Continental Shelf Research 78 (2014) 75–84

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

An investigation of anticyclonic circulation in the southern Gulf of Riga during the spring period

Edith Soosaar*, Ilja Maljutenko, Urmas Raudsepp, Jüri Elken

Marine Systems Institute at Tallinn University of Technology, Akadeemia 15a, 12618 Tallinn, Estonia

ARTICLE INFO

Article history:
Received 20 December 2012
Received in revised form
29 October 2013
Accepted 8 February 2014
Available online 22 February 2014

Keywords:
Anticyclonic circulation
ROFI
Vorticity
River discharge
Numerical modeling
Gulf of Riga

ABSTRACT

Previous studies of the gulf-type Region of Freshwater Influence (ROFI) have shown that circulation near the area of freshwater inflow sometimes becomes anticyclonic. Such a circulation is different from basic coastal ocean buoyancy-driven circulation where an anticyclonic bulge develops near the source and a coastal current is established along the right hand coast (in the northern hemisphere), resulting in the general cyclonic circulation. The spring (from March to June) circulation and spreading of river discharge water in the southern Gulf of Riga (GoR) in the Baltic Sea was analyzed based on the results of a 10-year simulation (1997–2006) using the General Estuarine Transport Model (GETM). Monthly mean currents in the upper layer of the GoR revealed a double gyre structure dominated either by an anticyclonic or cyclonic gyre in the near-head southeastern part and corresponding cyclonic/anticyclonic gyre in the near-mouth northwestern part of the gulf. Time series analysis of PCA and vorticity, calculated from velocity data and model sensitivity tests, showed that in spring the anticyclonic circulation in the upper layer of the southern GoR is driven primarily by the estuarine type density field. This anticyclonic circulation is enhanced by easterly winds but blocked or even reversed by westerly winds. The estuarine type density field is maintained by salt flux in the northwestern connection to the Baltic Proper and river discharge in the southern GoR.

1. Introduction

Fresh water from rivers contributes significant amounts of buoyancy to large areas of the coastal sea. The region where buoyancy input by rivers is comparable to or exceeds the seasonal input of buoyancy as heat is called ROFI (Region Of Freshwater Influence; a term adapted by Simpson (1997)). Buoyancy input results in a circulation pattern where lower density water from river output forms a circulating bulge near the source and a coastal current along the right hand coast (in the northern hemisphere) (Yankovsky and Chapman, 1997). Such a circulation pattern is believed to be the result of the combined effect of the inertial and Coriolis forces and is confirmed by multiple in situ measurements and laboratory and numerical simulations (Horner-Devine et al., 2006; Yankovsky and Chapman, 1997).

Local winds, tides and ambient currents modify the spreading of buoyant plume (see Osadchiev and Zavialov, 2013 and reference therein). Regarding local effects, winds that favor downwelling (towards the buoyant coastal current) compress the plume to the coast (Whitney and Garvine, 2006) and enhance the coastal current (Jurisa and Chant, 2012). Winds that favor upwelling (opposite to the buoyant coastal current) spread buoyant water offshore and can reverse the coastal current (Whitney and Garvine, 2006), so that new discharged water is transported leftwards from the source (Choi and Wilkin, 2007). On the basin scale of large lakes and enclosed seas, spatially uniform wind drives barotropic circulation with downwind currents at the coast and return flow in the center of the basin (Bennett, 1974).

A study by Fujiwara et al. (1997) shows theoretically that when an estuary is wider than the internal Rossby deformation radius, the combination of classical longitudinal estuarine circulation and the Earth's rotation may cause the surface circulation to become anticyclonic at the estuary head. In the northern hemisphere, this circulation will eventually transport fresh water from the river along the left hand coast. Anticyclonic residual circulation has been observed at the estuary head in Ise Bay, Osaka Bay and Tokyo Bay (Fujiwara et al., 1997). The presence of an anticyclonic circulation in the ROFIs is also confirmed by an observational study in the Kattegat–Skagerrak region, which is a transition area between the brackish Baltic Sea and the saline North Sea (Nielsen, 2005).

---

* Correspondence to: Marine System Institute at Tallinn University of Technology. Akadeemia tee 15a-321, Tallinn, Estonia.
E-mail address: edith.soosaar@msi.ttu.ee (E. Soosaar).

http://dx.doi.org/10.1016/j.csr.2014.02.009
0278-4343 © 2014 Published by Elsevier Ltd.

Measurements in the Kara Sea show the presence of an anticyclonic circulation in the Ob River discharge region in the late summer period (McClimans et al., 2000). The process was reproduced by numerical simulations (Panteleev et al., 2007). In the Gulf of Trieste, in the northern Adriatic, an anticyclonic gyre covers the surface layer during the stratified season (Malačič and Petelin, 2009). In all of these cases, the salinity distribution consists of vertical stratification, i.e. a brackish upper layer and a more saline lower layer, and a horizontal salinity gradient in the surface layer.

The morphological characteristics and hydrographic conditions in the Gulf of Riga (GoR) in the eastern Baltic Sea are well suited for the emergence of an anticyclonic circulation in the GoR head. The GoR is an almost bowl-shaped brackish-water semi-enclosed estuarine sub-basin (Fig. 1a). The area of the GoR is about 18,000 km^3 (140 km in length and 110 km in width), with a maximum depth of 56 m and mean depth of 22 m. The Daugava River located in the south-eastern part of the GoR is the main fresh water source. The river discharge ranges from 200 $\mathrm{m}^3\,\mathrm{s}^{-1}$ in late summer to 2500 $\mathrm{m}^3\,\mathrm{s}^{-1}$ in spring. The GoR has two openings connecting it to the Baltic Sea: the Irbe Strait (with a sill depth of 25 m and a minimum cross-section area of 0.4 km^2) in the west and the Virtsu Strait (with a sill depth of 5 m and a minimum cross-section area of 0.04 km^2) in the north (Fig. 1b).

As the GoR is shallow, water is usually well mixed throughout the period from December to March (Raudsepp, 2001). Ice is formed in the GoR every winter. The annual ice extent as well as duration of ice season has a wide range of variation determined by the severity of the winter (Soosaar et al., 2010). During severe winters ice starts to form in December and may last until the end of April. Increased freshwater discharge from the melting of snow and ice in early spring (March–April) stabilizes the surface layer and contributes to the seasonal stratification, resulting in a more or less two-layered salinity structure (Stipa et al., 1999). In summer and autumn the stratification is mostly maintained by temperature fluxes from the atmosphere. The tides are negligible in the GoR, which simplifies the problem by eliminating one cause of mixing.

Thus, the aim of our study is to investigate the springtime water circulation in the southern GoR, which is well preconditioned for the formation of anticyclonic circulation and is characterized by high river discharge. The input of freshwater buoyancy exceeds the input of buoyancy as heat, which is in accordance with the formal definition of ROFI by Simpson (1997). As there are no extensive field measurements of currents and salinity distribution available, we mainly rely on the results of numerical model simulations. Sparse in situ measurement data that are used in this study are available for May 1994 and 2006.

2. Materials and methods

2.1. Numerical model

In this study we use the fully baroclinic and hydrostatic ocean model GETM (General Estuarine Transport Model (Burchard and Bolding, 2002)) that is coupled with the GOTM (General Ocean Turbulence Model (Umlauf and Burchard, 2005)) which is used for vertical turbulence parameterization. The GETM uses a spherical coordinate system in the horizontal plane and a bottom-following vertical coordinate system. Using the mode splitting technique, GETM solves water dynamics on the Arakawa C grid (Arakawa and Lamb, 1977). The GETM is characterized by the advanced numerical techniques of advection schemes and internal pressure discretization schemes that minimize computational errors (Stips et al., 2004; Burchard and Rennau, 2008). Here we used the total variance diminishing (TVD) advection scheme for salinity, temperature and momentum (Pietrzak, 1998) and internal pressure parameterization suggested by Shchepetkin and McWilliams (2003).

For the current model simulations, the model domain covers the whole Baltic Sea (Fig. 1a). The bathymetry has been interpolated to the 2 nautical mile grid from the digital topography by Seifert et al. (2001). Depths have been adjusted so that the maximum depth is 260 m in the deepest areas of the Baltic Sea. The vertical water column is split into 25 sigma layers, where z_k is the layer depth and D is the depth of the water column.

The model simulation covers the period from 1 January 1997 to 31 December 2006. Initial salinity and temperature fields were interpolated from the climatic mean field constructed using the Data Assimilation System coupled with the Baltic Environmental Database at Stockholm University (http://nest.su.se/das). Initial sea surface elevation was set to zero. Atmospheric forcing was

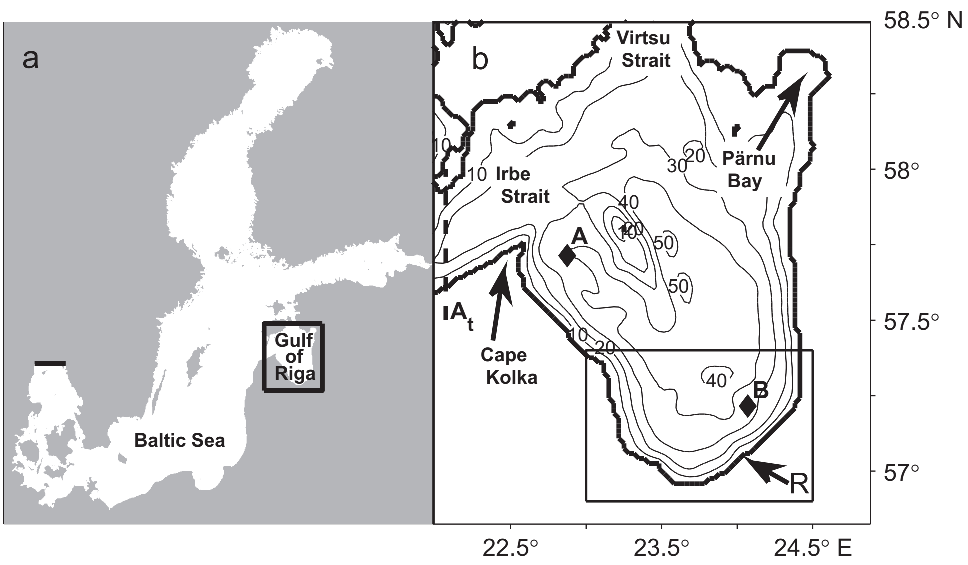

Fig. 1. Map showing the location of the Gulf of Riga (a) and its topography (b). R and arrow mark the location of the Daugava River outflow, At is the location of the north–south transect for the calculation of salt flux, A and B are sites where density is calculated (a depth of 30 m for A and 5 m for B).The box shows the area over which spatially averaged relative vorticity is calculated.