Response to the reviewers
Review 1

Comment 1: However, several parts of the methodology section should be further developed and details should be given about some choices performed. The validity of the satellite remote sensing imagery and numerical modelling methods followed should be proved to accurately detect and re-produce the plume dynamics.

The description of the methodology followed both through satellite remote sensing imagery and numerical modelling it is not sufficiently complete and precise to allow their comprehension and reproduction by other experts and therefore the results are not traceable.
Section 2.1: The methods to distinguish the turbid water from the clear sea water should be scientifically and precisely defined to allow the application of satellite remote sensing imagery to plume detection;
Reply: Additional information was added to the manuscript in order to make the satellite based results reproducible and traceable.
Two things that were missing and could help the reader are (1) the reference to the software (BEAM) that was used for image processing and (2) information about the used quality flags for masking invalid pixels. The missing information is now added to the manuscript. The BEAM, along with the algorithms in it, is a standard tool/method for MERIS data processing. The relevant information necessary for the reproduction of the results is as follows:
-Satellite sensor- ENVISAT/MERIS
- The database from which MERIS images were acquired- http://www.coastcolour.org/data/archive/
-Processing algorithm- C2R algorithm is described in detail by Doerfer and Schiller (2007). The algorithm has been validated in the Baltic Sea region in numerous studies. We added some extra references to the algorithm.
-Projection, resolution information- UTM34, 0.3 km
-Software package- BEAM (http://www.brockmann-consult.de/cms/web/beam/)
-Quality flags that were used in processing- ! l1p_cc_land and ! l1b_invalid and ! l1p_cc_cloud_shadow and ! case2_invalid and ! case2_whitecaps and ! case2_conc_oor and ! l1p_cc_glintrisk and ! l1p_cc_cloud_shadow and ! l1p_cc_cloud_buffer and ! l1p_cc_cloud_ambiguous and ! l1p_cc_cloud and ! sunglint and ! l1p_cc_snow_ice

Comment 2: Section 2.2: It is essential to perform a comparison between satellite imagery results and observations to prove the adequacy and validity of the methods applied;
Reply: The in situ measurements of TSM concentrations or optical properties were not conducted at the time of the study period. Therefore, the algorithm was not directly validated for the specific region and period. However, the C2R algorithm for the Baltic Sea has been validated in numerous previous studies (from Bothnia in the north to the Polish coast in the south, and from the Swedish coast in the west to the Gulf of Finland in the east) (Siitam et al 2014, Attila et al.2013, Vaičiūtė et al 2012) and its advantages and disadvantages are known. The C2R algorithm has been proven to be suitable for monitoring of water quality parameters (including TSM).
Satellite imagery studies of many river bulges (including Mendes et al. 2014, Horner-Devine et al 2008 etc) have exploited MODIS data, which has been processed with SeaDAS software package and algorithms. However, it is common knowledge, and has been pointed out also by Goyens et al (2013), that standard MODIS atmospheric correction algorithms give poor results in the Baltic Sea compared to other regions of the world ocean. The inaccurate atmospheric correction procedures impact the retrieval of remote sensing reflectance, IOPs and water quality parameters in the Baltic Sea from MODIS imagery using standard processing algorithms (including the ones in SeaDAS). Numerous studies in the Baltic Sea have proved that MERIS is more suitable for water quality monitoring than other sensors (eg. MODIS, Seawifs). This is due to the selection of spectral bands by

the MERIS instrument (sufficient spectral resolution in the range of wavelength above 555 nm), which is designed for monitoring optically complex waters like the Baltic Sea (Gitelson et al. 2009). The methods referred to in Mendes et al. (2014) and Horner-Devine et al. (2008) exploit SEADAS, which is not applicable in the Baltic Sea and causes heavy overestimation of water quality parameter values. While the analogous atmospheric correction, IOP and water quality parameter retrieval algorithm for MERIS, the C2R that we used, performs better in the Baltic Sea. Moreover, Mendes et al. 2014 found the normalized water leaving radiance at band 555nm (SeaDAS) to be the most suitable for bulge monitoring as it had sufficiently high correlation (r=0.56 for MODIS/Terra and r=0.60 for MODIS/Aqua) with river discharge. In the MERIS studies mentioned above, the TSM concentrations retrieved with the C2R algorithm from MERIS imagery were correlated with in situ measurements of TSM concentrations. The corresponding correlation coefficients (r) were between 0.72 and 0.87, which is significantly better compared to the Mendes et al (2014) study. Although the numbers are not comparable one-on-one, they impy that the MERIS-based TSM retrieval represents TSM variation in the upper layer reasonably well. Thus, the use of C2R algorithm for MERIS image processing over the Baltic Sea region is justified.

Section 2.2: Why the measurements of Gauja and Lielupe rivers fows were multiplied by 1.05 and 1.87, respectively? How were obtained these numbers? The use of this numbers has to be justified.
Reply: The coefficients are obtained as a ratio between the whole catchment area of those rivers and the catchment area of those rivers up to the place/station where the river flow was measured. Coefficient = whole catchment area / catchment area up to the measured location. Clarification was added in the revised manuscript.

Section 2.3: model calibration and validations results must be presented through comparison with in situ field data, and the model predictions accuracy has to be quantified; additionally, the comparison should prove the models accuracy in simulating the local river plumes dynamics;
Reply: A new section (2.4 Model validation) was added to the revised manuscript.

Section 2.3: The model TSM input used for the river discharges should be characterized (Realistic values? Real values measured in situ? Where?
Reply: TSM concentration in the river water was set to a unit value, as we do not have measurements of TSM concentrations in the river. The passive tracer was released to the GoR as Daugava River load of TSM being proportional to the Daugava River run-off starting from 20 March. Thus, the load is equal to TSM concentration multiplied with river run-off. The latter varying in time, as measured. We added clarification in the revised manuscript.

Section 3.1: the analysis presented should start before the plume establishment (maybe on #17th March) in order to allow the understanding of the plume dynamics in response to the high freshwater discharge event;
Reply: A 3-day spin-up period with a realistic salinity field and a linear increase of river run-off from zero to measured river run-off value on 20 March 2007 was used before including wind forcing on 20 March. Thus, we reached the peak value of freshwater discharge. During the spin-up period the wind speed was high, i.e. between 6 and 12 m/s (Fig. 2). As shown in Section 3.2, the wind of 4 m/s affects the bulge considerably, so we may expect that much stronger wind would mix river water with surrounding water in natural conditions. The satellite image on 20 March shows a much smaller plume and bulge than on the following images (Fig. 4a). Therefore, we suggest that this plume corresponds mainly to the initiation of the plume at midnight between 19 and 20 March when wind speed decreases from 6 to 2 m/s. Checking the sequence of tracer spreading in the numerical model showed that the bulge showing on the satellite image of 20 March (Fig. 4a) was destroyed by moderate wind of 5-6 m/s on 24 March (Fig. 2b). Upwelling favourable wind has significant effect on the bulge evolution, as shown with additional numerical experiments with constant wind from different directions (Fig.6 in revised ms). The plume on 26 March was the result of

the reset of the river plume on 24 March. The bulge analysed in the present study started to develop after March 24 at 05:00 and existed for the following 7-8-days. In order to retain the focus of the paper, we concentrated on a single long-lasting bulge evolution event.

Section 3.3: Why was used an ambient water salinity of 6? Please justify this assumption;
Reply: Based on the measurement study carried out between 1973–1995 in the GoR by Raudsepp (2001), long term average value for the salinity in the central GoR was about 6 (Raudsepp 2001, Figure 2b). We added T/S profile, adopted from Raudsepp (2001), to the Figure 1 in revised ms.

Section 3.3: simulations of rivers discharge into a homogeneous GoR with an ambient water salinity should also be performed considering idealized winds of growing intensity to analyse the wind effect in the evolution of the river bulge; without this the discussion and conclusions about the wind effect on the river bulge establishment and evolution are not solid;
Reply: We have made additional simulations with cross-shore and alongshore winds of 2 m/s and 4 m/s. We added paragraph and a figure to the revised manuscript.

Section 3.4: without comparison with in situ field data it is impossible to prove that model results are describing the local patterns and physics of the river bulge dynamics; -
Reply: Comparison of in situ data and model simulation results were made and a new section (2.4 "Model validation") has been added to the revised manuscript.

Section 3.4: the selection of threshold values based on visual inspection of TSM concentration maps on the satellite images is subjective and therefore not scientific; moreover, it is not acceptable that this threshold varied from image to image;

Reply: There is no established methodology to determine bulge edge. Multiple previous studies define the bulge edge based on selected constant threshold values. Horner-Devine et al (2006) estimated that a quadratic curve captures the bulge front for the central region but not on the bulge edges. Therefore, a constant 20% buoyancy contour was chosen as a reference value since isolines corresponding to lower buoyancy levels reflect too much variability and become difficult to fit. Gregorio et al. (2011) used reference velocity, 1.7cm/s, to define the coastal current front. Soosaar et al. (2015) defined the bulge edge to be 10% from the discharge depth.

We have removed from the revised manuscript the parts where bulge measures from satellite images are defined, described, calculated and discussed. We kept the bulge measures calculated from numerical model results. We calculated the bulge boundary with different threshold values. Although the actual boundary changes, the dynamics of the bulge does not depend on the selected threshold value. We have added text and modified the Fig 7 in the revised manuscript.

Section 3.4: methods such as those developed by Horner-Devine et al. (2008) or more recently by Mendes et al (2014) based on the normalized water-leaving radiance should be developed and applied for plume detection;
Reply: The methods referred to in Mendes et al. (2014) and Horner-Divine et al. (2008) exploit SEADAS, which is not applicable in the Baltic Sea and causes heavy overestimation of water quality parameter values. While the analogous atmospheric correction, IOP and water quality parameter retrieval algorithm for MERIS, the C2R that we used, performs better in the Baltic Sea. Moreover, Mendes et al. 2014 found the normalized water leaving radiance at band 555nm (SeaDAS) to be the most suitable for bulge monitoring as it had sufficiently high correlation (r=0.56 for MODIS/Terra and r=0.60 for MODIS/Aqua) with river discharge. In the MERIS studies mentioned above, the TSM concentrations retrieved with the C2R algorithm from MERIS imagery were correlated with in situ measurements of TSM concentrations. The corresponding correlation coefficients (r) were between 0.72 and 0.87, which is significantly better compared to Mendes et al. (2014) study. Alt-

hough the numbers are not comparable one-on-one, they imply that the MERIS-based TSM retrieval represent TSM variation in the upper layer reasonably well. Thus, the use of the C2R algorithm for MERIS image processing over the Baltic Sea region is justified.

We have removed the parts from the revised manuscript where bulge measures from satellite images are defined, described, calculated and discussed.

Section 3.4: Why was assumed that the bulge has a circular shape (equation 2)? This should be justified; -

Reply: Methodology is selected with the aim to maintain consistency with previous river bulge studies (Horner-Devine, 2009; Horner-Devine et al., 2008; Horner-Devine et al., 2006), where bulge radius is calculated assuming a circular shape, although the actual bulge is not circular. We have added clarification to the revised manuscript.

Remaining results, discussion and conclusion sections: as the results are all unproven due to the major flaws previously referred, these sections are purely speculative.

References

Doerffer, R. and Schiller, H.: The MERIS case 2 water algorithm. International Journal of Remote Sensing, 28(3-4), 517–535, 2007.

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Review 2

Comment 1. The paper describes many details of the observation and simulation that without enough explanation of why these features occur. It should be more concise and deliver a more focused “story” the readers.
Reply: We have tried to rewrite the paper in a more concise manner and to give more explanations.

Comment 2. It is mentioned in the paper that the tidal oscillation is small in the study region, thus tide forcing is not considered, however an additional case with tide forcing should be considered to approve that the tidal influence on the river bulge is negligible, as many studies show that tide-induced mixing have significant effect on the structure of the river plume (Chao, 1990; MacCready et al., 2009; Zu et al., 2014)

Reply: There is a big difference in the magnitude of tidal oscillation between noted studies and tides in the Baltic Sea and the GoR. MacCready et al., (2009) study is based on Columbia River and Zu et al. (2014) is looking at a Pearl River Estuary in South China Sea where tidal oscillations are in the range of 2-6m). In the Baltic Sea, tides vary in range 1-10 cm, which is mentioned in the text. In comparison with other forcing acting on the river bulge (wind, variation in river flow), tides in the GoR are marginal.
There are no studies on the effect of tidal mixing to the overall vertical mixing in the Baltic Sea. Lilover has calculated the contribution of the tidal shear on the gradient Richardson number in the Gulf of Finland. Results show that tidal contribution is about 10-20% if Ri = 1 (personal communication). Our ten month long measurements of currents in the GoR with ADCP show that tidal constituents are negligible in the current velocity spectrum (unpublished).

Comment 3. By using the term balance on a certain time, the paper concludes that geostrophic balance is valid for the entire mid-field of the bulge, which is different with previous results. However, time series of the term balance should be presented to approve that the conclusion is universal here, and is not an occasional event.
Reply: We calculated the time series of spatially averaged momentum balance terms, Eq. (3), for an ideal and real bulge and added a paragraph and Fig. 9 to the revised manuscript.

Comment 4. As many results are based on the model simulation, more detailed description of the model set up is needed, (i.e. numerical scheme, physical forcing, open boundary conditions ...)
Reply: Additional information was added to the model description section in the revised manuscript.

Comment 5.1 On page 4, at line 20-28, the author should add some short statement about the circulation in the Baltic Sea.
Reply: We assume that the reviewer meant the Gulf of Riga. As the GoR is a nearly closed gulf that connects with the Baltic Sea through two narrow straights, circulation in the Baltic Sea does not have relevant effect on the circulation in the GoR. We added a paragraph in the revised ms.

Comment 5.2 The observed representative T/S profile should be plotted in Figure 1.
Reply: T/S profiles were added to the Figure 1 in the revised ms.

Comment 6. On page 6, at line 20-21, the Baltic Sea has two large straits (Irbe Strait and Virtsu Strait) and these strait has important effects on the circulation in the Baltic Sea, why the model use the closed boundaries?
Reply: We assume that the reviewer meant the Gulf of Riga. In the study by Soosaar et al. (2014) it is quantified that in case of over a month long simulation correlation between circulation created in

a closed and open boundary, simulation has $R^2 = 0.93$. Differences were located in the immediate proximity of the straits. Our simulation concentrated on the south-east part of the GoR where the influence is negligible over a time period of two weeks, i.e. the model simulation period. An explanatory text is added to the revised ms.

Comment 7. On page 7, at line 5-6, the spin-up time of the model only 3 days. It seems too short?
Reply: A 3-day model spin-up time was used to smooth out small-scale spatial salinity discontinuities due to interpolation and to allow smooth input of fresh water from rivers to ambient saline water. As initial salinity fields were interpolated from the 1 nautical mile simulation for the Baltic Sea (Maljutenko and Raudsepp 2014) on 20 March 2007, we expect that the density field is consistent with hydrodynamical and meteorological conditions on 20 March 2007. Therefore, we expect that a 3-day geostrophic adjustment is sufficient to spin-up the velocity field. Using longer spin-up without wind forcing would result in considerably different salinity/density fields that were characteristic for 20 March 2007.

Comment 8. On page 12, at line 5, „the pulsation of the actual bulge" should be „the pulsation of the real bulge".
Reply: Corrected.

Comment 9. On page 12, at line 5-10 (shown in Figure 5). For ideal bulge, when bulge diameter increased, bulge mean depth increased. The statement "when bulge diameter increased, bulge mean depth decreased and vice versa." why?
Reply: We suggest that the fresh water volume in the bulge is roughly conserved. Therefore, the bulge depth responds to lateral bulge fluctuations. As the bulge area extends, the bulge depth decreases and vice versa. We do not have detailed explanation and future study is needed to have a solid answer, which we think is beyond the aim of this paper. Therefore, we like to keep it as a notification without any speculation provided in the text.

Comment 10. On page 14, at line 5-15, The real simulation gave $r_b \sim t^{0.50\pm0.04}$ while the ideal simulation gave $r_b \sim t^{0.28\pm0.0}$. And the satellite remote sensing gave $r_b \sim t^{0.31\pm0.23}$. Why is the evolution of the bulge in the ideal simulation more similar to that in the satellite remote sensing?
Reply: The approximation of the growth rate of the bulge radius from satellite remote sensing has large uncertainty (0.23) as there are too few satellite images available. We have removed from the revised manuscript the parts where bulge measures from satellite images are defined, described, calculated and discussed. Thus, the approximation, $r_b \sim t^{0.31\pm0.23}$, was removed from the revised manuscript.

Comment 11. On page 15, at line 24, " one km" should be "1km"
Reply: Corrected.

Comment 12. On page 16, at line 24, the bulge centre should be defined using geometric mean position of the distribution of the tracer concentration. The reason is that when ambient current overrode bulge circulation, the bulge centre was not defined using with closed streamlines, although the bulge still existed if we look at the distribution of the tracer concentration.

Reply: The bulge centre is defined from the velocity field because we calculate momentum balance and movement of the bulge centre. Momentum balance is calculated in a cylindrical coordinate system where the origin of coordinates is located at the point where angular and radial velocity components are zero. This definition is consistent with previous studies that address momentum balance calculation inside the bulge and movement of the bulge centre (Nof and Pichevin 2001; Horner-Devine et al. 2006; Horner-Devine 2009).

We have calculated the bulge centre as a geostrophic mean position of the distribution of the tracer concentration and from the velocity field for the real bulge (enclosed with answers to the reviewer, Fig. rv2.1). In the case of geometric mean, the bulge centre is close to the river mouth, but 5 km from the bulge centre defined from the velocity field. Placing the origin of cylindrical coordinates in the geometric mean positions and calculating the momentum balance hampers the interpretation and comparison of our results with previous studies. Over the course of the model simulations, the centres of ideal and real bulge defined using geometric mean remain closer to the river mouth than the centres from the velocity field (not shown).

Taking into account the above argumentation, we did not make changes in the revised manuscript.

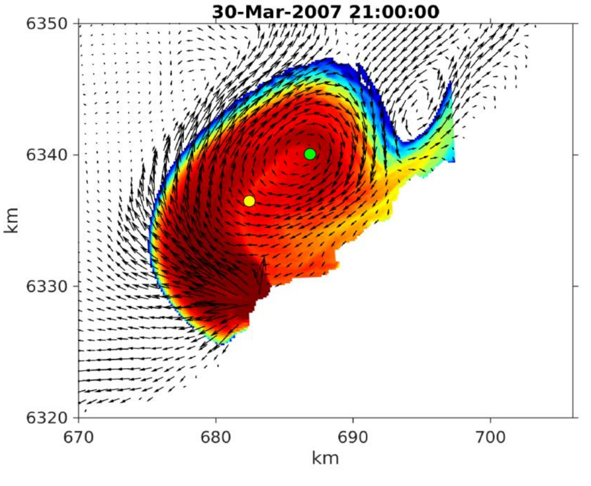

Figure rv.2.1. The bulge centre defined from the velocity (green dot) and as geometric mean position of the distribution of the tracer concentration field (yellow dot)

Comment 13. On page 18, at line 20-22, why the bulge centre was closer to the coast in the case of the ideal bulge than in the case of the real bulge?
Reply: We rephrased this sentence, so that in now offers an explanation there.

Comment 14. On page 30,what is the meaning of white blank area in the bulge in Figure 6 (left column)?
Reply: The blank area within the bulge is where the tracer concentrations were below the threshold values of the bulge definition. This is explained in the figure caption. We added (*see text for bulge definition*) in the figure caption of the revised ms.

Reference

Chao, S.-Y., 1990. Tidal modulation of estuarine plumes. J. Phys. Oceanogr. 20, 1115–1123.
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River bulge evolution and dynamics in a non-tidal sea – Daugava River plume in the Gulf of Riga, Baltic Sea

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Abstract

Satellite remote sensing imagery and numerical modelling were used for the study of river bulge evolution and dynamics in a non-tidal sea, the Gulf of Riga (GoR) in the Baltic Sea. Total suspended matter (TSM) images showed a clearly formed anti-cyclonically rotating river bulge from Daugava River discharge during the studied low wind period. In about 7-8 days the bulge grew up to 20 km in diameter, before being diluted. ~~Bulge growth rate was estimated as $r_b\sim t^{0.31\pm0.23}$ (R^2=0.87).~~ A high resolution (horizontal grid step of 125 m) General Estuarine Transport Model (GETM) was used for detailed description of the development of the river plume in the southern GoR over the period when satellite images were acquired. In the model simulation, bulge growth rate was estimated as ~~, the~~ $r_b\sim t^{0.5\pm0.04}$ (R^2=0.90). Both the model simulation and the satellite images showed that river water was mainly contained in the bulge and there were numerous intrusions at the outer perimeter of the bulge. We made numerical sensitivity tests with actual bathymetry and measured river runoff without wind forcing: 1) having initial 3-dimensional density distribution; 2) using initially a homogeneous ambient density field. In the first case, the anti-cyclonic bulge did not develop within the course of the model simulation and coastal current was kept offshore due to ambient density-driven circulation. In the second case, the river plume developed steadily into an anti-cyclonically recirculating bulge, with $r_b\sim t^{0.28\pm0.01}$ (R^2= 0.98), and a coastal current. Additional simulations with constant cross-~~-~~shore and along~~-~~shore winds ~~This~~ showed a significant effect of the wind in the evolution of the river bulge, even if the wind speed was moderate (3-4 m s^{-1}). ~~In the second case, $r_b\sim t^{0.28\pm0.01}$ (R^2= 0.98).~~ While previous studies conclude that mid-field bulge region is governed by balance between centrifugal, Coriolis and pressure gradient terms, our study showed that geostrophic balance is valid for the entire mid-field of the bulge, except during the 1-1.5 rotation period~~s~~ at the beginning of the bulge formation. In addition, while there is discharge into the homogenous GoR in case of high inflow Rossby number, the river inflow might split into two jets, with strong mixing zone in-between, in the plume near field region.

1 Introduction

River water entering a coastal ocean typically forms a buoyant plume with an expanding anti-cyclonically rotating bulge near the river mouth and a coastal current in the coastally trapped wave direction (Fong & Geyer, 2002). Coastal currents are favoured in the case of low-discharge conditions and downwelling winds, while bulge formation is favoured during high-discharge conditions and upwelling winds (Chant et al., 2008). The anti-cyclonically recirculating bulge is characteristic of the surface advective plume (Yankovsky and Chapman, 1997) being a prominent feature in rotating tank experiments and numerical simulations under ideal conditions (Avicola and Huq, 2003; Horner-Devine et al.~~,~~ 2006; Thomas and Linden 2007). Approximately 25-70% of river water is trapped in the bulge (Fong and Geyer, 2002).

Observational studies confirm that the bulge is a naturally occurring phenomenon with many rivers (Chant et al., 2008, Horner-Devine et al., 2008, Horner-Devine, 2009; Valente and da Silva, 2009; Saldias et al., 2012; Hopkins et al., 2013; Mendas et al., 2014; Pan et al., 2014; Fernández-Nóvoa et al., 2015), but an anti-cyclonic rotation inside a bulge is observed seldom (Kudela et al., 2010, Horner-Devine, 2009; Chant et al., 2008). Observations of the evolution of the bulge over a certain time period are almost non-existent, with the exception of the Niagara River plume (Horner-Devine et al., 2008) and the Tagus estuary plume (Valente and da Silva, 2009). However, both cases are without clear evidence of anti-cyclonic circulation within the bulge.

In natural conditions, the evolution of the bulge is affected by properties of the outflow (Yankovsky and Chapman 1997; Avicola and Huq 2003a), tides (Valente and da Silva, 2009), wind (Dzwonkowski and Yan, 2005; Whitney and Garvine 2005) and the ambient coastal current (Fong and Geyer 2002). Thus, the evolution of the structure and circulation inside the bulge is difficult to observe. Exploitation of optical satellite remote sensing has extended the possibilities of monitoring and understanding the river plume dynamics under various hydrological, morphological and hydrodynamical conditions. A number of existing papers provide composite maps, where plume location and structure is described in response to prevailing wind conditions. Neither evolution of the bulge nor anti-cyclonic circulation within it can be identified from the composite satellite remote sensing images. Although each river plume can be considered as specific, Horner-Devine et al. (2015) have summarized the dynamics of an anti-cyclonically rotating bulge, with special emphasis on the river water volume re-circulating within the bulge. In their study, with reference to Nof and Pichevin (2001), they summarize that with stronger anti-cyclonic circulation within the bulge, more water recirculates in the bulge.

The aim of the present paper is to provide additional evidence of a well-developed anti-cyclonically rotating river bulge, using consecutive optical remote sensing images from a non-tidal sea and to assess current theoretical understanding of river bulge internal structure and dynamics from the complementary numerical model simulation results. We focus on the evolution of an anti-cyclonically rotating bulge during one life-cycle, i.e. from its formation until its dilution with ambient water. The horizontal expansion of the bulge from remote sensing imagery and the reproduction by numerical simulation are compared with modelled undisturbed bulge development and existing theoretical knowledge. The bulge depth, volume of the river water trapped in the bulge and the movement of the bulge centre are evaluated from model experiments. The validity of gradient wind (or cyclostrophic) balance (see equation (2) below) is evaluated for specific time instants in the mid-field region of the plume.

The eastern sub-basin of the Baltic Sea, the Gulf of Riga (GoR), is used as the study area (Fig. 1a). The GoR is almost bowl-shaped, has brackish water and is semi-enclosed (connection with the Baltic Sea through the Irbe Strait, 25 m deep, minimum cross-section area 0.4 km^2 and through the Virtsu Strait which is 5 m deep, minimum cross-section area 0.04 km^2). The circulation in the GoR is mainly driven by wind forcing and 3-dimensional density gradient forcing (Raudsepp et al. 2003, Soosaar et al., 2014, Lips et al. 2016). The mean circulation in spring consists of two main gyres, with the cyclonic gyre covering the eastern and the anti-cyclonic gyre covering the western part of the GoR (Soosaar et al. 2014 Fig. 2.). This two-gyre system ~~, which~~ may transform into a single anti-cyclonic gyre/cyclonic gyre covering most of the basin area during the warm/cold season (Lips., et al., 2016). Small tidal oscillation (O [0.01-0.1 m]; Keruss and Sennikovs, 1999) allows us to consider it as a non-tidal estuary. The main freshwater source for the GoR is Daugava River in the south-east with a high discharge of 2500 $m^3 s^{-1}$ in early spring, which decreases to 200 $m^3 s^{-1}$ in late summer. The present study concentrates on the period from the last 12 days of March and early April 2007, when there was a high discharge of ~2500 $m^3 s^{-1}$ and low wind.

2 Materials and methods

2.1 Satellite Data

ENVISAT/MERIS (Medium Resolution Imaging Spectrometer) data with a 300m resolution from the CoastColour database (http://www.coastcolour.org/data/archive/) was used for monitoring bulge dynamics and structure. MERIS was designed to monitor coastal waters (Doerffer et al. 1999), and

~~it~~ therefore, it has sufficient spectral resolution in the range of wavelengths above 555 nm for monitoring ~~of~~ turbid and optically complex waters like the Baltic Sea (Gitelson et al. 2009). MERIS imagery was preferred to other similar sensors (e.g MODIS) as (i) MERIS based water quality retrievals in optically complex case-2 waters of the Baltic Sea are more accurate due to better performance of the atmospheric correction algorithm (Goyens et al. 2013). In addition, ~~and~~ (ii) MERIS has higher spatial resolution (300m), which enables to resolve detailed features of the river bulge. The MERIS images were processed using the Case-2 Regional (C2R) algorithm (Doerffer and Schiller 2007, Doerffer and Schiller 2008) in the BEAM software package (http://www.brockmann-consult.de/cms/web/beam/) in order to apply atmospheric correction and to obtain the reflectance values used for TSM retrieval. The following pixel quality flags/masks provided in the Level1 Coast Colour product and in the Level 2 C2R product were used to mask the invalid pixels affected by the following phenomena: land, whitecaps, sun glint, cloud, cloud shadow, snow and ice. The C2R algorithm has been validated in various locations in the optically complex waters of the Baltic Sea and it has proven to be suitable for water quality monitoring (e.g. Siitam et al 2014, Attila et al. 2013, Vaičiūtė et al 2012). We used total suspended matter (TSM) concentrations as a marker to distinguish turbid river water from “clear sea water”~~,~~ as TSM shows stronger contrast compared to other biological and physical parameters (SST, CHL etc). Moreover,~~Also~~ a comparative study by Beltrán-Abaunza et al. (2014) showed that TSM concentrations are more accurately retrieved by different standard remote sensing algorithms (including C2R) than ~~the~~ other water constituents. An overall of seven sufficiently cloud free images were available from 20, 26, 27, 29, 30 March and 1 and 4 April. The images were acquired at about 9 a.m.UTC. The satellite data was interpolated to a regular 0.3km 0.3 km grid on the UTM-34v projection. Then the TSM concentrations were smoothed using a 3 3 point median filter.

~~ENVISAT/MERIS (Medium Resolution Imaging Spectrometer) data with 300 m resolution (from http://www.coastcolour.org/data/archive/) was used for monitoring bulge dynamics and structure. The MERIS images were processed using the Case-2 Regional algorithm (Doerffer and Schiller, 2007). We used total suspended matter (TSM) concentrations as a marker to distinguish turbid river water from “clear sea water”, as TSM shows stronger contrast compared to other biological and physical parameters (SST, CHL etc). In studies performed by Siitam et al. (2014) and Attila et al. (2013), the reliability of the algorithm for TSM estimation in the coastal Baltic Sea was confirmed. An overall of seven sufficiently cloud free images were available from March 20th, 26th, 27th, 29th, 30th and April 1st and 4th. The images were acquired at about 9 a.m, UTC. The satellite data was interpolated to a regular 0.3x0.3 km grid on the UTM-34v projection. Then the TSM concentrations were smoothed using a 3x3 point median filter.~~

2.2 River runoff and wind data

Daily volume flux for Daugava River was measured 35 km upstream from the river mouth (coordinates – 56.8516 N; 24.2728 E). Daily volume flux for Gauja and Lielupe rivers (*see* Fig. 1 for locations) was calculated from measured data. As locations of measurement stations are 55 km and 95 km from the river mouth, the measured data was multiplied by factors 1.05 and 1.87 respectively[1], in order to obtain river discharge at the river mouth. The coefficients are obtained as a ratio between the whole catchment area of those rivers and the catchment area of those rivers up to~~ntil~~ the stations where the river flow was measured.

Wind data at one hour intervals was obtained from Ruhnu weather station, which is located on the Ruhnu Island in the central area of the Gulf of Riga (Fig. 1 and 2).

2.3 Numerical model setup: GETM

For numerical simulation we used the fully baroclinic and hydrostatic ocean model GETM (General Estuarine Transport Model (Burchard and Bolding, 2002)) that is coupled to the GOTM (General Ocean Turbulence Model (Umlauf and Burchard, 2005)) for vertical turbulence parameterization. The GETM uses a spherical coordinate system in the horizontal plane and a bottom-following vertical coordinate system. Using a mode splitting technique, GETM solves water dynamics on the Arakawa C-grid (Arakawa and Lamb, 1977). The GETM is characterized by advanced numerical techniques of advection schemes and internal pressure discretization schemes that minimize computational errors (Stips et al., 2004; Burchard and Rennau, 2008). In our setup 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). In our setup we used the third-order monotone total variance diminishing (TVD) advection scheme with the P2-PDM limiter and a half step directional split approach for salinity, temperature and momentum~~Advection scheme TVD P2-PDM was selected, as it has shown lower discrete variance decay rates than other widely used advection schemes~~ (Pietrzak 1998, Klingbeil 2014). Temporal discretization was conducted with a coupled explicit mode splitting technique for barotropic and baroclinic modes.

[1]Methodology worked out and in use for Gauja and Lielupe rivers in LVGMC - Latvian Environment, Geology and Meteorology Centre Institute. http://www.meteo.lv/en/.

The model domain covered the GoR with closed boundaries at the Irbe Strait and the Virtsu Strait. In the study by Soosaar et al. (2014), comparison of monthly mean circulations, with the Irbe and Suur straits being either closed or opened, showed only minor differences that occur mostly near the straits. The coefficient of determination between the two cases for April 1998 was R^2=0.93. Our analyses of model simulations concentrate on the south-eastern part of the GoR~~,~~ where the effect of closed straits is expected to be negligible over the simulation time period of two weeks. Topography was prepared using The Baltic Sea Bathymetry Database (BSHC 2013) and interpolated to a 125 m regular grid. Depths at the head of Daugava were adjusted to include Riga harbour fairway (depth 7 m). The vertical water column was split into 30 density adaptive layers, giving a vertical resolution of under 0.5 m within the stratified bulge area (Gräwe et al. 2015). The barotropic time step was three seconds and the baroclinic time step 60 seconds. Hourly river run-off input from the measurements of three rivers, Daugava, Lielupe and Gauja, were included. Daugava run-off was equally distributed over 7 grid cells. ~~Three rivers, Daugava, Lielupe and Gauja, were included~~. The meteorology was adopted from the EMCWF ERA-Interim dataset with a lateral resolution of 1/4° and a temporal resolution of 6 h (Dee at al., 2011). ~~The meteorology was adopted from EMCWF ERA-Interim dataset (Dee at al., 2011)~~

The model simulation covered the period from 20 March to 5 April 2007. Initial salinity fields were interpolated from the 1 nautical mile simulation for the Baltic Sea (Maljutenko and Raudsepp 2014). The density only depended on salinity. A 3-day spin-up period with a realistic salinity field and a linear increase of river run-off from zero to the measured river run-off value on 20 March 2007 was used before including wind forcing on 20 March (real simulation). TSM was used as a passive tracer for the detection of river water spreading in the model simulation. Initial TSM concentration was set to ~~with~~ zero ~~initial concentration~~ in the GoR and the TSM concentration in river water was set to a unit value. The passive tracer was released to the GoR only as the Daugava River load of TSM, being proportional to the Daugava River run-off starting from 20 March. ~~and with unit concentration load from rivers was set as tracer variable.~~

2.4 Model validation

In situ measurements suitable for the model validation from the study area during high Daugava River runoff are ferry-box measurements on -board the ship travelling between Riga and Stockholm. The available measurements for the estimation of the ~~model~~ ability of the model to reproduce Daugava River bulge dynamics cover the period from 20 March to 4 April 2014. This period com-

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Formatted: Font color: Black, English (United Kingdom) prises the increase of the Daugava River runoff from 600 m^3 s^{-1} to~~until~~ the peak value of 1100 m^3 s^{-1} and the decrease of the runoff to 800 m^3 s^{-1} (Fig. 3a). In total, eight transects from the Daugava River mouth to the central GoR with 2-day intervals fall into the period (Fig. 1). The model setup for the validation run was made similarly to the one described in Sec. 2.3. The d~~D~~aily river run-off input from the measurements of the Daugava River was included. The meteorology was adopted from the HIRLAM-ETA dataset, with a lateral resolution of 11 km and a temporal resolution of 3 h (Unden et al., 2002). Initial salinity fields were interpolated from the HIROMB 1 nautical mile simulation for the Baltic Sea on 20 March 2014 (Funkquist and Kleine, 2000). The density only depended on salinity. No spin-up period was included.

The m~~M~~id-field bulge front can be characterized as~~by~~ the location of maximum salinity gradient. We calculated the salinity gradient along the ship transect from measurements and model results. Maximum gradient location from in situ measurements stayed mostly at 5 km from the river mouth (Fig. 3c). There are two exceptions, on 29 March and 2 April, when the maximum gradient was located at 10 km (Fig. 3c) following a period of wind to the west (Fig. 3b). In the model simulation, the bulge front increase~~s~~d from 1 km on 21 March to 15 km on 24 March. That period corresponded~~s~~ to the period of increase of river runoff and low winds (Fig. 3a,b). Since the evening of 24 March the wind speed increased and the bulge was destroyed. The front retreated to a position ~~was back~~ at 1 km from the river mouth. The b~~B~~ulge started to increase on 27 March and reached a maximum extent of 20 km on the~~at~~ night of 28 March. This corresponds to a peak in river runoff and calm winds. During the rest of the simulation period, the bulge front remained between 2 and 10 km. The root mean square deviation between the locations of simulated and observed bulge front was 2.4 km.

3 Results

3.1 Satellite imagery and model simulation

The first satellite image on 20 March showed the development of three river plumes. The Daugava River plume was far larger (about 8 km in diameter) than Gauja and Lielupe river plumes (Fig. ~~3~~4a) which can also be seen on the numerical model (Fig. 4h). The wind conditions favoured the development of river plumes. From 15 to 19 March~~,~~ wind speed increased from 2 to 10 m s^{-1} (Fig. 2b), which could have generated sufficient mixing to destroy previously formed river plumes as well as avoided the development of a clearly distinguishable river plume. Just prior to the first satellite image, the wind speed dropped from 11 m s^{-1} to 2 m s^{-1}, which may have considerably reduced wind mixing and enabled the free development of river plumes. From 17 to 20 March Daugava River discharge increased from 1500 m^3 s^{-1} to 2500 m^3 s^{-1} (Fig. 2a). The discharges of Lielupe and Gauja rivers were 230 m^3 s^{-1} and 180 m^3 s^{-1} respectively. The river plumes were well distinguishable, as the ambient TSM concentrations was 2 g m^{-3}, compared to 20 g m^{-3} in the bulge centre, in the southern part of the GoR (Fig. 4a). In all three cases, the river water had most likely initially spread offshore, then turned to the right and formed a coastal current. In the bulge, current velocities were up to 50 cm s^{-1}~~,~~ while ambient currents were about 5 cm s^{-1} (Fig. 4h). ~~Thus, a~~All three plumes consisted of a bulge area and a coastal current (Fig. 4a). Coastal current was detached from the coast, leaving a stripe of lower TSM water near the coast (Fig. 4a,h). The offshore location of the maximum currents parallel to the coast and a counter-current at the coast (Fig 4h) were remnants of the previous spreading of river water ~~together~~along with wind- and density-driven currents in the GoR. ~~Lielupe River plume was less pronounced than other river plumes, due to the blocking effect of the Daugava River plume on the right and the decline of the river discharge.~~

~~The wind conditions favoured the development of river plumes. From 15 to 19 March, wind speed increased from 2 to 10 m s^{-1} (Fig. 2b), which could have generated sufficient mixing to destroy previously formed river plumes as well as avoided the development of a clearly distinguishable river plume. Just prior to the first satellite image, the wind speed dropped from 11 m s^{-1} to 2 m s^{-1}, which may have considerably reduced wind mixing and enabled the free development of river plumes.~~

The next image was obtained on 26 March. Checking the sequence of tracer spreading in the numerical model showed that the plume on 26 March was the result of the reset of the river plume on 24 March. The winds of 6 m s^{-1} from the northeast had hampered the free development of the river plume by mixing river water and transporting it offshore. The Daugava River bulge had a diameter of ~~grown significantly, to~~ ~16 km ~~in diameter~~ (Fig. 4~~3~~b). The core of the bulge was almost circular, with many intrusions along the outer rim. In the core of the bulge, freshly discharged water with high TSM concentration formed a jet with an anti-cyclonic spreading pattern along the left side of the bulge. The existence of coastal current could not be verified on the satellite image and the bulge manifested itself as more of a separate feature of the plume. The coastal current had formed as a narrow band pressed against the coast in the numerical model (Fig. 4i). Since the reset of the river plume on 24 March, ~~Meanwhile~~ the wind had been from the northeast, with the~~a~~ speed dropping from 6 to~~of~~ 2 ~~-6~~ m s^{-1} (Fig. 2b, c). As shown in Sec. 3.2, ~~T~~this type of upwelling favourable wind may push the bulge offshore and ~~may~~ cause several intrusions at the open sea area of the bulge (Fig 6b). Model simulation showed strong background anti-cyclonic circulation of about 20 cm s^{-1} in the

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south-eastern GoR (Fig. 4i). ~~have caused slight upwelling at the southeastern coast, downwind coastal currents over the shallow area and an offshore Ekman drift, resulting in the destruction of the coastal current and separation of the bulge.~~ The Gauja River plume consisted of a bulge area and a coastal current attached to the coast. ~~In the previous image, the coastal current of Gauja River plume had been slightly detached from the coast.~~ The Lielupe River plume was almost undetectable, as the volume discharge had decreased to 130 $m^3 s^{-1}$.

During the next 4 days, i.e. until 30 March, the wind speed was very low, between 0-~~2~~3 $m s^{-1}$. We may assume that wind-driven currents and mixing were negligible. The Daugava River bulge remained almost circular and further detached from the coast (Fig. 4c-e, i-l). The main feature within the bulge was anti-cyclonically turning river water with high TSM concentration (Fig. ~~3~~4c-e) and well-established anti-cyclonic circulation in the bulge, with a characteristic current speed of 20 cm s^{-1} (Fig. 4i-l). This gives direct confirmation that water in natural buoyant bulges circulates anti-cyclonically in the northern hemisphere. More water intruded the southern GoR at the western boundary of the bulge. Even low onshore wind may cause significant intrusions at the western boundary of the bulge (Fig 6d). This intrusion spread anti-cyclonically, probably due to ambient circulation, and diluted with surrounding water. No clear coastal currents were visible.

By 1 April, the wind speed had increased to 4 $m s^{-1}$ and was blowing from the north. Daugava River discharge had reduced from ~2000 to ~1500 $m^3 s^{-1}$ (Fig. 2). The image from 1 April still showed a circular bulge with a notably smaller TSM concentration than previously (Fig. ~~3~~4f). The bulge had been transported westward and was nearly detached from the Daugava River outlet. The numerical model captured the tendency of westward transport of the bulge from 30 March to 1 April, but the bulge was more distorted (Fig. 4 m). The strong wind event of 10 $m s^{-1}$ on 2 April had destroyed the bulge and river water with higher TSM concentration had smeared over the southern GoR by 4 April (Fig. ~~3~~4g,n).

~~3.2 Realistic simulation~~

~~The numerical model provides an opportunity for better and more detailed description of the development of the river plume in the southern GoR over the period when satellite images were acquired. The model considers TSM input only from the river discharges (no biology or resuspension from the sediments).~~

~~Daugava bulge had developed by 20 March in the numerical model (Fig. 3h). In the bulge, current velocities were up to 50 cm s^{-1} while ambient currents were about 5 cm s^{-1}. Strong momentum input by rivers caused spreading of tracers away from the coast, which matched the SPM pattern on the satellite image. In the case of the Daugava River plume, coastal counter-current blocked the spreading of tracers at the coast and the formation of a classical coastal current of the river plume. The offshore location of the maximum currents parallel to the coast and counter-current at the coast were remnants of the previous spreading of river water together with wind- and density-driven currents in the GoR.~~

~~By 26 March, bulge has not expanded as much as would be expected (Fig. 3i) based on satellite images from 20 and 26 March (Fig. 3a, b). In addition to strong momentum input from Daugava River, where current velocities were up to 30 cm s^{-1} in the bulge, the strong background anti-cyclonic circulation of about 20 cm s^{-1} prevailed over the south-eastern GoR. This circulation had pushed previous river water offshore and supported northward intrusion of bulge water. The coastal current had formed as a narrow band pressed against the coast. Bulge orientation, offshore extent, northward intrusion at the northern rim and south-westward intrusion at the south-western rim of the bulge were qualitatively comparable to similar features on the satellite image. Checking the sequence of tracer spreading in the numerical model showed that the plume on 26 March was the result of the reset of river plume on 24 March. The winds of 6 m s^{-1} from the northeast had hampered the free development of the river plume by mixing river water and transporting it offshore. Further developments of the Daugava River plume and especially the bulge until 30 March were quite consistent in the model and on the satellite images (Fig. 3i-l). Well-established anti-cyclonic circulation in the bulge, with a characteristic current speed of 20 cm s^{-1}, was confirmed in the model results. The numerical model captured the tendency of westward transport of the bulge from 30 March to 1 April. The bulge retained a circular shape on the satellite image, but was more distorted in the model (Fig. 3l, m). The numerical model showed that the regular river plume started to distort on 31 March (Fig. 3n). The strong wind event of 6-10 m s^{-1} on 2 April started to destroy the bulge in the model as well (Fig. 2).~~

3.2~~3~~ Idealized simulations

In the realistic model simulation, the Daugava River plume was affected by river discharge, ambient currents and wind-driven currents. We made numerical sensitivity tests with 1) river discharge into a stratified GoR, while wind forcing was switched off; 2) river discharge into a homogeneous GoR with an ambient water salinity of 6 g kg^{-1}, while wind forcing was switched off (ideal simulation). In the first case, the anti-cyclonic bulge did not develop within the course of the model simulation and the coastal current was kept offshore due to ambient circulation (Fig. ~~4~~5a). In the ideal run, river plume developed steadily into an anti-cyclonically recirculating bulge and a coastal current (Fig. ~~4~~5b). The bulge length (offshore extent) and width (along-shore extent) as well as the width of the coastal current increased steadily in the course of the model simulation.

Additional simulations with cross-shore and along-shore winds were made with wind speeds of 2 and 4 m s^{-1}. A w~~W~~ind speed of 2 m s^{-1} caused minor, if any, alterations ~~if any~~ in the case of all wind directions (not shown). A ~~W~~wind speed 4 m s^{-1} altered the bulge in agreement with the classical Ekman transport theory. The alongshore downwelling favourable wind pushed~~s~~ the bulge towards the coast and the coastal current was~~is~~ well-developed (Fig. 6a). The alongshore upwelling favourable wind pushed the bulge offshore, so that the bulge was~~is~~ detached from the coast and no coastal current developed~~s~~ (Fig 6b). The bulge had~~s~~ irregular shape with several intrusions at the open sea area of the bulge. In case of offshore wind, the bulge mid-field region was~~is~~ less uniform, was~~is~~ more flat and coastal current was~~is~~ enhanced (Fig. 6c). Onshore wind tilted~~s~~ the bulge to the upcoast direction, with significant intrusions at the upcoast rim of the bulge (Fig. 6d). Coastal current was~~is~~ restrained and had~~s~~ an irregular shape. Thus, comparison of the real run with test cases showed a significant effect of wind in the evolution of the river bulge, even if wind speed was moderate (*see* Fig. 2b).

3.~~3~~4 Temporal evolution of the bulge

The evolution of the river bulge is classically described by the spreading of the offshore front of the bulge and an increase of bulge depth (e.g. Avicola and Huq 2003, Horner-Devine et al. 2006). There are uncertainties in the determination of the edges of a bulge as well as the volume of a bulge. In natural conditions, diffusion and mixing at the edges dilutes river water with surrounding water (Horner-Devine et al. 2015). Multiple previous studies defined the bulge edge based on a preselected threshold value. Horner-Devine et al. (2006) cho~~o~~se a constant 20% buoyancy contour as the reference value. Gregorio et al. (2011) used~~s~~ a reference velocity, 1.7cm/s, to define the coastal current front. Soosaar et al. (2015) defined~~s~~ the bulge edge to be~~as~~ 10% from the discharge depth.

We used TSM concentration to define the bulge boundary. ~~On the satellite images, the threshold values were selected after a visual inspection of TSM concentration maps. Horner-Devine et al.~~

~~(2008) have used a threshold value of normalized water-leaving radiance (nLw) in the 555-nm band to define the edges of the Niagara River plume on SeaWIFS satellite images.~~ Our main criterion was to capture the circular part of the bulge and neglect coastal current as well as most of the intrusions. ~~The threshold concentration varied from image to image as: 1) the TSM concentration of river water was variable and unknown for us; 2) locally, TSM concentration may have changed due to biological activity. The threshold value of $log_{10}(TSM)$ was 1.0 for the image on 20 March, 1.2 for the images on 26, 27, 29 and 30 March and 1.1 for the image on 1 April. No bulge was defined for the image on 4 April. We checked the option to define the edges of the bulge, using spatial gradients of the TSM concentrations. Firstly, this approach did not eliminate the uncertainties, as the local maximum gradient isolines were discontinuous. Secondly, the boundaries of the bulge did not differ significantly from the boundaries that were determined using a threshold value for TSM concentration.~~ In the numerical model, the bulge boundary was defined where $I=log_{10}(TSM)$>-0.15. Different values of I>-0.05, -0.10, -0.20, -0.25 were also used for the bulge boundary. The bulge radius increase~~ds~~d with decreasing I (Fig. 7b) as well as bulge mean depth (not shown), but the dynamics of the bulge di~~does~~d not depend on the selected threshold value for the bulge boundary.

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We compared the temporal evolution of mean depth, radius and volume of the real and the ideal bulge from the numerical model.

In order t~~T~~o be consistent with previous river bulge studies (Horner-Devine, 2009; Horner-Devine et al., 2008; Horner-Devine et al., 2006), ~~T~~the bulge effective radius, r_b, was estimated through the area of the bulge, A_b, assuming a circular shape of the bulge

$$r_b = \left(\frac{A_b}{\pi}\right)^{\frac{1}{2}}. \tag{1}$$

According to the criterion of the bulge definition, the bulge is defined after about 0.5T, where T is rotation period of the earth (Fig. ~~5~~7a, b) and T=0 ≡ 24 March 2007 05:00. Steady increase of the real bulge took place during seven rotation periods. Both mean depth and radius as well as the volume were larger for the real bulge than for the ideal bulge. We would like to note the pulsation of the ~~actual~~ real bulge - when bulge diameter increased, bulge mean depth decreased and vice versa. The decrease of the bulge diameter was faster than the decrease of bulge mean depth during the dissipation phase, which started from 7T. Occasionally, bulge depth even increased. Thus, the water in the bulge was mixed deeper during the dissipation phase.

The volume of river water that went into the bulge increased relatively fast during the first two rotation periods (Fig. ~~5~~7c). In the real case, almost 60% of river water was trapped inside the bulge, while in the ideal case the volume reached 45%. We estimated the volume that was transported away by the coastal current. In order to be consistent with our bulge definition, we calculated water flow at the transect through the model grid cells where *I*>-0.15. During 2T, a negligible amount of river water was transported by the coastal current. During 2T the fraction of river water inside the bulge decreased monotonically, while the volume of coastal current increased (not shown). In the real case, water volume in the bulge increased until the bulge started to dissipate, but steadily retained its 50 % river water content. The fraction of river water started to increase from 4T, but did not exceed 5% until the end of the simulation. In the case of the real bulge, our estimations showed that about 50% of river water could be determined as either coastal current or as bulge due to intrusions and mixing at the boundaries of the bulge and the coastal current (*see* Fig. ~~3~~4), unless we broaden the definition of the bulge. Still, it is obvious from satellite images and simulation results that a far larger amount of river water stayed within the bulge and was transported offshore by intrusions than the amount that formed a coastal current. In the ideal bulge, the fraction of river water decreased after 2T, while the coastal current increased. During 11T, the fraction of volume in the bulge and in the coastal current equilibrated. Thus, we may conclude that in the present case of the Daugava River plume, density- and wind-driven currents oppose the development of the coastal current.

The bulge radius was non-dimensionalized with the bulge Rossby radius

$$L_b = \left(\frac{2Qg'}{f^3}\right)^{\frac{1}{4}} \qquad (2)$$

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where *Q* is river runoff. In our case, the bulge Rossby radius varied between 2.7 and 3.1 km in time, according to the actual runoff of the Daugava River. Time series of increase of non-dimensional bulge radius from numerical simulations are presented in Fig. 7d. We approximated the growth rate of the bulge radius using a power function. In the real case, we excluded the time period when the bulge started to dissipate, i.e. ~~keeping~~maintaining the values ~~until~~ up to 8T. The real and the ideal simulations gave $r_b \sim t^{0.50\pm0.04}$ and $r_b \sim t^{0.28\pm0.01}$, with the coefficients of determination being R^2=0.90 and R^2= 0.98, respectively. Thus, in the real model simulation, the growth of the bulge radius was faster than in the ideal simulation. It can be explained by prevailing upwelling favourable winds

(Fig. 2b,c)~~,~~ which even with a speed of 3-4 m s^{-1} restrained the development of a coastal current and retained more water ~~remains~~ in the bulge (Fig. 6b). Using~~ the~~ thermal wind balance, Avicola and Huq (2003) estimated the growth rate of the bulge radius $r_b{\sim}t^{1/4}$, although in the laboratory experiments they obtained the growth rate $r_b{\sim}t^{2/5}$. From laboratory experiments, Horner-Devine et al. (2006) estimated that a buoyant surface advective bulge expands radially as ${\sim}t^{1/4}$ during the first 5 rotation periods and later as ${\sim}t^{2/5}$~~ at later times~~. The measurement study for the Niagara River bulge (Horner-Devine et al., 2008) gave ${\sim}t^{0.46\pm0.29}$.

3.4~~5~~ Bulge momentum balance

The dynamics of the river bulge are described as balance between centrifugal, Coriolis and pressure gradient terms:

$$\frac{v_\theta^2}{r} + f v_\theta = g' \frac{\partial h}{\partial r} \qquad (~~2~~3)$$

as hypothesized by Yankovsky & Chapman (1997) and confirmed by Horner-Devine (2009) for the Columbia River plume. In (~~2~~3), the v_θ is depth averaged angular velocity, r is radial distance from the bulge centre, f is Coriolis' parameter, g' is reduced gravity and h is bulge thickness. Left side of the equations is centrifugal (T1) and Coriolis term (T2) respectively, right side of the equation is pressure gradient term (T3). We calculated these terms for the case of the real bulge and the ideal bulge development on 29 March 2007 at 20:00 (Fig. ~~6~~8). As was the case previously, the bulge was defined where I>-0.15. The currents were strongest at the steepest slope of the bulge (Fig. ~~6~~8a, b). Although the ideal and real bulges were similar quantitatively, the bulge centre was much closer to the coast (3 km) for the ideal bulge than for the real bulge (6 km). The outer thin area of the ideal bulge was wider than in the case of the real bulge. All terms in (~~2~~3) showed higher absolute values at the steepest slope of the bulge (Fig. ~~6~~8c-h). With the exception of the near field region, the centrifugal force was nearly an order of magnitude smaller than the Coriolis' term and the pressure gradient term. Geostrophic balance was valid for the entire mid-field of the bulge (Fig. ~~6~~8m, n). Taking into account the balance, (~~2~~3), the error even increased slightly (Fig. ~~6~~8o, p).

We calculated the time series of spatially averaged momentum balance terms, Eq. (3), for the ideal (Fig. 9a) and the real bulge (Fig. 9b). In the case of the ideal bulge, all three terms contributed sig-

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nificantly to the momentum balance during the initial phase of bulge development, i.e. up to~~ntil~~ 1T (Fig. 9a). Between 1T and 2T the contribution from the centrifugal force decreased~~s~~, so that this term became~~omes~~ nearly an order of magnitude smaller than the Coriolis term and the pressure gradient term. In the case of the real bulge, the centrifugal force~~ component~~ also decreased during 1T and 2T (Fig. 9b). However, already at the beginning, the initial value of the centrifugal force was~~is~~ an order of magnitude smaller than the Coriolis and pressure terms~~ from the beginning~~. The Coriolis and pressure gradient terms does not have clear increasing or decreasing trend.

~~3.6 Non-dimensional bulge spreading~~

~~The bulge radius was non-dimensionalized with the bulge Rossby radius~~

$$\cancel{L_b = \left(\frac{2Qg'}{f^3}\right)^{\frac{1}{4}}} \qquad \cancel{(3)}$$

~~where Q is river runoff. In our case, the bulge Rossby radius varied between 2.7 and 3.1 km in time, according to the actual runoff of the Daugava River. Time series of increase of non-dimensional bulge radius from satellite images and the respective numerical simulations are presented in Fig. 7. We approximated the growth rate of the bulge radius using a power function. In the real case, we excluded the time period when the bulge started to dissipate, i.e. keeping the values until 8T. The satellite remote sensing and the ideal simulation gave $r_b \sim t^{0.31\pm0.23}$ and $r_b \sim t^{0.28\pm0.01}$, with the coefficient of determination being R^2=0.87 and R^2= 0.98, respectively. In the real simulation, $r_b \sim t^{0.50\pm0.04}$ (R^2=0.90). Thus, in the real model simulation, the growth of bulge radius was faster than in the ideal simulation. Using the thermal wind balance, Avicola and Huq (2003) estimated the growth rate of the bulge radius $r_b \sim t^{1/4}$, although in the laboratory experiments they obtained the growth rate $r_b \sim t^{2/5}$. From laboratory experiments, Horner-Devine et al. (2006) estimated that a buoyant surface advective bulge expands radially as $\sim t^{1/4}$ during the first 5 rotation periods and as $\sim t^{2/5}$ at later times. The measurement study for the Niagara River bulge (Horner-Devine et al., 2008) gave $\sim t^{0.46\pm0.29}$.~~

4 Discussion

A prominent feature in the satellite images and the model simulations was a well-developed anti-cyclonic circulation in the river bulge, which persisted for about 7-8 days. High river discharge and low wind conditions enabled undisturbed development of the bulge. The ideal model simulation showed that the bulge continued to develop steadily for at least 10 rotation periods. Horner-Devine et al. (2006) argues that in the case of high inflow, i.e. large Froude number, $Fr = U(g'H)^{-1/2}$, where $U = Q(HW)^{-1}$, W is river width and H is river depth, the plume becomes unstable after 5-6 rotation periods. In our case, the Froude number stayed between 0.9 and 1.5 during the whole modelling period (W = 700 m, H =7 m). The plume was also stable in the numerical experiments of Nof & Pichevin (2001) and Fong & Geyer (2002).

We estimated the movement of the bulge centre in the ideal simulation. The bulge centre moved steadily to the north, completing about 8 km during nine rotation periods (Fig. ~~8~~10a). As the centre also moved downstream actual offshore reach of the centre was 6 km. The radius of the ideal bulge increased from 4 to 9 km from 0.5T to 10T. Thus, by the end of our simulation the ratio of bulge centre, y_c, to bulge radius was less than 0.7, which according to Horner-Devine et al. (2006) means that the bulge does not separate from the wall and flow into the coastal current does not decrease. The latter was evident from our numerical simulation with the ideal bulge.

The movement of the real bulge centre was more "chaotic" (Fig. 10~~8~~b). At each one-hour timestep, the bulge centre was defined if the anti-cyclonic circulation with closed streamlines existed (i.e. Fig. ~~3~~4k). When ambient current overrode bulge circulation, the bulge centre was not defined (i.e. Fig. ~~3~~4i), although the bulge still existed if we look at the distribution of the tracer concentration. Thus, the movement of the bulge centre was not followed continuously. The main feature in the movement of the bulge centre was offshore-onshore oscillations (Fig. ~~8~~10b). This behaviour is somewhat similar to bulge pinch-off described by Horner-Devine et al. (2006). Horner-Devine et al. (2006) proposed the ratio of internal radius, $L_i = U / f$, to bulge Rossby radius, $L^* = L_i / L_b$, to estimate bulge behaviour. In the case of the Daugava discharge, that ratio was between 0.81-1.26, which corresponds to situations where the bulge is forced offshore relative to its radius (Horner-Devine et al.~~,~~ 2006, Fig. 17d-g). In the case of a high Froude number and/or low g' (in our case 0.045 m s^{-2}), the bulge becomes unstable and the flow to the coastal current is reduced (Horner-Devine~~,~~ et al. 2006). The behaviour of the Daugava river bulge from satellite images and the real numerical model simulation (Fig. ~~3~~4) showed that river water was mainly contained in the bulge and there were numerous intrusions at the outer perimeter of the bulge, which is qualitatively similar to the bulge behaviour in the model simulation by Horner-Devine et al. (2006, his Fig. 14).

Horner-Devine et al. (2015) summarise the results of the volume fraction going into a coastal current ~~current~~ relative to river discharge, depending on inflow Rossby number. A relatively high Rossby number O [1] implies that most freshwater stays in the bulge while a lower Rossby number would imply that there is less water going into the bulge and more into the coastal current. In the Daugava River outflow, the inflow Rossby number varied between 3.4 and 5.7, which suggests that almost all of the river water should have been trapped in the bulge. Our estimates from the numerical model calculation showed that the fraction of river water that formed a coastal current was up to ten times smaller than the amount of river water that remained in the bulge. In the ideal case, considerable volume went into the coastal current, although the *Q*, *Fr*, *Ro* and *g'* were the same for ideal and real model simulations.

The explanation of the discrepancy between the ideal bulge and laboratory experiments could be the different behaviour of the plume in a near-field region. In a near-field region, river flow has a lift off point in the location where river water detaches from the bottom and the upper layer Froude number is equal to one (Horner-Devine et al., 2015). At the lift off point, vertical velocities cause shoaling of the plume interface and acceleration of the upper layer flow at a more seaward region. This, in turn, increases the Froude number, resulting in intense vertical mixing. In our idealized numerical simulation, the lift off occurred at about 0.5 km from the river mouth (Fig. ~~6~~8a). The most intensive mixing started at ~~one~~ 1 km from the coast where tracer concentrations were below the limit of the bulge definition (white area in Fig. ~~6~~8a and low tracer concentration in Fig ~~4~~5a). The intensive mixing suppressed horizontal flow and the current velocities were low right behind the intense mixing zone, while the current velocities were higher at the left and right side of the mixing zone (Fig. ~~6~~8a). Thus, the intensive mixing zone created a barrier for the river water flow and splitted it into two jets. The jet on the right formed a rotating bulge. As the barrier altered the flow direction, the flow angle was notably smaller than 90 degrees, resulting in a bulge centre located closer to the coast (Avicola and Huq, 2003b). The jet on the left remained on the outer edge of the bulge. Such a barrier region is not observed in laboratory simulations. Natural buoyant river plumes have a small vertical to horizontal aspect ratio, O [10^{-3}], where vertical turbulent flux of density is considered to be dominant over horizontal turbulent fluxes (Horner-Devine et al., 2015). For laboratory simulations, the aspect ratio is at least an order of magnitude smaller. Horizontal turbulence flux would be comparable in magnitude with vertical mixing and a sharply separated region of intense mixing is far less likely to form. In addition, in our numerical simulations, the Daugava River runoff was smeared over 5 horizontal grid points right at the coast, which enables a better resolution of the river plume in the near field than, for instance, achieved by Hetland (2005).

In the case of the realistic model simulation, wind mixing overpowered the local mixing, therefore avoiding creation of the barrier region. The density-driven and wind forced background currents restricted the development of a plume coastal current and pushed the river bulge offshore. As a result, the bulge centre was further away from the coast (see Fig. 10~~8~~b).

5 Conclusions

Satellite TSM images showed a clearly formed river bulge from the Daugava River discharge during the studied low wind period. Satellite images also confirmed anti-cyclonic rotation inside the bulge. The bulge grew up to 20 km in diameter before being diluted. A high-resolution numerical model simulation repeated the plume behaviour satisfactorily and enabled a detailed study of the bulge dynamics. While previous studies conclude that balance in equation (~~2~~3) is valid for the bulge, our study showed that geostrophic balance is valid for the entire mid-field of the bulge except during 1-1.5T at the beginning of the bulge formation. Comparison of realistic and idealized model simulations showed a significant effect of wind-driven and density-driven circulation in the evolution of the river bulge, even if the wind speed was moderate.

The bulge radius was non-dimensionalized with the bulge Rossby radius. The real model simulation (measured wind and realistic ambient density) ~~satellite remote sensing~~ and the ideal simulation with no wind and uniform ambient density gave $r_b \sim t^{0.50\pm0.04}$ and $r_b \sim t^{0.28\pm0.01}$, with the coefficients of determination being R^2=0.90 and R^2= 0.98, respectively. ~~gave the growth of the non-dimensional bulge radius as $r_b \sim t^{0.31\pm0.23}$ and $r_b \sim t^{0.28\pm0.01}$, with the coefficient of determination being R^2=0.87 and R^2= 0.98 respectively. In the real model simulation (measured wind and realistic ambient density), the $r_b \sim t^{0.50\pm0.04}$ (R^2=0.90).~~ The bulge spreading rates agree well with laboratory experiments ($\sim t^{1/4}$ by Horner-Devine et al. (2006)) and fit in the margin of the Niagara River bulge study ($\sim t^{0.46\pm0.29}$ by Horner-Devine et al. (2008)).

Mean depth and radius as well as the volume were larger for the realistic model bulge than for the idealized bulge. River bulge behaviour from satellite images and the real numerical model simulation showed that river water is mainly contained in the bulge and there were numerous intrusions at the outer perimeter of the bulge ~~due to~~ caused by prevailing upwelling favourable and onshore winds. The fraction of river water that formed a coastal current was up to ten times smaller than the amount of river water that remained in the bulge.

In the ideal simulation, considerable volume went into the coastal current, although the Q, Fr, Ro and g' were the same for ideal and real model simulations. The ideal numerical model simulation showed that in the case of high inflow Rossby number the river inflow might split into two jets in the plume near field region, with a strong mixing zone in-between. Although the ideal and real bulges were similar, the splitting of the outflow into two jets caused the bulge centre ~~was~~ to be closer to the coast in the case of the ideal bulge than in the case of the real bulge ~~due to splitting of the outflow into two jets~~.

Acknowledgement

Volume flux data for Gauja and Lielupe rivers were provided by state limited Liability Company “Latvian Environment, Geology and Meteorology Centre” in Riga, Latvia. Volume flux data for river Daugava was provided by "Latvenergo AS" (State joint stock Company that provides electricity for the country's citizens). The work was financially supported by institutional research funding IUT (19-6) of the Estonian Ministry of Education and Research.

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Figure captions

Figure 1. Map showing the location of the Gulf of Riga in the Baltic Sea (a). Embedded are mean (bold) temperature (dashed) and salinity (dash dotted) profiles with standard deviations (thin) from the central Gulf of Riga (adopted from Raudsepp, 2001). Topography of the Gulf of Riga (b). Arrows mark river mouth locations for the Daugava (D), Lielupe (L) and Gauja (G) rivers. The square shows the location of the weather station. Bold dashed line shows the transect of ferry-box measurements used for the model validation.

Figure 2. Time series of daily mean Daugava River discharge (a), hourly wind speed (b) and wind direction (c) measured at Ruhnu weather station. Black dots show time instants when satellite images were acquired. The gray area marks the period between the first and last available satellite image from the study period (March 20 to April 4).

Figure 3. Time series of (a) daily mean Daugava River discharge; (b) 3-hour wind speed (bold), east (solid) and north (dashed) wind components from the HIRLAM-ETA dataset at Ruhnu Island, and 3 m s^{-1} wind speed (dash dotted); c) offshore location of the maximum salinity gradient from model (solid) and ship measurements (open square) for the period from 20 March to 5 April 2014. Distance is measured along the ship track from the mouth of the Daugava River.

Figure 4. TSM concentration maps for the southern part of the Gulf of Riga from satellite images (left column) and TSM concentration and surface velocity maps from the numerical simulation (right column). Bold contour on satellite images shows the indicative edge of the Daugava River bulge. Black contours on the numerical model simulation maps represent TSM concentrations of $\log_{10}$(TSM)=-0.15 and =-0.05. The former is used for the determination of the Daugava River bulge. The coordinate system is on the UTM-34v projection. (*Cont)*

Figure 5. Instantaneous surface velocity and TSM concentration maps for simulation with realistic ambient density and no wind forcing (a) and idealized model simulation with uniform ambient density and no wind forcing (b) at noon on 29 March 2007. Solid lines represent TSM concentrations of $\log_{10}$(TSM)=-0.15 and =-0.05. The coordinate system is on the UTM-34v projection.

Figure 6. Instantaneous surface TSM concentration maps for simulation with uniform ambient density and a constant wind speed of 4 m s^{-1} blowing in a downstream (a), upstream (b), offshore (c) and onshore (d) direction at 6T from the start of the simulation. Solid lines represent TSM concentrations of $\log_{10}$(TSM)=-0.15 and =-0.05. The coordinate system is on the UTM-34v projection.

Figure 7. Time series of the Daugava River bulge mean depth (a), bulge radius (b), bulge volume (c) and the bulge effective radius scaled with bulge Rossby radius (d). The solid line represents the real model simulation and the dash-dotted line the idealized model simulation. Time series of the bulge radius where bulge is defined $I=log_{10}(TSM)$>-0.05; -0.10; -0.20; -0.25 (dotted) (b). Time series of cumulative river water (dashed), bulge volume (black) and volume of the coastal current (red) in the real model simulation (solid) and ideal model simulation (dash-dotted) (c). Triangles represent the rotation period of the earth starting from 24 March 2007 05:00.

Figure 8. Bulge depth and depth averaged velocities, the terms (T_1, T_2, T_3) of the balance (see Eq. (3)) and the combinations of the terms for idealized (left column) and realistic (right column) model simulations on 29 March 2007 at 20:00. Bulge depth and depth averaged velocities (a-b), centrifugal term (T_1) (c-d), Coriolis term (T_2) (e-f), pressure gradient term (T_3) (g-h), T_1+T_2 (i-j), T_1-T_2 (k-l), T_2-T_3 (m-n) and T_1+T_2-T_3 (o-p). The contour interval is 1 m s^{-2}. The red isoline represents zero. The blank area within the bulge is where the tracer concentrations were below the threshold values of the bulge definition (*see text for bulge definition*). The origin of the coordinate system is at the mouth of the Daugava River. True north is shown with the arrow. (*Cont.)*

Figure 9. Time series of spatially averaged momentum balance terms (see Eq. (3)): centrifugal term (T_1) (solid), Coriolis term (T_2) (dashed), pressure gradient term (T_3) (dash dotted) for ideal (a) and real bulge (b). Triangles represent the rotation period of the earth starting from 24 March 2007 05:00.

Figure 10. The trajectories of the bulge centre for the idealized simulation (a) and the realistic simulation (b) from 24 March 2007 05:00 to 5 April 2007 00:00. Each dot shows the location of the bulge centre at hourly intervals. Dashed lines show the normal and tangent to the coastline, distance

of the bulge centre from the location at 1T up to the end of the simulation, the distance of the bulge centre at the end of the simulation to the coast in the direction of the normal to the coast. 1T and 4T show the location of the bulge centre after one and four rotation periods of the earth starting from 24 March 2007 05:00 (a). Discontinuities in the bulge trajectories for the realistic model simulation exist because the bulge centre was defined only if anti-cyclonic circulation with closed streamlines was present (b).