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ORIGINAL RESEARCH ARTICLE

On the buoyant sub-surface salinity maxima in the Gulf of Riga

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Summary Thermohaline structure in the Gulf of Riga (GoR) was investigated by a multi-platform measurement campaign in summer 2015. Stratification of the water column was mainly controlled by the temperature while salinity had only a minor contribution. Buoyant salinity maxima with variable strength were observed in the intermediate layer of the Gulf of Riga. The salinity maxima were likely formed by a simultaneous upwelling—downwelling event at the two opposite sides of the Irbe strait. The inflowing salty water did not reach the deeper (> 35 m) parts of the gulf and, therefore, the near-bottom layer of the gulf remained isolated throughout the summer. Thus, the lateral water exchange regime in the near bottom layer of the Gulf of Riga is more complicated than it was thought previously. We suggest that the occurrence of this type of water exchange resulting in a buoyant inflow and lack of lateral transport into the near-bottom layers might contribute to the rapid seasonal oxygen decline in the Gulf of Riga.

1. Introduction

The water exchange regime of semi-enclosed basins largely determines their physical and ecological nature. The classical estuarine circulation scheme in the estuaries with positive freshwater flux includes an outflow in the upper layer and inflow in the deep layer (Geyer and MacCready, 2014). The exact water exchange regime and faith of the inflowing denser water depends on the size and shape of the estuary as well as its mouth area (Valle-Levinson, 2010). Nevertheless, typically the inflowing water is in contact with the bottom of

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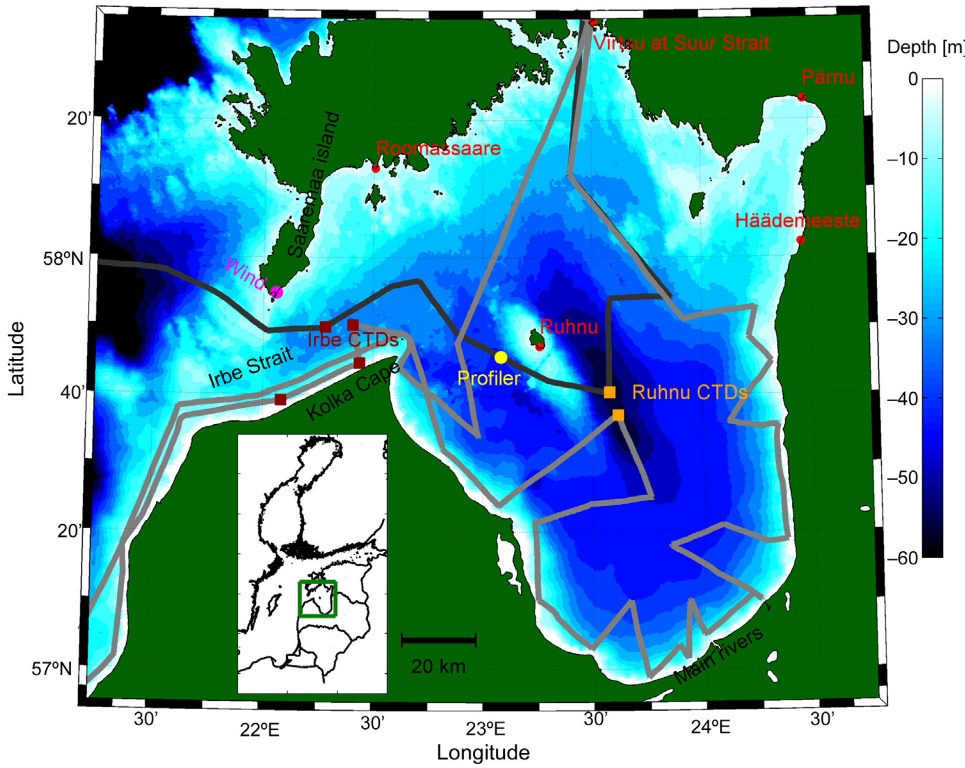

Figure 1 Map and topography of the Gulf of Riga. Color scale shows depth [m] of the study area. Lines show tracks of the RV Salme thermosalinograph surveys in July (darker gray) and August (brighter gray) 2015. Yellow circle represents the location of the moored profiler (buoy station), and red circles show locations where the coastal sea surface temperature time-series were acquired. Locations of Conductivity-Temperature-Depth (CTD) measurements at the Irbe Strait and Ruhnu Deep are shown as dark red and orange squares, respectively. The location of wind measurements at the Sõrve Cape station is shown as a magenta circle. The green box in the inlay map shows the location of the study area (Gulf of Riga) in the Baltic Sea.

the estuary. Exceptions might appear for the estuaries, which are separated from the adjacent sea basin by a sill. If the deeper layers of the estuary are filled with the saline water originating from the sporadic inflows, then the quasi-continuous water exchange over the sill involves inflowing water, which is too light to penetrate to the deepest layers of an estuary. Such regime can be found for several fjords (e.g. Belzile et al., 2016) and the Baltic Sea (Feistel et al., 2004). In the present study, we show that such water exchange regime can seasonally occur in a relatively large but shallow brackish estuary, the Gulf of Riga (GoR) as well.

The Gulf of Riga is a sub-basin of the eastern Baltic Sea. The gulf covers the area of 17 900 km^2, and its mean depth is 26 m. The deepest ($>$ 50 m) area is in the central part of the gulf (Fig. 1). The gulf is connected to the Baltic Sea via two straits: the Irbe Strait in the west with the sill depth of 25 m, width of 28 km and cross-section of 0.4 km^2 and the Suur Strait in the north with the sill depth of 5 m, width of 6 km and cross-section of 0.04 km^2.

The water and salt budgets of the gulf are formed by the two sources: the saltier water from the open Baltic Sea (Baltic Proper) and the freshwater from the rivers and due to precipitation (e.g. Raudsepp, 2001; Skudra and Lips, 2016). The water from the open Baltic flows to the deep layer of the GoR (Laanearu et al., 2000) while the riverine water occupies the upper layer. Thus there is a vertical salinity gradient present in the GoR (Skudra and Lips, 2016). The average river run-off to the gulf has been estimated approximately as 1000 m^3 s^{-1} (Berzinsh, 1995) while the average net precipitation to the gulf is about 80 m^3 s^{-1} (Omstedt and Axell, 2003). The 86% of the river run-off is discharged into the southern part of the gulf (Fig. 1, "Main rivers") from the Daugava, Lielupe and Gauja rivers (Berzinsh, 1995). This river discharge, in combination with the water exchange through the two straits in the northern part of the gulf, forms the latitudinal salinity gradient (e.g. Stipa et al., 1999). Due to the strong inter-annual variability and seasonality of the river run-off, salinity in the gulf varies remarkably at the same time-scales (e.g. Raudsepp, 2001; Skudra and Lips, 2016; Stipa et al., 1999). Due to the shallowness of the Irbe and Suur Strait, water from beneath the permanent halocline of the Baltic Sea (e.g. Reissmann et al., 2009) cannot penetrate into the GoR. There are strong salinity fronts at both straits, which change their position influenced by the wind forcing and sea level differences between the basins (Astok et al., 1999; Lilover et al., 1998).

The heat budget of the gulf (like the whole Baltic) is driven by the fluxes through the sea surface. The gulf is stratified during summers when the temperature exceeds 18°C in the upper mixed layer (Skudra and Lips, 2016). In autumn—winter, the water column is mixed down to the bottom due to the thermal convection. Further, temperature falls