation of intensive mesoscale cyclones in the outflow through the Denmark Strait [3]. Comparing well-known outflows through the Gibraltar Strait, the Faroe Bank Channel and the Denmark Strait, they argued that the first two are two-layer, density-driven exchange flows, in which a dense lower layer overflows from the marginal sea and is replaced by a lighter inflow of the oceanic water and do not display the formation of intensive mesoscale cyclones. The Denmark Strait appears to be unique in that the coupled effect of large-scale wind and buoyancy forcing, produces a highly stratified (high potential vorticity (PV)) outflow throughout the water column and the intensive mesoscale cyclones form, downstream, the sill where the outflow encounters a rapidly deepening bottom. Spall and Price [19] suppose that the mesoscale cyclones in the Denmark Strait are generated during the adjustment of the high PV outflow to the low PV oceanic environment by vortex stretching (so-called the PV outflow hypothesis).

Our numerical experiments showed a remarkable resemblance between the Denmark Strait and Słupsk Furrow outflows in that both are driven by a coupled effect of buoyancy and wind forcing which produces a unidirectional, high PV outflow throughout the water column. In the case of the Słupsk Furrow, the eastward, high PV outflow is seen by the southern slope of the furrow (see Figs. 3 and 4). However, in contrast to the Denmark Strait, where mesoscale cyclones form mainly due to vortex stretching over a rapidly deepening bottom, the change in bottom depth is not critical to form mesoscale cyclones by the Słupsk Furrow; it was proven by a numerical experiment with flat bottom (see Section 3.5). The cyclone just east of the Słupsk Furrow is likely generated during geostrophic adjustment of the high PV inflow water column, entering the East Gotland Basin (a relatively low PV environment of about the same depth). A similar cyclonic eddy supposedly of the same origin was simulated in the Bornholm Basin just northeast of a strait between the Bornholm Island and Swedish coast (Section 3.8).

Some more evidence for the PV outflow hypothesis to work in the case of the mesoscale cyclone formed just east of the Słupsk Furrow, was found in the dam experiment (Section 3.7). A virtual dam, restricting exchange between the Bornholm and Gotland Basins to the limits of the Słupsk Furrow, forced a two layer (two-directional) exchange flow in the furrow which results in drastic weakening of the cyclones formed just east of the furrow.

The PV outflow hypothesis can be useful to understand the process of generation of relatively small cyclones along the saline intrusion pathway to the Gotland Deep. It is clearly seen in Fig. 3 that the northerly wind produces a northeast countercurrent in the intermediate layer just along the saline intrusion pathway to the Gotland Deep (that is, along an inclined trough between the east end of the Słupsk Furrow and the Gotland Deep). The countercurrent is strong enough to suppress the southwest drift in the surface layer. Therefore, the coupled effect of wind and buoyancy forcing does produce the high PV northeast flow throughout the water column along the deepening trough. In accordance with Spall and Price's [19] findings, such a flow configuration is favourable to form mesoscale cyclones by vortex stretching.

The numerical experiments also yielded an evidence in favour of the high PV column stretching, caused by the bottom deepening, as the dominant process to form mesoscale cyclones along the saline intrusion pathway.

First, the model simulates cyclones south of the deepest point of the Gotland Deep, and an anticyclone just north of it. It suggests that the deepening of the bottom is critical to form small cyclones along the saline intrusion pathway.

Second, a double-concave shape of salinity/density isolines in the cyclones (Fig. 2 and 5, b, d) can be kinematically produced if we consider a horizontally uniform halocline over a deepening bottom, place a bolus of saltier water in the bottom layer at some sea depth and then translate such a water column along the deepening bottom, stretching it to fit the increase in sea depth. Actually, we do not see any other reasonable scenario to form the double-concave shape of salinity/density other the above.

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