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A numerical study of circulation in the Gulf of Riga, Baltic Sea. Part I: Whole-basin gyres and mean currents

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ABSTRACT

A regional model of the Gulf of Riga (GoR) with horizontal grid spacing of 0.5 nautical miles was applied to study the features and driving forces of the whole-basin circulation in the GoR. The initial conditions and atmospheric forcing were taken from the operational models High Resolution Operational Model for the Baltic (HIROMB) and High Resolution Limited Area Model (HIRLAM), respectively. The wind stress curl is shown to be a major contributor to the whole-basin circulation pattern. An anticyclonic circulation pattern in the summer is determined by a combined effect of the negative wind stress curl, thermal density stratification and bottom topography. Positive values of the wind stress curl and a cyclonic circulation pattern prevail during the cold period of the year when seasonal thermocline is absent. During calm periods, the anticyclonic type of circulation is established due to a combined effect of the river runoff, saltier water inflow into and mixed water outflow from the GoR. Two seasonal baroclinic jet-like currents are identified in the summer: the Northward Longshore Current in the western GoR and Southward Subsurface Longshore Current in the eastern GoR. The alteration of the circulation pattern in the GoR from cyclonic in the cold period of the year to anticyclonic in the summer, and vice versa, was shown to be observed not every year due to inter-annual variability of wind forcing.

1. Introduction

The Gulf of Riga (GoR) is a semi-enclosed basin in the eastern part of the Baltic Sea with the area of 17,913 km^2 and volume V_{GoR} $=405$ km^3 (Leppäranta and Myrberg, 2009). A specific feature of the GoR is the presence of two straits – the Irbe Strait (sill depth of 25 m and cross-section of 0.4 km^2) in the western part and the Muhu Strait (sill depth of 5 m and cross-section of 0.04 km^2) in the northern part of the GoR (Fig. 1). The average depth of the GoR is 26 m, which is approximately two times less than that of the Baltic Sea. The northern part of the GoR is quite shallow and contains many islands (e.g. Abruka, Kihnu, and Manilaid) and banks. The Ruhnu Island situated in the central part of the GoR is a continuation of a relatively large bank – Gretagrund – dividing the deep-water zone into the western and eastern regions. The deep-water zone reaches depths of about 56 m in the east of the Ruhnu Island, although, the deepest spot in the whole gulf is Mersraga trough (width about 50 m and length 4.5 km) with the depth of 66 m (Stiebrins and Väling, 1996) which is situated approximately 13 km to the north from the village of Mersrags.

The catchment area of the gulf covers 134,000 km^2 (Ojaveer (1995)) with five large rivers discharging into the GoR-Daugava, Lielupe, Gauja, Pärnu and Salaca. All these rivers are located in the southern or eastern part of the GoR. The annual freshwater runoff into the gulf varies between 17.2 and 55.1 km^3 (Yurkovskis et al., 1993) and the average runoff has been stated as $Q_{Rivers}=30$ km^3/yr, from which 86% fall into the southern part of the gulf (Berzinsh, 1995). The biggest contributor to the freshwater inflow is the Daugava River, which gives about 70% of the overall river input into the GoR (Yurkovskis et al., 1993).

Due to substantial river input to the GoR and relatively restricted water exchange with the Baltic Proper (BP), the mean salinity in the GoR ($S_{GoR}=5.6$ g/kg) is by 1.6 g/kg lower than the mean salinity in the adjacent region of the BP ($S_{BP}=7.2$ g/kg). If assuming the annual balance of water volume and salt content in the GoR in the form of $Q_{out} = Q_{in} + Q_{Rivers}$ and $Q_{out}S_{GoR} = Q_{in}S_{BP}$, where Q_{out} and Q_{in} are the annual outflow and inflow volume rates through the straits between the GoR and BP, one can obtain $Q_{out} = Q_{Rivers}S_{BP}/(S_{BP} - S_{GoR}) = 135$ km^3 yr and estimate the water renewal period for the GoR as $V_{GoR}/Q_{out} \approx 3$ yr (Lilover et al., 1998).

A general cyclonic type circulation scheme with southward

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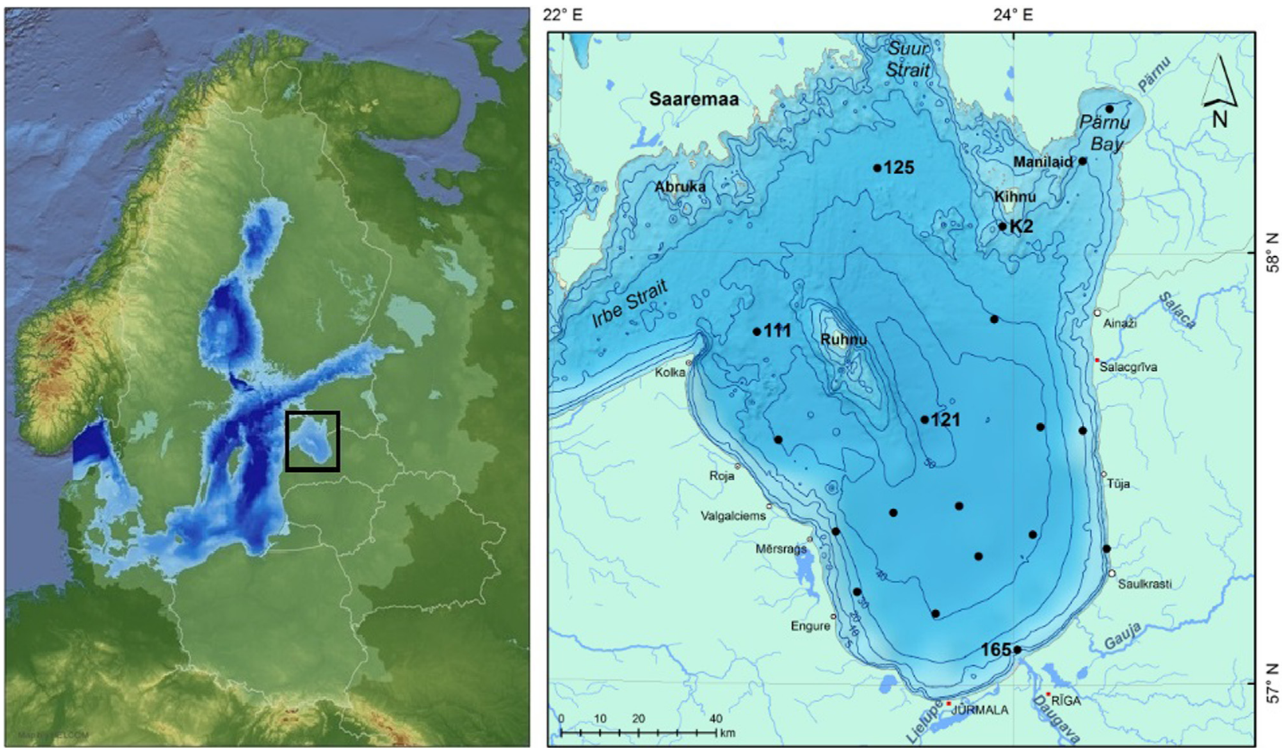

Fig. 1. Map of the Baltic Sea region with the Gulf of Riga highlighted (left panel). Bathymetric map of the Gulf of Riga (right panel). The black dots are the positions of CTD measurements used for the model validation. Examples of temperature and salinity profiles from CTD stations 165, 111, 125, K2 and 121 are presented in Figs. 4 and 5.

flow at the western side and northward flow at the eastern side of the GoR has been described based on a rather limited number of direct measurements (Yurkovskis et al., 1993). This scheme is consistent with density-driven estuarine circulation in a wide non-tidal estuary (e.g. Elken et al., 2003). In accordance with this scheme, most of the freshwater supply in its south-eastern region propagates to the north along the gulf's eastern shore as a buoyant coastal plume, while the saltier water entering the gulf mostly through the Irbe Strait in the northwest corner propagates to the south along the gulf's western slope as a geostrophically balanced bottom gravity current.

On the other hand, in a closed, non-stratified basin of variable depth, the closed circulation loops of depth-averaged currents, which are called "topographic gyres", develop in response to spatially uniform wind impulse (Csanady, 1975). These loops are paired with downwind currents near the coasts and return flow in the center (deep part) of the basin. Note that the formation of "topographic gyres" is related to generation of potential vorticity by uniform wind forcing over sloping bottom and is not directly related to bottom friction and rotation. The dynamic effect of the earth's rotation manifests itself through the cyclonic propagation of the wind-generated basin-scale topographic wave that appears in cyclonic rotation of the current velocity vector with the period of 3–4 days (Raudsepp et al., 2003).

Some insight into the variations of the circulation in the northern part of the Gulf of Riga was obtained from synoptic CTD surveys performed on monthly basis from May to November, in 1994 (Lips et al., 1995). Using the dynamic topography at 5 dbar relative to 20 dbar, a northward flow was shown to dominate over the central part of the gulf in May and June with moderate winds mainly from NE and NW corresponding to the "topographic gyres". During calm weather in July and August, the flow was southward in the eastern gulf and northward in the western gulf corresponding to a whole-basin anticyclonic gyre. The ADCP transect performed on 17–18 July 1994, over the northern half of the gulf confirmed the described flow pattern. From September to November, the flow was mainly northward again, while the wind was variable in direction, but weak. A presumably anticyclonic pattern of surface circulation in the GoR was reconstructed from aerial surveying of currents in August and September 1965 (Baranov, 1970), which corresponds to the findings by Lips et al. (1995). The reduced surface salinity in the western GoR in comparison to that in the eastern GoR was also reported by Berzinsh (1980) on the basis of measurements in August–September 1971–1975. It corresponds to the transport of the Daugava River runoff by a whole-basin anticyclonic gyre.

A study of the springtime water circulation in the southern GoR was recently conducted by Soosaar et al. (2014) based on the results of a 10-year simulation (1997–2006) using the General Estuarine Transport Model (GETM). Monthly mean currents in the surface layer of the GoR revealed a double gyre structure dominated either by an anticyclonic or cyclonic gyre in the near-river-mouth south-eastern part and by a corresponding cyclonic or anticyclonic gyre in the near-open-sea-exit north-western part of the gulf. The anticyclonic circulation pattern in the southern GoR was enhanced by easterly winds but blocked or even reversed by westerly winds. The authors suggested that such circulation pattern is different from the basic coastal ocean buoyancy-driven circulation where an anticyclonic bulge develops near the river mouth and a coastal current is established along the right hand coast (in the northern hemisphere; see a simple analytical model by Yankovsky and Chapman (1997)).

We argue that in relation to the whole-basin circulation patterns in the GoR the following open questions still exist: What kind of whole-basin circulation gyre (cyclonic or anticyclonic) is typical in the GoR in different seasons? What processes control the whole-basin circulation pattern in the GoR? Are there any quasi-permanent, at least in seasonal sense, currents in the GoR?

This work is an attempt to answer these questions based on numerical experiments with an eddy-resolving circulation model. In sense of methodology, our approach is similar to that of Schwab and Beletsky (2003) who, using different model scenarios, have