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Submesoscale structures related to upwelling events in the Gulf of Finland, Baltic Sea (numerical experiments)

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ABSTRACT

The appearance of submesoscale structures in the Gulf of Finland was investigated using model simulations for series of coastal upwelling events in July–September 2006. We applied the Princeton Ocean Model. The horizontal step of the model grid was refined to 0.5, 0.25 and 0.125 nautical miles in the gulf and reached 4 times the resolution in the rest of the Baltic Sea; there were 60 σ-levels in the vertical direction for all simulations. The contribution of salinity to the strength of baroclinic front of upwelling along the northern and southern coasts and thereby to the submesoscale dynamics of the gulf's surface layer was analyzed. Model results with refinement of the grid size to 0.125 nautical miles revealed different forms of submesoscale structures in the gulf's surface layer such as the high Rossby number (Ro) threads (elongated spots of Ro > 1 with typical width and length of 2–3 km and 10–50 km, respectively), cyclonic vortices with Ro > 1 core of 4–6 km diameter, and spiral cyclonic eddies (spirally wrapped high Rossby number threads) of 10–15 km diameter. The high potential vorticity threads presumably formed during the development phase, while the cyclonic vortices and spiral cyclonic eddies during the relaxation phase of upwelling. One of the simulated submesoscale cyclonic eddies, at the beginning with the Ro > 1 core extension as deep as 31–66 m was traced for the period of 33 days. The power spectral density of temperature and velocity fluctuations in the surface layer pointed at some increase of spectral levels and shallowing of spectral slopes towards −2 on the shorter (submesoscale) wavelengths with the refinement of model grid.

1. Introduction

High-resolution satellite and field observations and model simulations showed that considerable spatial variability of water mass properties exists in submesoscale (10–1 km) and processes at these scales significantly contribute to the horizontal and vertical transport in the ocean (e.g. Thomas et al., 2008; Bouffard et al., 2012; Schroeder et al., 2012; Gula et al., 2014; Martin et al., 2015; Shcherbina et al., 2015; Swart et al., 2015). Submesoscale flows can be defined based on their dynamics, as those where the bulk Rossby number, $Ro_b = U/fL$ and the bulk Richardson number, $Ri_b = N^2H^2/U^2$, are both of the order of unity (Thomas et al., 2008). Here U, H, and L are the characteristic speed, vertical length scale, and horizontal length scale of the velocity field, respectively, f is the Coriolis parameter, $N^2 = b_z$ is the square of the buoyancy frequency (Brunt-Väisälä frequency), $b = -g\rho/\rho_0$ is the buoyancy, ρ is the density, g is the gravity acceleration, and $\rho_0 = 1000$ kg m^{-3} is the reference density. Submesoscale processes with horizontal length scale of the order of 1 km are particularly dominant in the upper ocean layer including the upper mixed layer and upper thermocline where they are frequently displayed in the form of elongated regions, typically related with filaments or outcropping isopycnals, within which the relative vertical vorticity $\varsigma = v_x - u_y$ being positive (cyclonic) equals or exceeds the planetary vorticity f. Moreover, submesoscale processes are characterized by a conspicuous asymmetry of the relative vertical vorticity and vertical velocity distributions with an enhancement of cyclonic (positive) vorticity and downwelling. Submesoscale processes are supposed to be vital for the transport of vorticity, buoyancy, momentum, matter and biogeochemical properties throughout the upper mixed layer and upper thermocline (e.g. Capet et al., 2008).

The Gulf of Finland, an elongated basin (about 400 km long and 48–135 km width) lies in the north-eastern part of the Baltic Sea (Fig. 1). The maximum depth at cross-gulf sections decreases from 80 to 110 m at its entrance to 20–30 m in the eastern part. The freshwater runoff, mainly the River Neva (an average 77.6 km^3 yr^{-1}, Bergström et al., 2001) in the eastern part and saltier northern Baltic Proper water intrusion from west cause surface layer salinity decrease from 6 to 7 g kg^{-1} at the entrance to about 1 g kg^{-1} in the Neva estuary. The surface layer salinity decreases across the gulf towards the north and typically is between 4.5 and 5.5 g kg^{-1} in the central part of the gulf. The bottom layer salinity varies between 8 and 11 g kg^{-1} at the

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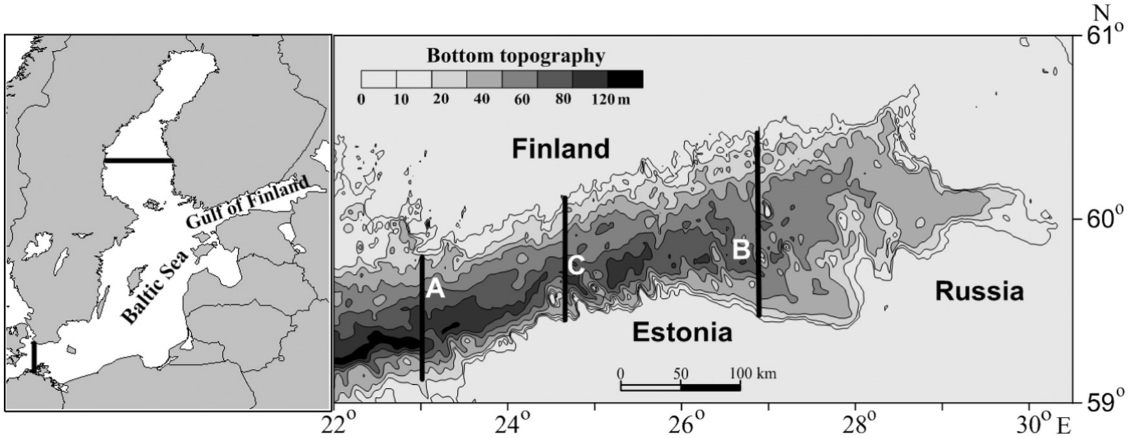

Fig. 1. A map of the Baltic Sea (left panel) and Gulf of Finland (right panel). Bold black lines (left panel) mark the model domain boundaries at the west and north. Bold black lines (right panel) mark the western (A) and eastern (B) borders of sea area where from simulated data are used for statistical analysis. Bold black line (C) marks transect along longitude 24.7° E. The bottom topography is drawn from the gridded topography in meters (Seifert et al., 2001).

entrance. Seasonal thermocline lies at the depths of 10–15 m and the permanent halocline at the depths of 60–70 m (see the review by Alenius et al., 1998).

Summer coastal upwelling is a typical phenomenon in the Baltic Sea. The Gulf of Finland is an area of the Baltic Sea known for frequent wind-induced upwelling events. Mesoscale filaments and eddies related with outcropping isotherms/isopycnals and controlled by the baroclinic Rossby radius were repeatedly identified in the Gulf of Finland using satellite sea surface temperature (SST) imagery (e.g. Kahru et al., 1995; Uiboupin and Laanemets, 2009; Lehmann et al., 2012), in situ measurements (e.g. Vahtera et al., 2005; Lips and Lips, 2014) and numerical modeling (e.g. Myrberg and Andrejev, 2003; Zhurbas et al., 2008; Laanemets et al., 2011) during upwelling events. In the narrow elongated Gulf of Finland, upwelling along one coast is usually accompanied by downwelling along the opposite coast (e.g. Zhurbas et al., 2008; Lips et al., 2009). Two longshore baroclinic jets and related thermohaline fronts develop simultaneously. Zhurbas et al. (2006; 2008) showed that instability of a longshore baroclinic jet associated with upwelling (downwelling) leads to the development of mostly cyclonic (anticyclonic) squirts and eddies thus increasing lateral mixing. Based on the NEMO (Nucleus for European Modelling of the Ocean) code, Vankevich et al. (2015a, 2015b) have recently developed a submesoscale-resolution model of the Gulf of Finland (0.5 km horizontal grid). The simulation results showed better reproduction of summertime thermohaline stratification by the 0.5 km resolution model in comparison with the 2 km resolution model.

As the submesoscale structures are strongly related to energetic mesoscale flow field (e.g. Capet et al., 2008; Thomas et al., 2008; Zhong and Bracco, 2013; Gula et al., 2014), the objective of this study is to re-visit coastal upwelling events of summer 2006 in the Gulf of Finland (Laanemets et al., 2011), to simulate them using the refined, submesoscale-permitting horizontal grid. Based on the simulation results, we hope to investigate individual and statistical features of submesoscale structures generated during the upwelling period and to compare those with results of the mesoscale-resolving simulation.

2. Model setup

We applied the Princeton Ocean Model (POM) (Blumberg and Mellor, 1983) version ATOP (Oey et al., 2013) in the Baltic Sea. The POM is a primitive equation, sigma coordinate, free surface, hydrostatic model with a second moment turbulent closure sub-model embedded (Mellor and Yamada, 1982). The model domain includes almost whole Baltic Sea to the east of 13° E and to the south of 62° N; the domain was closed at its western and northern boundaries. The horizontal step of the model grid was 0.5, 0.25 and 0.125 nautical miles in the Gulf of Finland to the east of 23° E (Fig. 1) and 2.0, 1.0 and 0.5 nautical miles in the rest of the Baltic Sea, respectively; there were 60 σ-levels in the vertical direction. Subgrid lateral eddy diffusivity was resolved using the Smagorinsky formulation (Smagorinsky, 1963). The origin for the digital topography of the Baltic Sea (1 nautical mile) is taken from Seifert et al. (2001) and for the Gulf of Finland (0.25 nautical miles) from Andrejev et al. (2010, 2011).

Atmospheric forcing (wind stress and surface heat flux components) was calculated from wind, solar radiation, air temperature, total cloudiness and relative humidity data taken from HIRLAM (High Resolution Limited Area Model) version of the Estonian Meteorological and Hydrological Institute with the spatial resolution of 11 km and forecast interval of 1 h ahead of 54 h, recalculated after every 6 h (Männik and Merilain, 2007). Wind velocity components at the10-m level along with other HIRLAM meteorological parameters were interpolated to the model grids. The model domain was closed at the Danish straits (more precisely at 13° E) since the spatially mean Baltic Sea level was very stable during the simulation period. By the estimates of Laanemets et al. (2011) from the open boundary model, the variations were <0.05 m while the long-term variations of the mean sea level of the Baltic may exceed 1 m (Lehmann et al., 2004). Freshwater supply, although of secondary importance for the upwelling dynamics, was applied as the average Neva river inflow of 2460 $m^3\ s^{-1}$ (Bergström et al., 2001). Note that after the completion of the St. Petersburg's Flood Protection Barrier the path of river water into the Gulf of Finland has changed significantly (Andreev et al., 2013) which can influence the dynamics of an easternmost part of the Gulf (excluded from consideration in the present study).

Initial thermohaline fields were taken from HIROMB (High-Resolution Operational Model of the Baltic Sea), a z-level model, from the 1 nautical miles grid step version as provided by SMHI (Funkquist, 2001). The vertical grid step in HIROMB was 4 m in the surface layer down to 12 m and increased towards greater depths, resulting in 16 layers at 230 m. Thermohaline fields of HIROMB were first interpolated to our horizontal model grids and transformed from z-levels to σ-levels. In the present study, the initial fields of temperature and salinity had larger horizontal and smaller vertical gradients in the Gulf of Finland compared to the observations presented by Lips et al. (2009). Zhurbas et al. (2008) showed that high-resolution (0.5 nautical miles) POM is able to reproduce mesoscale variability related to upwelling in the gulf, including filaments/squirts and eddies, starting from quite smooth initial thermohaline conditions, motionless state and zero surface elevation.

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