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Study of the hydrodynamical processes in the Boka Kotorska Bay with a finite element model

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ABSTRACT

Boka Kotorska Bay, located in the southeastern Adriatic Sea along the Montenegro coastline, is a complex morphological structure, consisting of three embayments. They are connected and interact with the sea through narrow straits and the bay can be considered one of the main freshwater inputs into the southern Adriatic Sea. In the framework of the ADRICOSM-STAR project, a hydrodynamical model of this region provided results that are compared with CTD data and hydrodynamic scenarios are discussed for the bay. A finite element coastal model nested in a finite difference model that runs on the Adriatic Sea has been used to reproduce the complex morphology of the bay. Hydrodynamic modeling allows studying the main characteristics of this bay, identifying it as a Region of Freshwater Influence (ROFI). The freshwater input coming from the numerous sources present in the bays can strongly modify temperature, salinity and current patterns. The computation of the buoyancy ratio of the thermal and haline buoyancy flux showed that the Kotor and Morinj Bays experience a major effect of surface heating in summer, while the rest of the bay seems to be mostly affected by freshwater influence from precipitation and river discharge. An average estuarine situation is seen, presenting a surface outflow and a bottom inflow of water. Specific hydrodynamic processes can be detected in the channels that connect the different sub-basins of the Boka Kotorska Bay. Moreover, the computation of the Kelvin number in correspondence of the internal

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straits suggests classifying the Kotor and Morinj Bays differently from the outermost areas. The innermost Kotor and Morinj Bays, generally exchange little water with the sea and they have high values of residence times. However, their fresh water springs and rivers have the highest discharges that can change abruptly the picture with increase of the total water exchange between the bay and the sea.

1. Introduction

In the eastern border of the Adriatic Sea, characterized by fragmented coastlines, islands, bays and coastal embayments, several examples of transitional areas can be found. Bays and estuaries interact with the main basin influencing and being influenced by it, in terms of circulation patterns and freshwater supply. Several studies started to recognize the presence of sub-basins, like narrow coastal embayments, gulfs and lagoons, and their interaction processes as important topics in coastal hydrodynamic studies in the Adriatic Sea. Even though a lot of information can be found on these types of environments in the northern part of the Adriatic Sea (i.e. the Venice Lagoon, Bellafiore and Umgiesser, 2010; Ferrarin et al., 2010a and the Grado and Marano lagoons, Ferrarin et al., 2010b) much less is known about other important coastal areas of the Adriatic basin. The southern part of the Adriatic Sea plays a fundamental role in the general Adriatic Sea circulation, especially along Montenegro and Albania. The whole area can be identified as a ROFI (Region of Freshwater Influence) mainly because of the presence of several rivers and of the abundant precipitations induced by the orographic conformation with steep and high mountain ranges. An estimated 45% of the total freshwater input coming from rivers is due to the contribution of the eastern Adriatic coast (Raicich, 1994). Raicich (1994) provided statistics based on the measured river discharges but the role and the internal dynamics of embayment in the area is, so far, not well known. Therefore, an investigation of the small scale dynamics, by means of measurements and modeling tools, and the identification of the main hydrodynamic processes in the transitional environments of the area would be a step forward also in the basin general circulation studies. This is the main goal of the present work.

Boka Kotorska Bay (Fig. 1) is one of the most important transitional areas of the region, from both an environmental and a socio-economic point of view. It is formed by three indented branches. The innermost one has two embayments to the South-East and North-West (Kotor and Morinj-Risan Bays, respectively) and is connected by the narrow Verige Strait to the central Tivat Bay. The Kumbor Strait connects the Tivat Bay to the West to the Herceg Novi Bay, which flows into the Adriatic Sea to the South. Karst is present elsewhere, particularly in the Morinj-Risan and Kotor Bays, where subaerial and submarine springs, among them Sopot and Ljuta, can reach peak discharges as large as 200 m^3/s in a very short time. This bay is a primary collector of the freshwater supply coming from springs and karst structures along its border. The investigation of this ROFI system, in terms of dynamics of buoyancy and density flows inside the bay, main circulation patterns and effects of the combined action of forcings (wind, tides, precipitation and river freshwater) in the bay, would continue the work already started in the northern part of the basin in quantifying the role of transitional areas in the more general coastal dynamics of the Adriatic Sea.

A big effort has been done during the ADRICOSM-STAR Project in providing new measurements along the whole North Albania and Montenegro coastal areas that were particularly focused on the Buna/Bojana River and Boka Kotorska Bay. During several cruises with the Dallaporta and Urania Research Vessels in 2008 the water column and the sediments were investigated for physical, biogeochemical and geological studies. New bathymetric data were collected with modern multibeam methods and physical and biochemical properties of the water column, including temperature, salinity, fluorescence, oxygen, nutrients, were carried out by deploying several CTD casts repeated seasonally. In a recent study (Marini et al., 2010) the influence of coastal rivers has been investigated, in terms of eutrophication sources. Other specific studies in Boka Kotorska carried out during oceanographic

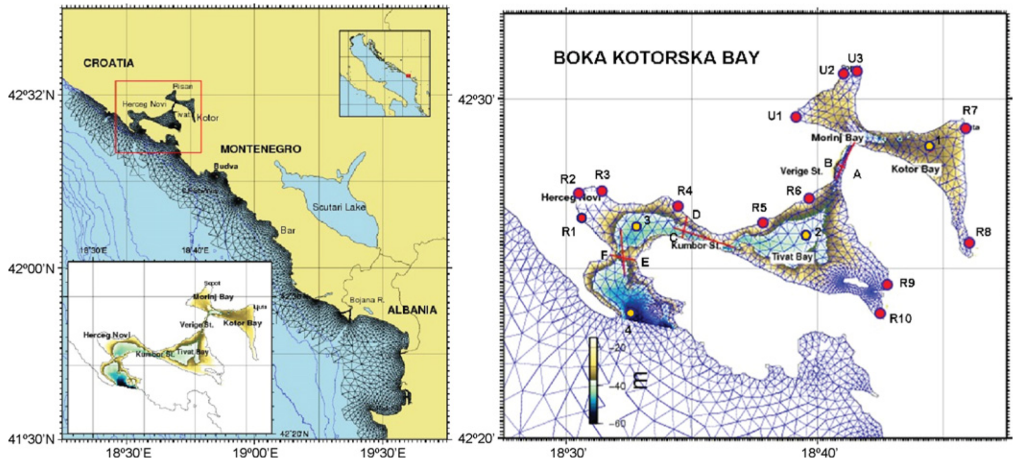

Fig. 1. Geographical setting (left panel). Zoom on the Boka Kotorska Bay, with indication of the bathymetrical structure (right panel). The SHYFEM unstructured grid is shown. Red dots define the location of the freshwater sources and yellow dots are the CTD stations used for the comparison with model results. The across and along-channel sections are indicated in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

cruises inside the bay, concentrated on the spatial distribution of physical, chemical and biological variables in the area (Campanelli et al., 2009).

The spatial characterization of processes and their temporal evolution in such a complex environment can be obtained by means of monitoring, field campaigns and data sampling. Moreover, a tool that can become fundamental in hydrodynamic studies is modeling and the synergy between implementation of models and field data, can provide a wider picture of phenomena. The physical properties of coastal waters in the area have already been investigated by means of both a finite difference model that runs operationally on the whole Adriatic Sea, and measurements from field surveys (Marini et al., 2010). This model that runs on a regular grid with $1/45 \times 1/45$ degrees spatial resolution is suitable for mesoscale investigation. However, to approach more coastal and shallow water domains and investigate smaller scale dynamics, a different modeling tool is needed.

In this work we present and discuss an application of such a modeling tool, aimed at studying the hydrodynamic patterns of the Boka Kotorska Bay and identifying the main characteristics of this ROFI. A nesting experiment between the finite difference model, already tested and applied in the area (Marini et al., 2010), and a finite element coastal model is implemented, thus allowing the description of the bay hydrodynamics with a higher degree of resolution compared to the results of Guarnieri et al. (2010) and Marini et al. (2010). A previous attempt to model the Boka Kotorska Bay was presented in Stevanović and Maksimivić (2007). A finite volume model was used that reproduced the bay morphology putting the open boundaries just outside the bay mouth.

Instead in this work we use a combined approach by means of the nesting technique where both the Adriatic Sea basin and the Boka Kotorska Bay are simulated together. Therefore, the interaction between the two basins is maintained and reproduced. As seen in similar areas, where semi-enclosed sub-basins interact with the main basin (i.e. the Venice Lagoon and its inlets), it can be stated that the simulation of the coupled basins is the only way to be able to identify in a realistic manner the influence of the open sea on this transitional area and the coastal dynamics due to the presence of the bay (Bellafiore et al., 2008; Bellafiore and Umgiesser, 2010).

In the next section a description of the modeling tool, the model setup and the set of data used for the validation and process investigation is provided. In Section 3 the model's ability to reproduce the Boka Kotorka Bay temperature and salinity fields is presented by means of a comparison with in situ data. Also an attempt to characterize the bay hydrodynamics driven by typical winter and summer freshwater scenarios is analyzed. Temperature, salinity, current patterns and residence times are given.

On the basis of model results, the river freshwater/surface heat flux competition is quantified and the ROFI system is characterized by means of the Kelvin number. Then some conclusions are drawn.

2. Methods

2.1. Models description and setup

In this application a nested model system is used. It consists of a coastal finite element model, SHYFEM (Shallow water HYdrodynamic Finite Element Model) (Umgiesser et al., 2004; Bellafiore and Umgiesser, 2010), nested in the outer finite difference model AREG2 (Adriatic Sea Regional Model) (Oddo et al., 2005; Guarnieri et al., 2010).

AREG2 is a POM (Princeton Ocean Model) based operational model that runs on the Adriatic Sea. It is a free surface 3D finite difference model that uses an Arakawa C grid discretization horizontally, with a resolution of $1/45 \times 1/45$ degrees and computes variables on 31 σ layers vertically (Marini et al., 2010). In this version, it resolves also the tidal dynamics.

SHYFEM is a 3D model, based on the solution of primitive equations; it applies the hydrostatic and the Boussinesq approximation. It is a finite element model that runs on an unstructured grid with an Arakawa B-grid type horizontal discretization, usually applied with the finite element method (Umgiesser et al., 2004). It computes scalars (temperature, salinity, water levels) on nodes and vectors (velocity) in the center of each element. Vertically Z layers are introduced. A maximum of 33 layers, with variable thickness from 1 m near the surface to 320 m for the deepest layers in the Adriatic Sea, are imposed.

The unstructured grid covers the coastal area and the main rivers of Montenegro and northern Albania and the Boka Kotorska Bay morphology with a resolution that reaches 50 m (Fig. 1). The resolution reached by SHYFEM inside the bay allows direct comparisons with measured data (e.g. the extraction of the modeled values from the node closest to the considered station, avoiding the introduction of interpolation errors). The bay morphology is accurately reproduced by the finite elements, result that cannot be obtained with coarser resolution models. The coastal area covered by the SHYFEM model grid reaches around 100 km offshore, following the coastline. This choice allows modeling also the main coastal features of the Southern Adriatic Coastal Current (SACC) and providing a realistic picture of the interaction processes between the main basin, the Adriatic Sea, and the transitional area here studied. This is a fundamental aspect, from a modeling point of view, taking into consideration different spatial scales to reproduce the interaction processes that can affect the internal dynamics.

The coastal model is laterally forced with daily averaged temperature and salinity and hourly water levels and currents from the AREG2 model that runs operationally on the whole Adriatic Sea basin. The meteorological surface forcing, in terms of wind fields, atmospheric pressure, air temperature, relative humidity and cloud cover, is taken from the ECMWF T511 0.5×0.5 degrees model while shortwave radiation is from the AREG2 model. The monthly climatological precipitation of Legates and Willmott (1990) is used for the computation of the surface water fluxes. Evaporation is computed by the coastal model. Finally, the climatological values from Raicich (1994) are used for the coastal river runoff discharges.

2.2. Bathymetries and CTD Data

Multibeam bathymetric data for Boka Kotorska Bay were collected from the R/V Urania during ADRICOSM-STAR cruise ADR02-08, using RESON 8160 and PDS2000 navigation and acquisition software. Sound speed profiles were obtained by CTD casts with a Mod. 911 SeaBird probe. Processing was performed by the Kongsberg's Neptune package. Final grids were computed by the GMT package (Wessel and Smith, 1995) merging the filtered multibeam data with very shallow water depths obtained from published maps, to avoid gaps. Resolutions of 0.35 arcsec and 10 m were obtained in the geographical domain and UTM, zone 34, projection, respectively. The coastal offshore bathymetric mesh was obtained by bilinear interpolation of USGS data at the resolution of 7.5×7.5 arcsec.

The bathymetric data collected in Boka Kotorska reach 10 m of spatial resolution and this information, interpolated on the high resolved unstructured grid of the coastal model, allows an accurate reproduction of the bay morphology.

Temperature and salinity data were collected with a SeaBird Electronics SBE 911-plus CTD during four cruises aboard R/V G Dallaporta in the periods 21–29 January 2008, 9–15 May 2008, 24–29 June and 23 October 2008 (Campanelli et al., 2009). Data were processed following UNESCO Standards (AAVV, 1988). The 4 stations in Boka Kotorska used for the model data comparison are indicated in Fig. 1.

3. Results

The study of Boka Kotorska hydrodynamics by means of the modeling tool, with a specific focus on the factors characterizing it as a ROFI – i.e. river freshwater and surface heat and water mass flux effects in density driven currents formation – is here presented. First, we verified the modeling approach, to define the capability of the nested coastal model to reproduce the temperature and salinity fields. T/S modeled profiles have been compared with CTD measurements collected in the 2008 cruises, identifying the effect of river discharge. Moreover, the two extreme river inflow scenarios, the maximum and the minimum Discharge, have been studied, providing maps of spatial temperature and salinity variability. Within the framework of the two aforementioned scenarios, the water circulation in the bay and channels and the relative residence times have been analyzed, aiming at obtaining a full picture of the bay hydrodynamics. The residence time here computed is defined, accordingly to the work of Cucco and Umgiesser (2006) and Cucco et al. (2009), as the time required for each element of the domain to replace most of the mass of a conservative tracer with new water. The complete formulation is defined in Takeoka (1984a,b). The choice to use this RT formulation, instead of the one based on transit time (WTT), defined as the time it takes for any water particles of the sample to leave the basin through its outlet, is derived from Cucco et al. (2009). In fact Cucco et al. (2009) see how RT is not affected by the phase of the tidal forcing at the beginning of the computation, as instead happens for WTT. Therefore, the RT formulation is chosen due to the introduction of tidal forcing in this work.

Finally, trying to characterize Boka Kotorska bay as a ROFI system two quantities are analyzed: the Kelvin number, the ratio between the width of the basin and the internal Rossby radius of deformation that allows a classification of studied ROFI system (Garvine, 1995); and the absolute value R of the buoyancy ratio between the surface thermal and the haline components acting in the freshwater/heating-mixing competition (Birol Kara et al., 2008). Since we are aware of the fact that we are dealing with idealized scenarios, the aim was to depict major differences between the modeled hydrodynamics in the two scenarios.

3.1. T/S profile comparison in Boka Kotorska

Zooming on Boka Kotorska, a comparison is made between the modeled temperature and salinity profiles and the field CTD data. The investigation has been performed for the four field surveys on 25 January, 10 and 12 May, 26 June and 23 October 2008.

The set of simulations given in this section are defined considering the information from previous studies (Stevanović and Maksimivić, 2007; Campanelli et al., 2009). On (Stevanović and Maksimivić, 2007) yearly average, minimum and maximum discharge values of freshwater sources in the bay are provided. Their locations are shown in Fig. 1 and values are listed in Table 1. The nomenclature uses R for surface sources and U for underground sources. Since there is no data of temperature of freshwater inputs available, and only statistics on spring discharges inside the bays are provided from the literature (Stevanović and Maksimivić, 2007), several scenarios are tested, to define the best model setup that matches the measurements. This set of simulations allowed identifying the degree of variability for T/S profiles reproduction due to different spring freshwater inputs.

The SHYFEM model is forced with climatological precipitation of Legates and Willmott (1990), that gives an indication of the characteristics of the precipitation in the bay but it cannot follow the real behavior. Instead, trying to match the field CTD data against the model data obtained by mod-

Table 1
Minimum, maximum and average discharge for each freshwater source inside Boka Kotorska Bay, as shown in Fig. 1. These values are obtained from Stevanović and Maksimivić (2007) keeping the same names and are used as freshwater inputs for model simulations.

		Minimum discharge [m^3/s]	Maximum discharge	Average discharge
R1	Herceg Novi	1.0	40	15
R2		0.4	6.0	3
R3		0.4	20.0	7.0
R4		0.5	10.0	4.0
R5		0.0	1.0	1.0
R6		0.0	1.0	1.0
U1	Kotor	0.5	9.5	10.0
U2		0.05	30.0	20.0
U3		0.0	50.0	25.0
R7		0.1	330.0	100.0
R8		0.8	30.0	20.0
R9	Tivat	0.5	5.0	5.0
R10		0.1	2.0	2.0

ulating freshwater discharges in the bay between minimum and maximum values, we have further information on the relationship between freshwater outflows and precipitation in the studied periods.

For each period, the different setups were tested. First, following the indication from climatological precipitation, freshwater discharges in the bay are imposed, putting the maximum values in correspondence of high precipitation periods (January, June) or minimum values in correspondence of low precipitation periods (October). The hypothesis that high precipitation is directly connected with high spring discharges will be analyzed, knowing that karst areas are present all around the bay and that there can be effects of stock volume.

The simulation setup is described in Table 2, defining the forcing variations in terms of freshwater discharges and temperatures.

3.1.1. January 2008 simulation

January is a month when high precipitation occurs; the first simulation imposes the maximum discharge for freshwater sources, as indicated in Stevanović and Maksimivić (2007). As a first approximation the freshwater temperature is set equal to the basin temperature, applying a radiation condition (sim AJAN). Fig. 2 upper panel shows the root mean square (RMS) error and the bias, between the field CTD data and the model temperature and salinity profiles. These values are computed considering measurements in the four stations taken the 26th of January 2008. A small bias is present for temperature, with a small model overestimation (1 °C) in the first layers and a small underestimation (−0.5 °C) in the lower layers. On the other hand, a large underestimation of salinity is found. Therefore

Table 2
Set of coastal model simulations.

Comparison date	Simulation	River runoff discharge in Boka Kotorska	River water temperature
26th January 2008	AJAN	Maximum	Basin temperature
	BJAN	Average	Basin temperature
	CJAN	Minimum	Basin temperature
14th May 2008	AMAY	Minimum	T river (30 °C) > T basin
	BMAY	Average	T river (30 °C) > T basin
	CMAY	Maximum	T river (30 °C) > T basin
25th June 2008	AJUN	Maximum	Basin temperature
	BJUN	Average	Basin temperature
	CJUN	Minimum	T river (30 °C) > T basin
23rd October 2008	AOCT	Average	Basin temperature
	BOCT	Minimum	Basin temperature
	COCT	Minimum	T river (20 °C) > T basin

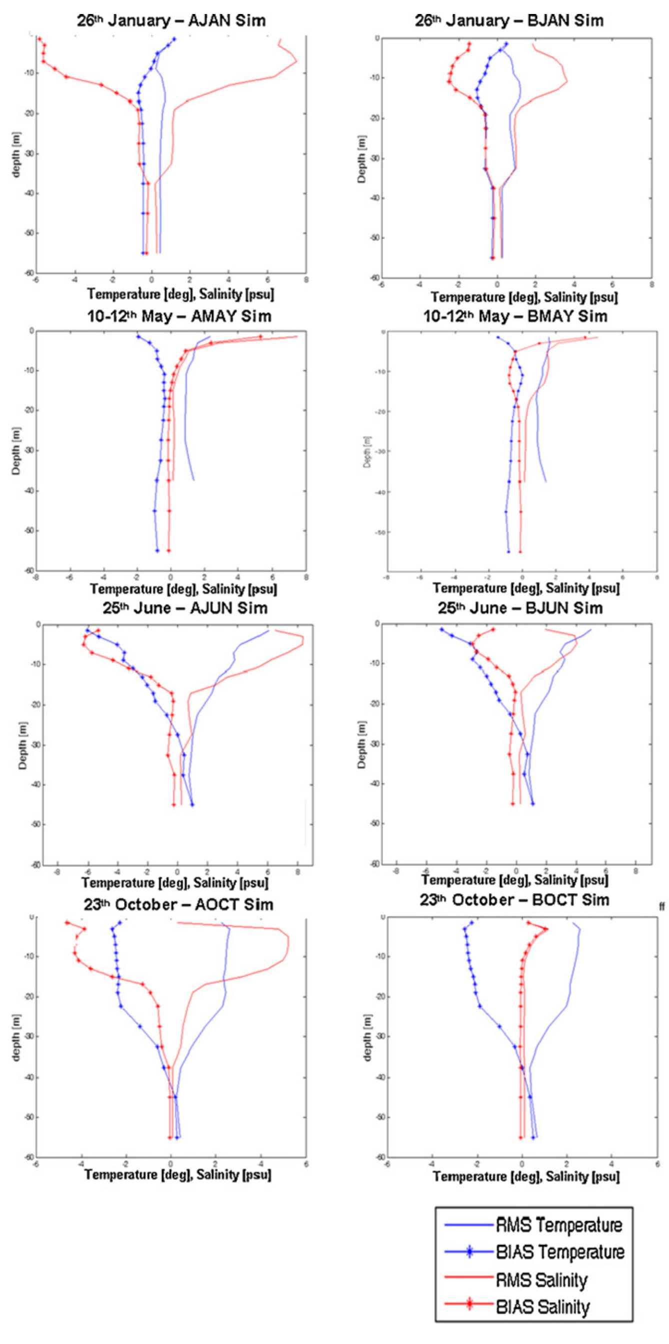

Fig. 2. Temperature RMS error and BIAS (blue) and salinity RMS error and BIAS (red) profiles between CTD data and the results of simulations in January, May, June, October 2008 (see Table 2). The profiles are the average of four stations in January, May and June, and eigth stations, in October 2008, in Boka Kotorska. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

it can be hypothesized that high precipitation, for January 2008, could not be automatically connected with simultaneous high spring discharges. Therefore, a second simulation was performed imposing the average freshwater discharge (sim BJAN, central panel). The salinity bias (−2 psu) and RMS are smaller than the previous case. A third simulation (CJAN), imposing the minimum discharge values, resulted in positive T/S biases in the upper layers.

3.1.2. May 2008 simulation

May 2008 situation was previously considered for test simulations, not shown here, to identify the best model setup for coastal application. From these tests we already know that freshwater sources have a higher water temperature than the basin. For the three runs here presented, we set river water temperature at 30 °C, obtaining a bias of [−1,−1.5] °C. In the first simulation (Sim AMAY, minimum discharge) the model salinity is bigger than the measured one, with a bias of +6 psu in the surface layers (Fig. 2). Applying the average discharge values (Sim BMAY) salinity bias is smaller (+4 psu) but, still, there is an overestimation in the upper layers. Forcing with the maximum discharge for freshwater sources (Sim CMAY) salinity bias becomes negative in the upper layers (−2 psu).

3.1.3. June 2008 simulation

Since this period is climatologically characterized by high precipitations, Sim AJUN (Fig. 2 central panel), imposes maximum freshwater discharge at the basin temperature. RMS error and the bias for temperature and salinity showed a big underestimation of the model both for temperature (−6 °C) and salinity (−6 psu) in the surface layer. These results suggest, for the BJUN setup, the setting of average freshwater discharge, keeping its temperature as the basin one. A big improvement in salinity reproduction is obtained (−2 psu, Fig. 2 central panel), whereas only small changes are seen in temperature RMS and bias from sim AJUN. In sim CJUN the minimum freshwater discharge is imposed, with freshwater temperature of 30 °C, considering that June is generally characterized by freshwater temperature higher than basin temperature. There is an improvement in temperature bias, keeping the underestimation to −3 °C in the surface layers (Fig. 2). With warmer freshwater inputs the solution might better match the results. Moreover, a positive salinity bias is registered in the surface (+2 psu, Fig. 2).

3.1.4. October 2008 simulation

Sim AOCT sets the average freshwater discharge at the same temperature of the basin. There is a big underestimation of the surface salinity by the model (−4 psu, Fig. 2 lower panel), while temperature is underestimated by about 2 °C. In sim BOCT, following the indication from precipitation climatology that states that October is a minimum precipitation period, a minimum freshwater discharge at basin temperature is introduced. The salinity bias becomes smaller, almost zero in the lower layers, with an overestimation of less than 1 psu in the deep layer. In sim CJUN the same setup of the previous simulation is kept but freshwater sources are imposed at 20 °C. As is clear from the central and the lower panel of Fig. 2, no differences in temperature bias and RMS error can be detected.

3.2. Characterization of the Boka Kotorska Bay hydrodynamics

The comparison between CTD data and model results point out that variations of discharge and temperature values, in the internal spring and underground sources, can strongly affect the T/S fields inside the bay. Moreover, the previous comparison stresses the need to collect data to provide realistic values of temperature and discharge for the internal freshwater sources. In cases like this, the modeling tool allows investigating the major hydrodynamic features of a basin by means of idealized scenarios as approximations of extreme conditions occurring in it. In this section we try to characterize the Boka Kotorska hydrodynamics, considering two extreme scenarios patterns having (a) the maximum freshwater discharge, describing a winter configuration with high precipitation, and (b) the minimum freshwater discharge, common in the dry summer season.

Applying the minimum and maximum discharge data from Stevanović and Maksimivić (2007) for the freshwater sources shown in Fig. 1, we run the model for January 2008, maximum discharge imposed, and for August 2008, minimum discharge imposed. The initial conditions, in terms of T/S fields are horizontally extrapolated from the AREG2 model due to the lack of T/S measured profiles inside the bay for both the scenarios (available for January 2008 but not for August 2008). The simulations are run for 35 days, considering the first five days as spin-up. The two month simulations are forced with the ECMWF atmospheric forcing and, as in all the previous simulations, they are forced at the lateral and surface boundaries with AREG2 data.

These two scenarios patterns were chosen to study periods of both large and small freshwater supply in the bay, from river discharges and precipitation. Therefore, even though T/S initial and boundary conditions and meteorological forcings for January and August 2008 are used, the scenarios should not be considered as representative of these specific months.

The monthly average temperature (Fig. 3), salinity (Fig. 6) for the surface layer and the 13th layer (25 m, hereafter called deep layer) and vertically integrated values are analyzed. Temperature and salinity sections, across and along the channels connecting the three bays that form the Boka Kotorska Bay (Fig. 1), are also shown to add information of the interaction between sub-basins. To quantify the river freshwater/heating competition in the formation of the density driven flows the absolute value of the buoyancy ratio *R* of the thermal and haline buoyancy flux (Birol Kara et al., 2008) is also computed.

In addition to this, current velocity maps (Fig. 10) and sections (Figs. 11 and 12) are analyzed and residence times for each scenario are computed (Fig. 13).

Finally, introducing this work in the context of ROFI systems studies, the Kelvin number, for the whole bay and for the three across-channel sections shown in Fig. 1, is computed. The Kelvin number is recognized as a useful quantity for the classification of a ROFI system (Garvine, 1995; Simpson, 1997; Valle-Levinson, 2008).

3.2.1. Temperature

In Fig. 3 surface (top panel), deep layer (central panel) and the integration over the all water column temperature maps are shown. The maximum discharge scenario shows a homogeneous pattern, with temperature that varies only around 1 °C in Boka Kotorska, in the range [12.5–13.5] °C. Temperature does not vary particularly in the water column, suggesting a vertically homogeneous structure. The map of vertically integrated temperature shows how colder water is present in the inner part of the bay (12 °C), while the warmer one is present approaching the open sea (14 °C). A more spatially varying situation is seen in the minimum discharge August 2008 scenario. In the surface layer there is a temperature gradient from 19 °C in the inner part of the Bay to 16–17 °C approaching the open sea (Fig. 3). A similar structure is seen in the vertically integrated temperature map. In the summer simulation the deeper layer is colder than the surface, while in the winter scenario a slightly unstable temperature stratification is seen but with values in the range of some tenths of one degree.

From the across-channel sections shown in Fig. 4 more results can be carried out: for both scenarios there is a horizontally homogeneous behavior in the inner section while the other sections show, for the maximum and minimum discharge scenarios, respectively, lower (13.1 °C) and higher (18–19 °C) temperatures in the south-eastern side of the channels (from a bay to sea perspective). This is more evident in the minimum discharge scenario. Almost a 0.5–1 °C gradient can be seen along the Tivat and the Herzeg Novi sections. It seems that a surface vein of warmer water flows following the left border of the bays to the sea. On the other hand, in the maximum discharge scenario a less defined surface cold water vein follows the same path, but it can be recognized only in the Herzeg Novi section. Moreover, the along-channel section of the Verige Strait (Fig. 5) shows a temperature gradient in correspondence of a sill keeping a pool of colder (12.5 °C) and warmer (19.5 °C) water in the Kotor-Morinj Bay, for the maximum and the minimum discharge scenarios, respectively.

3.2.2. Salinity

The biggest difference between the two scenarios can be detected in the salinity maps (Fig. 6). The maximum discharge produces a salinity gradient from 28 psu in the Kotor-Morinj Bay to 37 psu near the inlet mouth. A more homogeneous and saline structure is seen in the minimum discharge scenario (values around 38.5 psu).

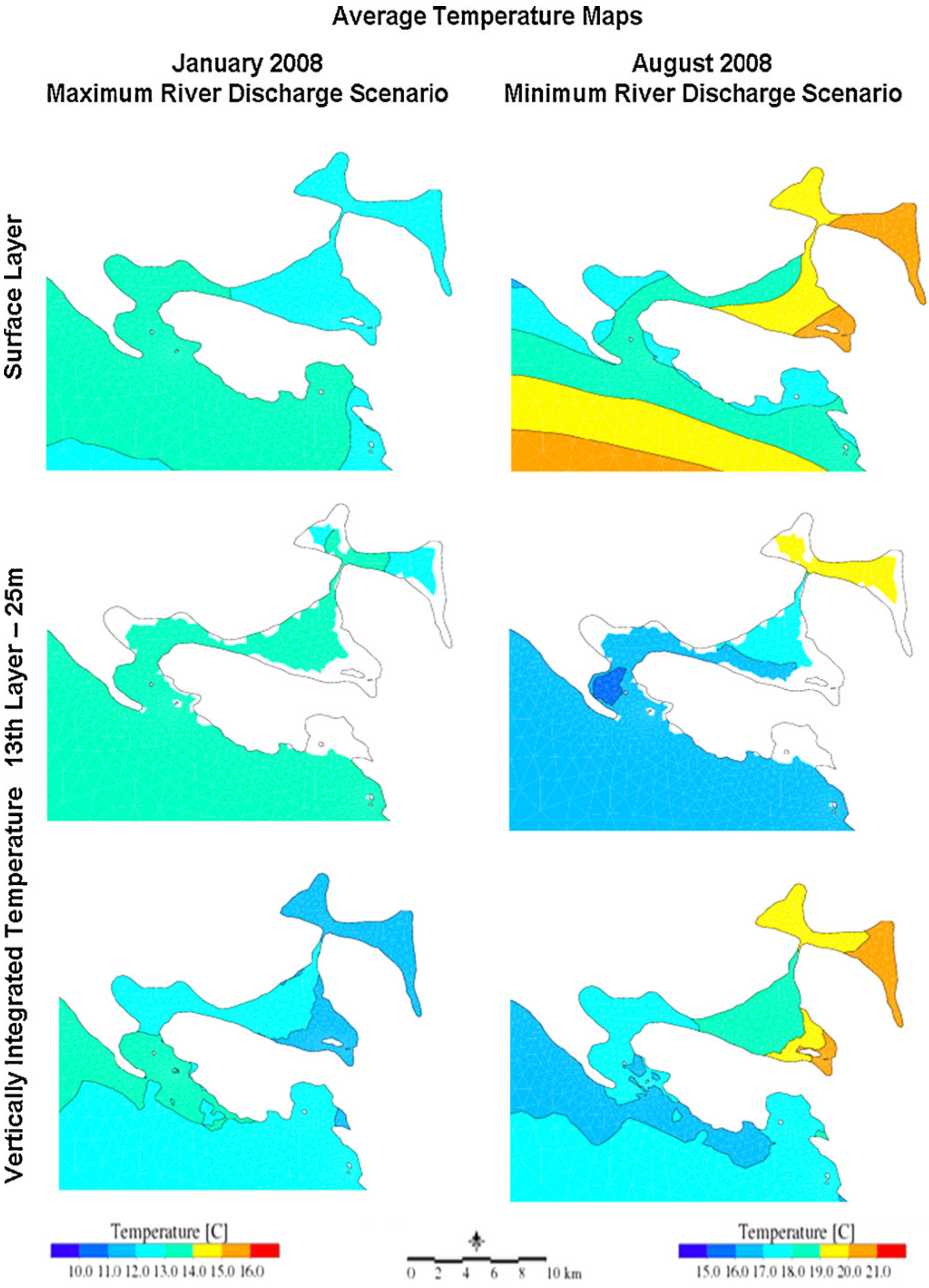

Fig. 3. Model results. Surface (upper layer), deep layer depth 25 m (central panel), and vertically integrated temperature (lower panel) in Boka Kotorska for two freshwater discharge scenarios. Left panels show the monthly average temperature for January 2008 forced with maximum discharge of freshwater sources in Boka Kotorska; right panels show the monthly average temperature for August 2008 forced with minimum discharge of freshwater sources in Boka Kotorska.

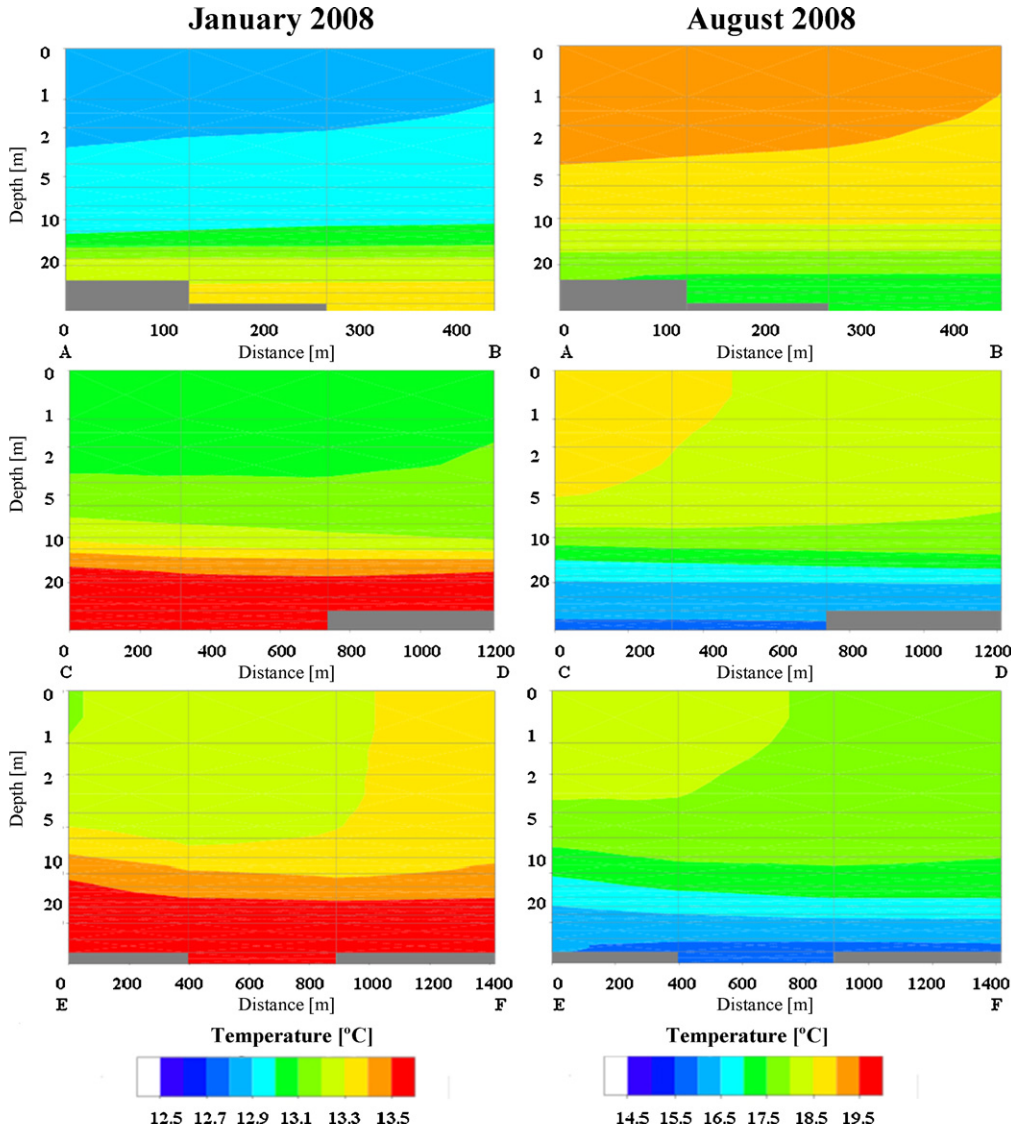

Fig. 4. Model results. Inner (top panels), central (central panels) and outer (bottom panel) temperature cross-channel sections. Left panels show the monthly average temperature for January 2008 forced with maximum discharge of freshwater sources in Boka Kotorska; right panels show the monthly average temperature for August 2008 forced with minimum discharge of freshwater sources in Boka Kotorska. The location of the sections are shown in Fig. 1.

A strong vertical salinity gradient (more than 12 psu) with a flow of freshwater in the surface is seen in the inner cross-channel section for the maximum discharge scenario, while the vertical stratification is attenuated for the outer sections (Fig. 7). With regard to the minimum discharge scenario no important vertical salinity variation can be detected (less than 0.2 psu in the inner cross-channel section). From the along-channel section of the Verige Channel (Fig. 8), as seen for the temperature profiles, also salinity feels the presence of the sill: for the maximum discharge scenario the surface salinity water layer is reduced in depth by the bottom effects of the sill but still flows in the Tivat

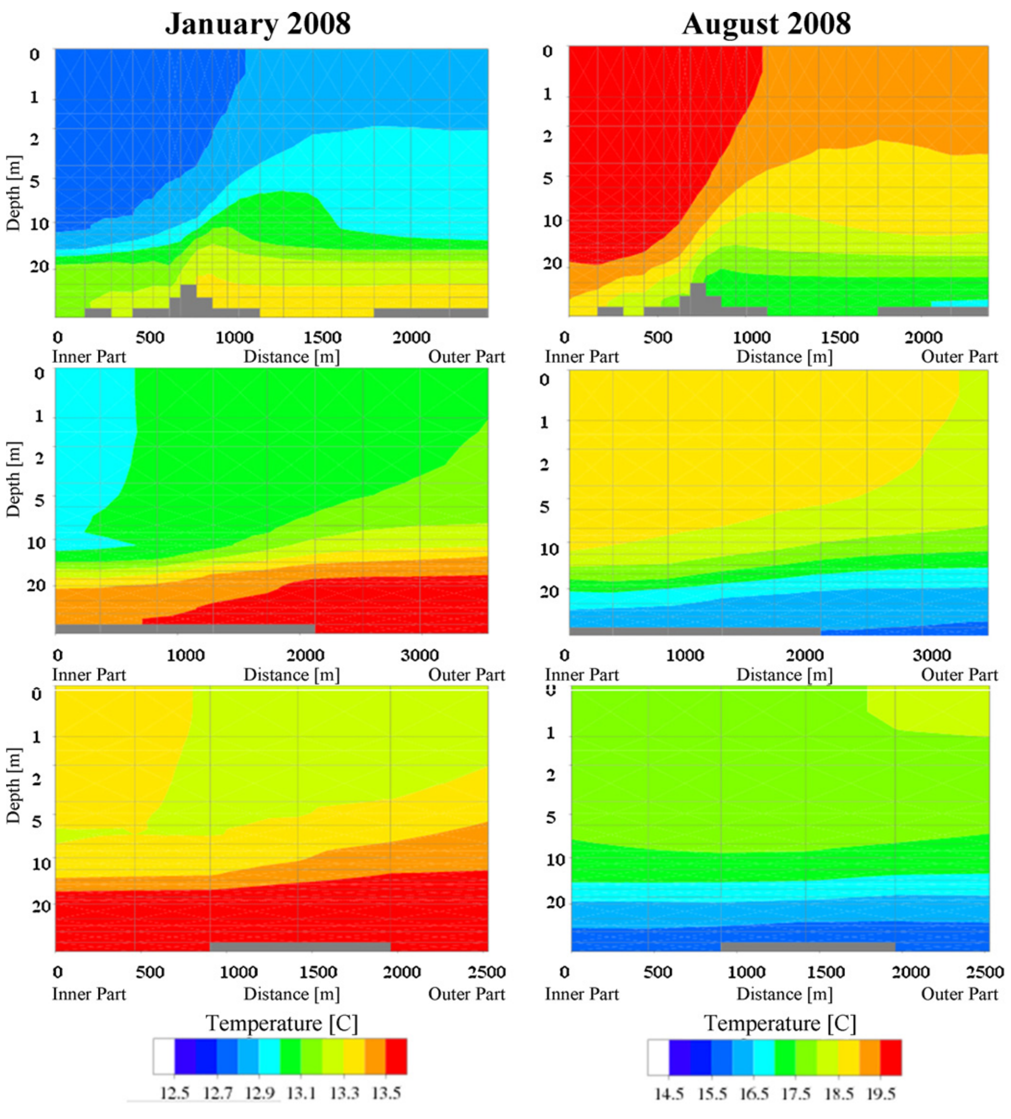

Fig. 5. Model results. Inner (top panels), central (central panels) and outer (bottom panel) temperature sections, along the channels. Left panels show the monthly average temperature for January 2008 forced with maximum discharge of freshwater sources in Boka Kotorska; right panels show the monthly average temperature for August 2008 forced with minimum discharge of freshwater sources in Boka Kotorska. The location of the transversal sections are shown in Fig. 1.

Bay, while a salinity front is seen for the minimum discharge scenario even if the salinity gradient is smaller (38.2–38.3 psu, upper right panel Fig. 8).

3.2.3. Buoyancy ratio

In order to identify whether the vertical changes in temperature or the ones in salinity are more effective in the formation of density driven flows, the absolute value of the buoyancy ratio *R* of the

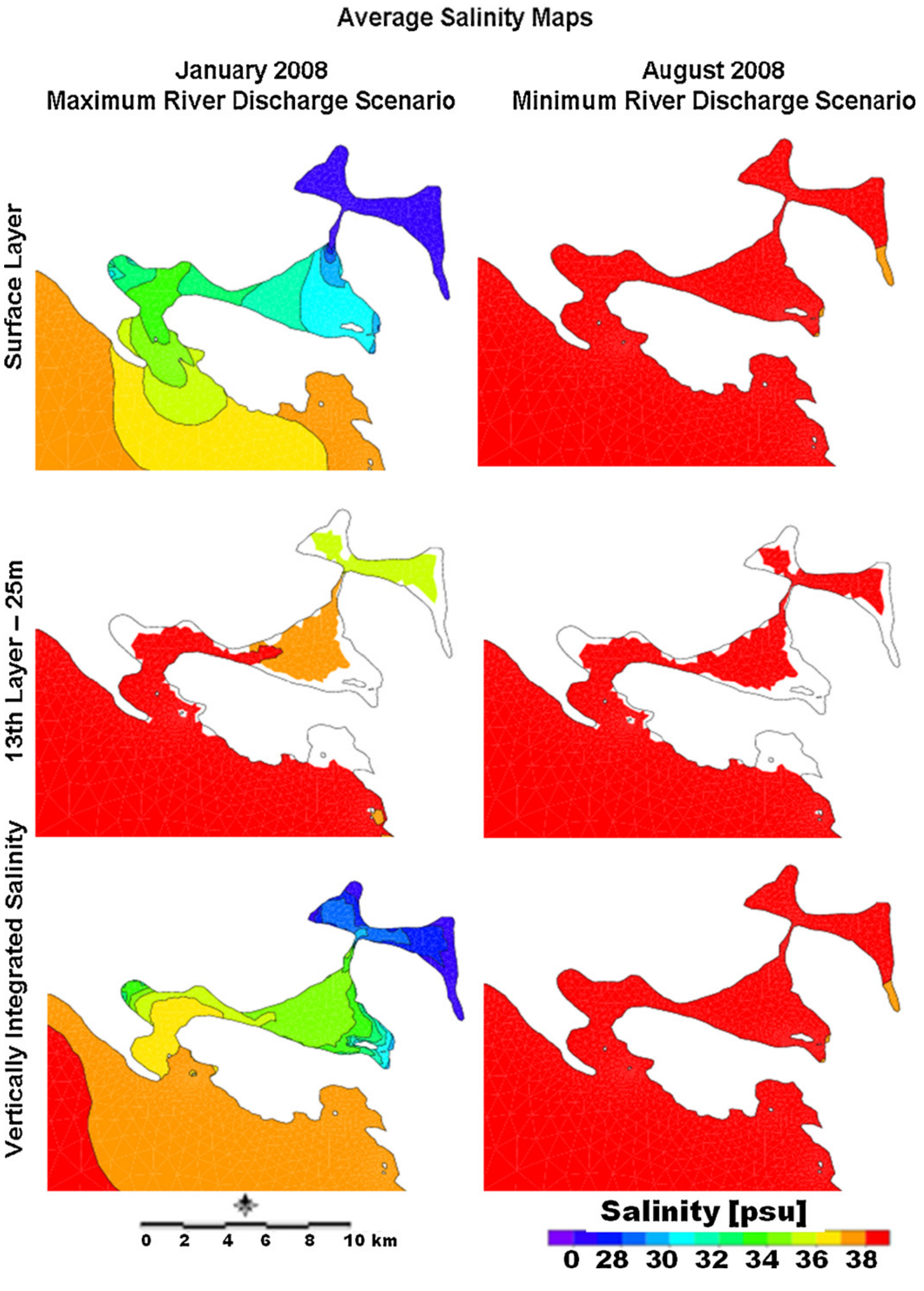

Fig. 6. Model results. Surface (upper layer), deep layer depth 25 m (center panel), and vertically integrated salinity (lower panel) in Boka Kotorska for two freshwater discharge scenarios. Left panels show the monthly average salinity for January 2008 forced with maximum discharge of freshwater sources in Boka Kotorska; right panels show the monthly average salinity for August 2008 forced with minimum discharge of freshwater sources in Boka Kotorska.

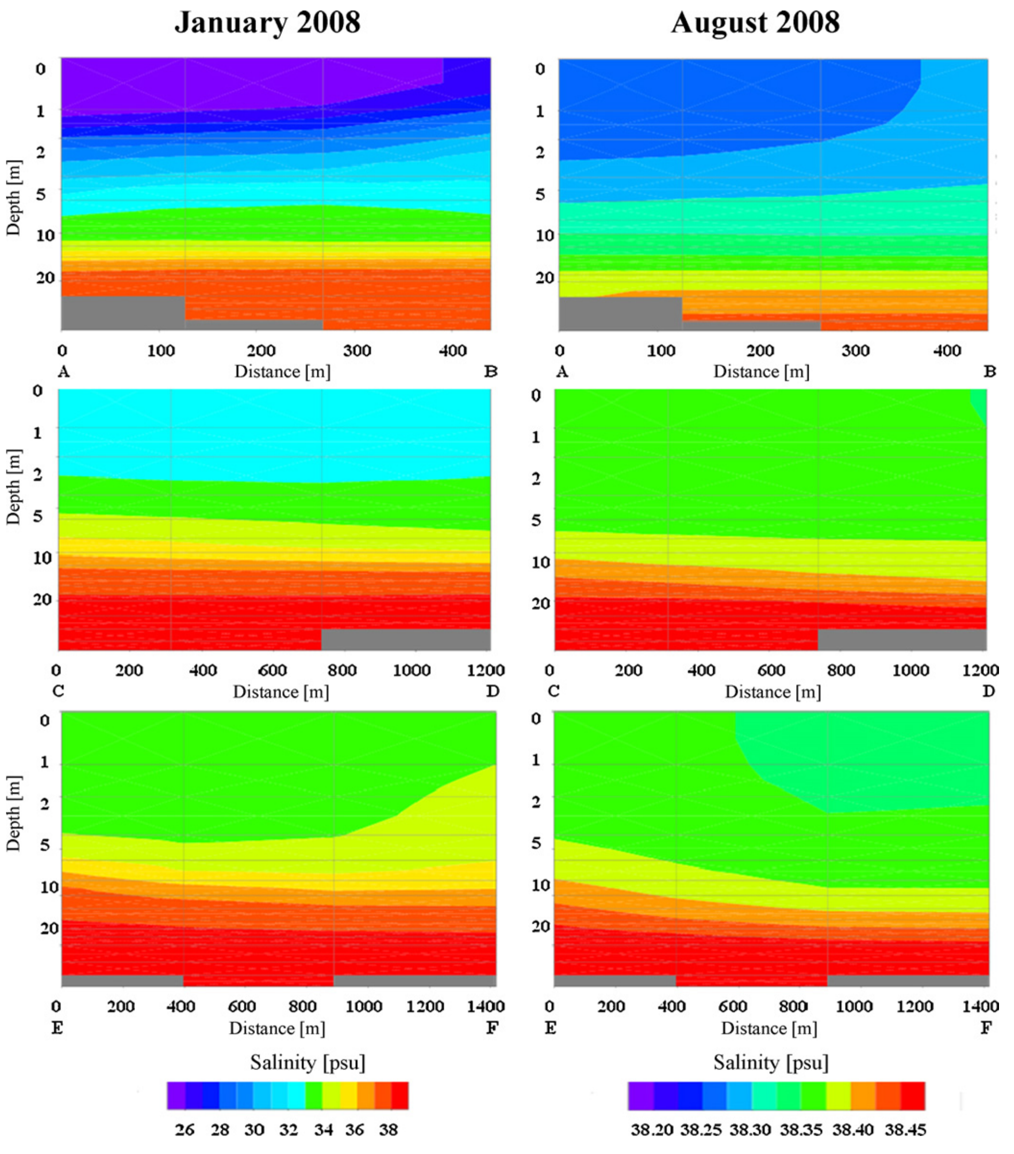

Fig. 7. Model results. Inner (top panels), central (central panels) and outer (bottom panel) salinity sections. Left panels show the monthly average salinity for January 2008 forced with maximum discharge of freshwater sources in Boka Kotorska; right panels show the monthly average salinity for August 2008 forced with minimum discharge of freshwater sources in Boka Kotorska. The location of the sections are shown in Fig. 1.

thermal and haline buoyancy fluxes is here computed for the two scenarios. The buoyancy ratio is computed as follows:

$$|R| = \left| \frac{Q_a \alpha(T, S)}{\rho_0 C_w \beta(T, S)(E - P)S} \right| \tag{1}$$

where Q_a is the net heat flux at the sea surface (W m^{-2}, $\alpha(T, S)$ and $\beta(T, S)$ are the thermal and haline expansion coefficients, C_w is the ratio of interior local buoyancy frequency and the one at the entrainment depth, ranging between 1 and 2 values, $P - E$ is the net freshwater flux at the sea surface

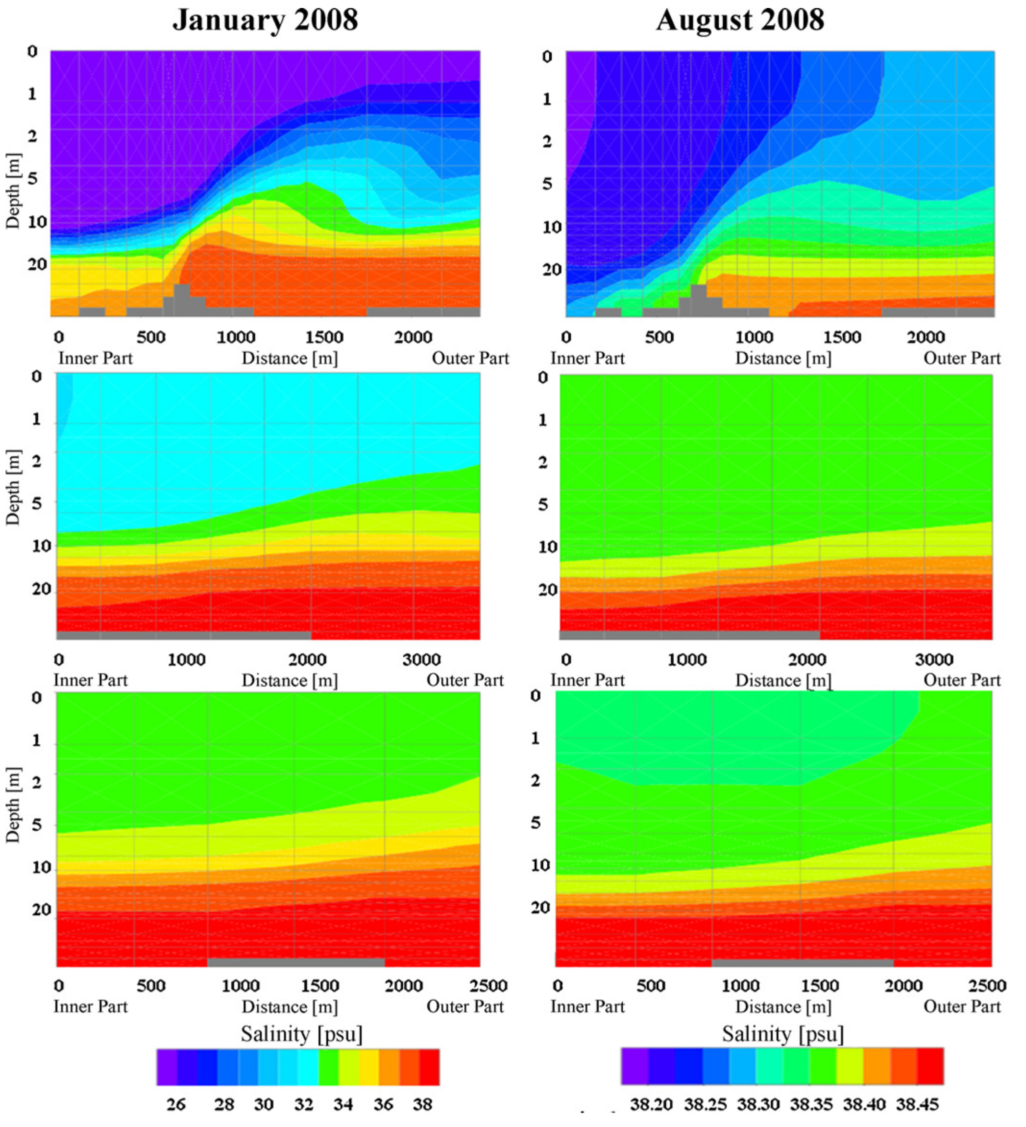

Fig. 8. Model results. Inner (top panels), central (central panels) and outer (bottom panel) salinity sections, along the channels. Left panels show the monthly average salinity for January 2008 forced with maximum discharge of freshwater sources in Boka Kotorska; right panels show the monthly average salinity for August 2008 forced with minimum discharge of freshwater sources in Boka Kotorska. The location of the transversal sections are shown in Fig. 1.

(kg m^{-2} s^{-1}. $P-E$ considers both precipitation-evaporation and freshwater supply from internal rivers (Birol Kara et al., 2008). In Fig. 9 the buoyancy ratio maps for the two scenarios are shown. For the maximum discharge scenario R reaches values always lower than 1, near zero, homogeneously over the whole bay. Therefore, the buoyancy effects due to the haline gradients is stronger for this scenario. In the case of the minimum discharge scenario, a different picture is shown: the Morinj-Kotor Bay is characterized by R values higher than 2, while the rest of the Boka Kotorska Bay keeps R values nearly around zero. It seems that the thermal buoyancy effects are of major importance in the inner bay, while haline effects are generally more relevant, for both scenarios, in the Tivat and Herceg Novi Bays.

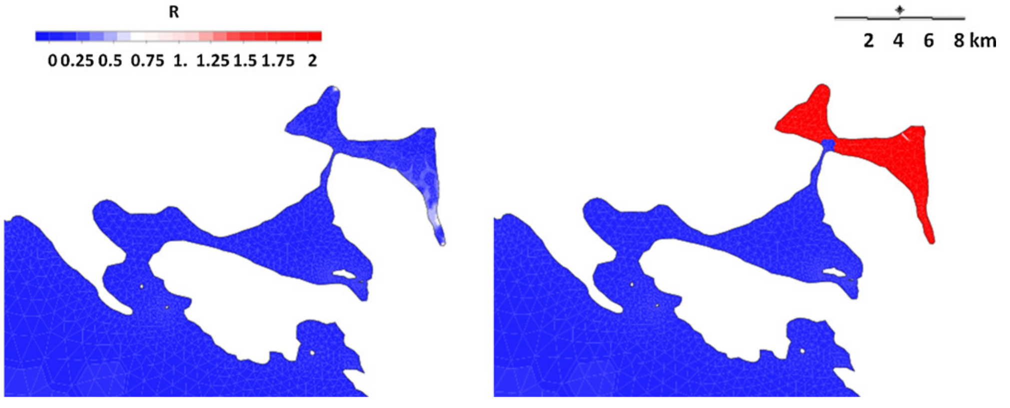

Fig. 9. Buoyancy flux ratio *R*, as the ratio of the thermal and the haline buoyancy fluxes; monthly average values for January 2008 (left panel) and August 2008 (right panel) forced, respectively, with maximum and minimum discharge of freshwater sources in Boka Kotorska.

3.2.4. Current patterns

The current maps are shown in Fig. 10. Stronger currents are seen, for both scenarios, in the surface layer. The highest current values are seen in the Verige Strait for the maximum discharge scenario (>20 cm/s) and a surface anti-cyclonic pattern is present in the Tivat Bay. Smaller scale structures can be detected in the inner part of the bay, in the maximum discharge scenario. The minimum discharge scenario shows surface currents around 10 cm/s generally directed to the South-East. Deep layer currents are directed inside the bay and are stronger for the maximum discharge scenario (10–15 cm/s). In both scenarios, a surface outflow circulation is detected, while the sea water is entering the bay at the bottom. The vertically integrated velocity maps also identify an anticyclonic circulation in the bay, stronger in the case of maximum discharge scenario, in which also recirculation cells can be seen at the Boka Kotorska mouth.

The mean estuarine circulation is particularly evident in the current velocity cross-channel sections shown in Fig. 11 (positive current values are directed from inside the bay to the sea) and in the along-channel sections (Fig. 12). In this scenario a clear two-layer structure can be detected, with a 20 cm/s current in the surface layers and an equal and opposite current flowing along the bottom. A less defined situation, but still keeping the estuarine circulation structure is seen for the minimum discharge scenario. Here an almost complete attenuation of bottom inflows in the inner section is found (Fig. 11). From the along-channel sections (Fig. 12), the presence of the sill in the Verige channel affects the bottom layer currents, particularly for the maximum discharge scenario. In the maximum discharge scenario the central section presents lower bottom velocity compared with the other two sections. The along-channel central section (Fig. 12) shows the persistence of a 3-layer structure that does not maintain the estuarine flow but registers an inflow in the Tivat Bay, both from the surface and the bottom layers. Current values, in this case, are small (around 5–10 cm/s).

3.2.5. Kelvin number

The Kelvin number, the ratio between the width of the considered area and the internal Rossby radius of deformation is computed for the whole Boka Kotorska Bay. The Kelvin number is expressed with the following formulation:

$$K = \frac{Wf}{\sqrt{g'h}} \tag{2}$$

where W is the horizontal scale of the considered area (the basin or the straits in this case), f is the Coriolis parameter, $g' = g\Delta\rho/\rho_0$ is the reduced gravity and h is the depth of the buoyant layer. The horizontal length scale of the basin has been kept on the order of kilometers. The computed Kelvin number is 3.1 for the maximum discharge scenario, while it lowers to 1.7 for the minimum discharge

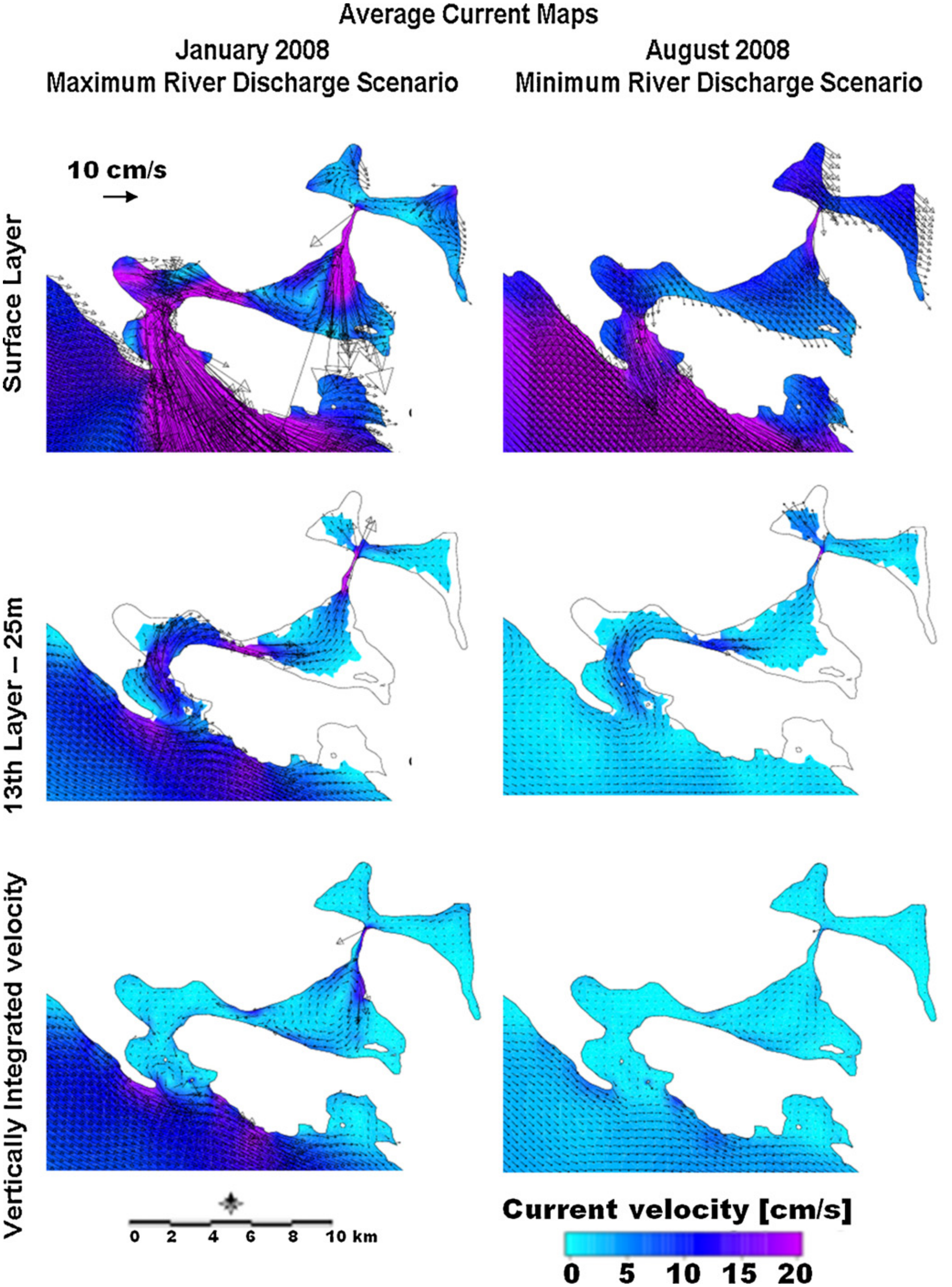

Fig. 10. Model results. Surface (upper layer), deep layer depth 25 m (center panel), and vertically integrated current maps (lower panel) in Boka Kotorska for two freshwater discharge scenarios. Left panels show the monthly average currents for January 2008 forced with maximum discharge of freshwater sources in Boka Kotorska; right panels show the monthly average currents for August 2008 forced with minimum discharge of freshwater sources in Boka Kotorska.

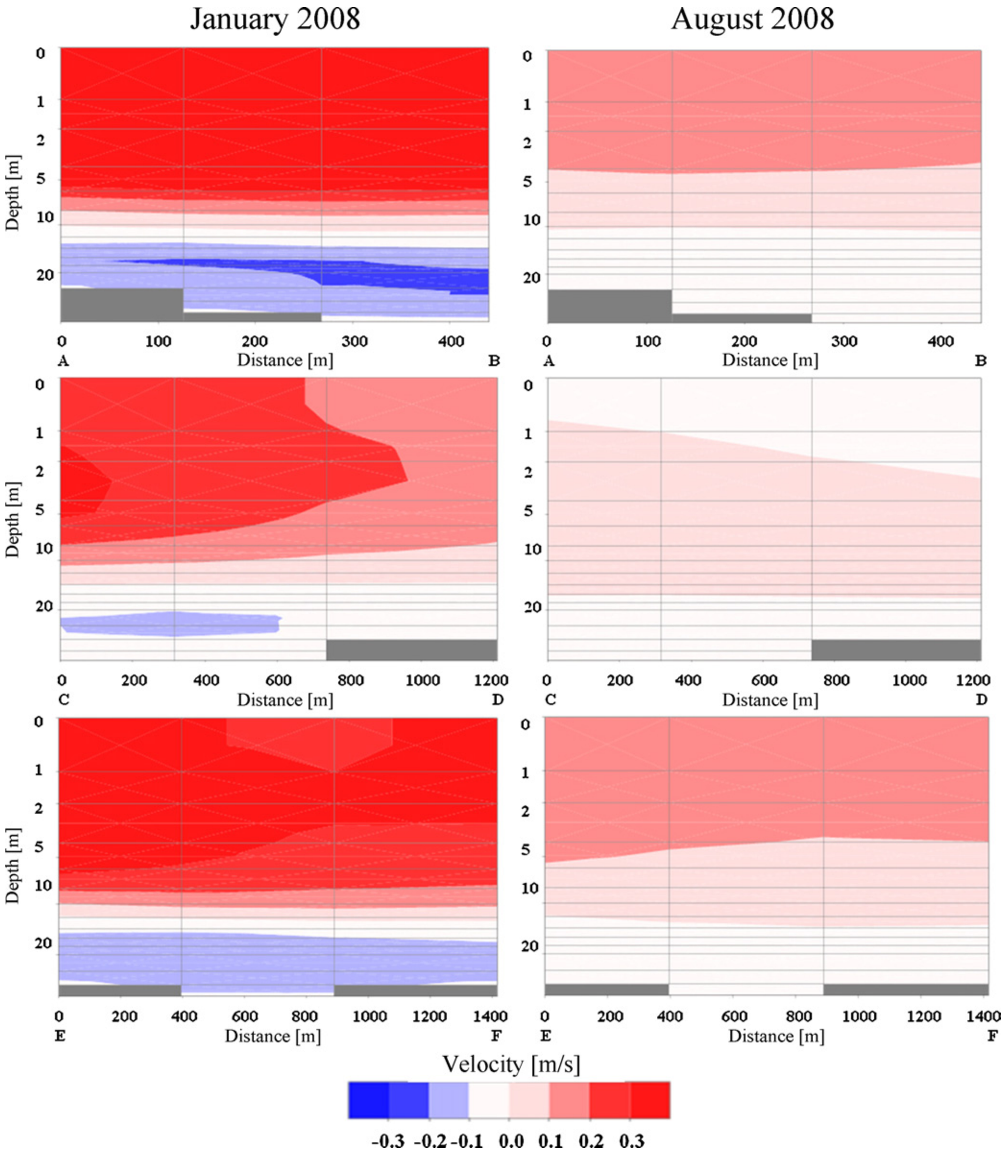

Fig. 11. Model results. Inner (top panels), central (central panels) and outer (bottom panel) current sections. Left panels show the monthly average currents for January 2008 forced with maximum discharge of freshwater sources in Boka Kotorska; right panels show the monthly average currents for August 2008 forced with minimum discharge of freshwater sources in Boka Kotorska. Positive current values are directed from inside the bay to the sea. The location of the sections are shown in Fig. 1.

scenario. The values of the Kelvin number at the three cross-channel sections of Fig. 1 are summarized in Table 3. For both scenarios, lower values are found in the innermost section, the Verige Strait, then slightly increasing approaching the sea (from 0.4 to 3). The maximum discharge scenario shows generally higher Kelvin numbers than the ones for the minimum discharge scenario. Following the ROFI classification based on the Kelvin number, presented in Garvine (1995), the small values seen in the Verige Strait make the innermost area of the bay behave similarly to a narrow river mouth, where

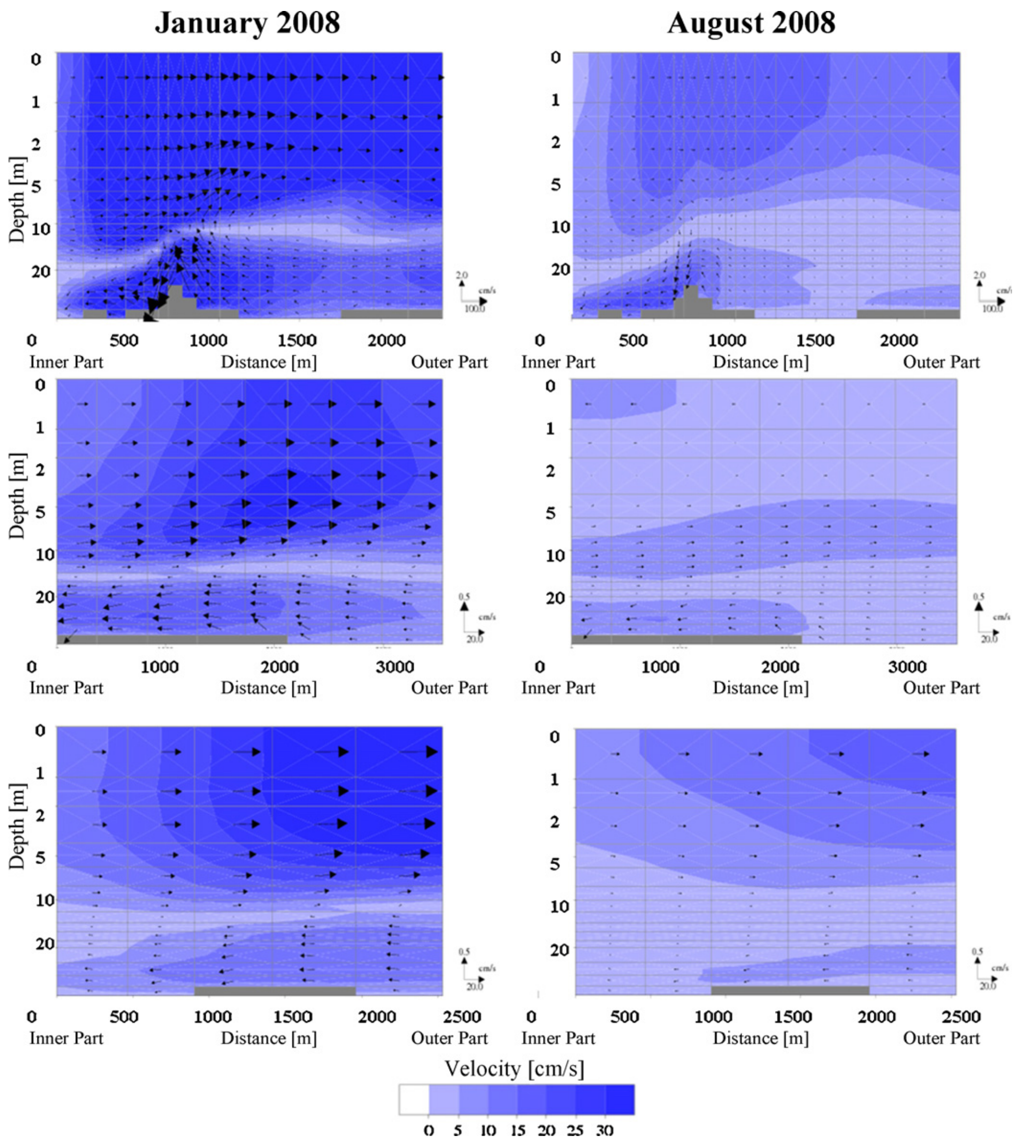

Fig. 12. Model results. Inner (top panels), central (central panels) and outer (bottom panel) velocity sections, along the channels. Left panels show the monthly average currents for January 2008 forced with maximum discharge of freshwater sources in Boka Kotorska; right panels show the monthly average currents for August 2008 forced with minimum discharge of freshwater sources in Boka Kotorska. The location of the transversal sections are shown in Fig. 1.

Table 3
Kelvin number values for the whole Boka Kotorska Bay, the Verige Strait (innermost), the Kumbor Strait (central channel) and the outermost channel shown in Fig. 1.

	Kelvin number			
	Whole Bay	Verige Strait	Kumbor Strait	Outermost Strait
Max. discharge, January 2008	3.1	0.4	1.8	3
Min. discharge, August 2008	2.3	0.3	1.1	1.7

non linear flows and hydraulic jumps can occur. The rest of the bay, with higher K values, is more similar to larger basins with thinner buoyant fluxes.

3.2.6. Residence time

Finally residence time (RT), defined as the time required for each element of the finite element domain to replace most of the mass of a conservative tracer (Cucco and Umgiesser, 2006), is presented (Fig. 13). In the maximum discharge scenario, residence time computed for the surface layer shows values ranging from 7 to 12 days with higher RT values in the eastern end of the Tivat Bay. The deep layer shows higher RT values in the inner bay, reaching 14 days in the inner East branch (Fig. 13). The vertically integrated RT map shows that RT is higher in the inner branches (11 days), but with smooth variations always in the range 11–7 days for the two internal bays, and lower approaching the sea. In the minimum discharge scenario a vertically more homogeneous behavior is seen with large horizontal variations of RT values. The inner branches can reach RT values around 70 days, while the Tivat Bay has RT values of 25 days in the surface and 15 days in the deep layer. Some areas quite near the channel to the open sea still maintain RT values of 5 days in surface, while lower values are seen in the deep layer.

4. Discussion and conclusions

All the analyses presented in the previous section allow a general discussion on the more relevant hydrodynamic characteristics of Boka Kotorska Bay.

The comparison between modeled and CTD T/S profiles, showed the strong influence of internal freshwater sources in the definition of temperature and salinity patterns. The discharge values are highly variable during the year, ranging from big amounts to drought conditions. As an example, we consider Station R7 (Fig. 1 and Table 1) which gives a discharge in the range [0.1–330] m^3/s (Stevanović and Maksimivić, 2007). Moreover, there is no clear connection between precipitation and river discharge, i.e. for the January simulation, the model setup that better matches results imposes high precipitation and low river discharges.

For this period of the year it would be more correct to keep the freshwater temperature at the basin temperature knowing that precipitation in the area could be collected in the karst areas, with effects of stock volume and water temperature smoothing. For the same reason it can be hypothesized that freshwater is flowing into the bay at a temperature higher than 20 °C (imposed in the more realistic simulation COCT) in October 2008. On the other hand, it is likely that the temperature bias, in October 2008, when the most realistic configuration indicates a small freshwater inflow, is mostly driven by other forcings, like surface heat fluxes.

Moreover, the salinity biases can be related to the differences between the real precipitation and climatology, used as model forcing, and to a possible lack in simultaneousness between high precipitation phenomena and high spring freshwater discharges. In January 2008, even though climatology indicates high precipitations, an injection of freshwater from internal rivers with a discharge between average and minimum climatological values is seen. The freshwater discharge in May 2008 falls in the range between average and maximum values. In June 2008, the freshwater discharge falls in the range from average to minimum discharge and October 2008 presents a minimum discharge of freshwater, differently from what would be expected from climatology.

For the whole set of simulations the coastal model better performs in the reproduction of temperature and salinity in the deeper layers and this suggests that a sudden forcing, as freshwater flowing near the surface, can deeply affect the model ability to correctly reproduce the T/S profiles. Measurements of freshwater temperature are needed for a correct simulation of the temperature profiles in the bay, since their strong effectiveness was proved.

Therefore the model T/S comparison with CTD profiles evidenced the need to quantify the competing action of freshwater supply and heating processes at the surface. The former comes from both precipitation and river discharge affecting the salinity field, and the latter is mainly acting on the temperature field. Therefore density driven flows can be due to one or both of these factors.

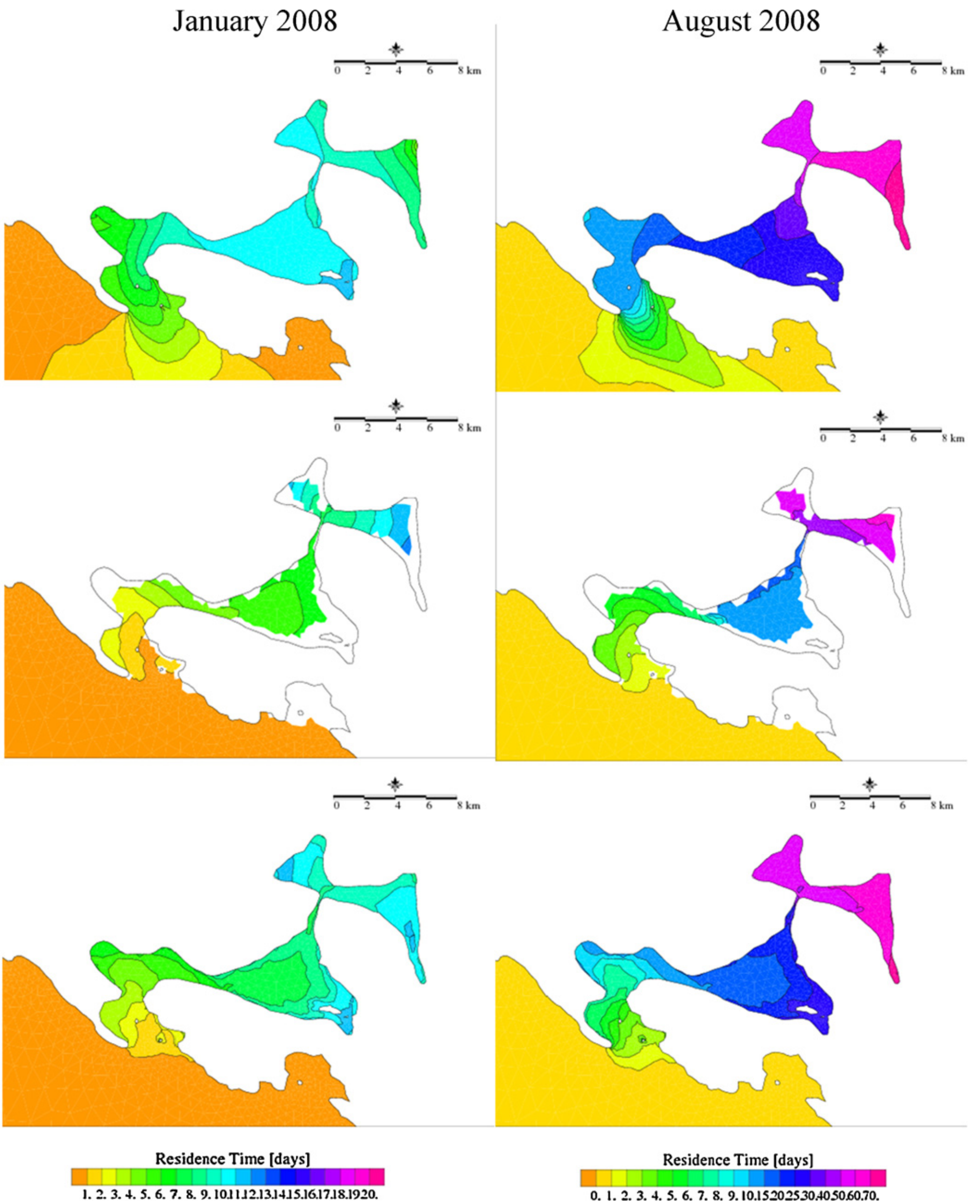

Fig. 13. Computed residence time (RT). Surface (top panels), deep layer depth 25 m (central panels), and vertically integrated maps (lower panel) in Boka Kotorska for two freshwater discharge scenarios. Left panels show the monthly average currents for January 2008 forced with maximum discharge of freshwater sources in Boka Kotorska; rigth panels show the monthly average currents for August 2008 forced with minimum discharge of freshwater sources in Boka Kotorska.

Analyzing the scenario simulations, considering two extreme cases of large and small freshwater supply (both from precipitation and rivers), an evaluation of temperature and salinity fields on the whole basin and the freshwater/heating processes competition, computed by means of the buoyancy ratio *R*, can be provided (Birol Kara et al., 2008). A deeper insight into the Boka Kotorska hydrodynamics is therefore possible.

From temperature maps and sections the effects of heat fluxes at the surface are seen that are considered an important process for the summer minimum discharge scenario and influence the vertical temperature stratification. Additionally, the effect of winds has to be considered for interpreting the small stratification seen in the winter maximum discharge scenario. Wind influences the surface structure and helps the mixing process. In this work a deeper analysis on wind effects is not performed because the available wind forcing used, with a spatial resolution of 0.5°, does not allow distinguishing spatially varying wind induced processes. Higher resolved forcings are needed to be able to quantify surface wind effects in the bay.

From the analysis of salinity fields (Fig. 6), it is evident how the freshwater sources tend to influence the salinity of the surface layers. Even if there are sub-surface sources of freshwater in the inner-northern part (U1, U2, U3, Fig. 1) they are less effective than other sources (R7, R8, Fig. 1) and all lead to the formation of a stratified salinity structure in the maximum discharge scenario. However, knowing that the minimum discharge scenario consists of very small freshwater discharges, it is not surprising that the surface and deep layer maps are more homogeneous in this case and present higher salinity (38–39 psu).

The fact that the major effect on salinity is due to the inner branch freshwater sources (R7, R8, Fig. 1) comes from Fig. 7 where the inner section shows the strongest vertical salinity gradient for the maximum discharge scenario. The vertical salinity stratification progressively is reduced in the outer sections and it can be hypothesized that the sea-bay interaction processes, also due to the tidal dynamics, enhance the mixing processes. It, however, has to be stressed that this is a micro-tidal environment and measurements along the coast show tidal excursion around 15 cm. Therefore tidal mixing can affect only the outermost portion of the bay and no mixing effects from tides can be seen in the inner parts of it.

If these temperature and salinity fields are interpreted considering also the computed buoyancy ratio R (Fig. 9), it appears evident that, generally, the effects of freshwater supply into the bay tends to be predominant in a maximum discharge scenario ($R \ll 1$). In this case the major buoyancy effect is due to the haline effects. Different responses can be seen for the minimum discharge scenario, where the inner area of the bay, Morinj-Kotor Bay, presents buoyancy effect mainly due to surface heating ($R \gg 1$), while the rest of the bay, approaching the sea, tends more to experience the action of freshwater ($R \ll 1$, Fig. 9).

Taking into consideration the surface velocity maps in Fig. 10, high current values are seen that should be associated with the action of winds. A number of structures due to thermo-haline forcings can be identified: the small scale patterns seen in the inner part of the bay, in the maximum discharge scenario, can be due to the inflow of freshwater. The current sections across the straits clearly identify the effects of freshwater in the occurrence of the detected estuarine circulation (Fig. 11): this pattern is seen in the inner section, where freshwater input is larger and defines the strong haline impact in the definition of the bay current patterns. From the along-channel section in the Verige Strait (Fig. 12) the bathymetric effects on currents can be seen, where the presence of a sill controls the bottom water exchange between the Kotor-Morinj Bay and the Tivat Bay. In the maximum discharge scenario, two vertical current cells, in the bottom layer before and after the sill, are present that tend to decrease the bottom inflow in the inner bay (Fig. 12 upper left panel). The other interesting pattern that characterizes both the scenarios is the anticyclonic circulation in the Tivat Bay. From the sections across the straits, it is possible to interpret the role of this anticyclonic circulation in the water exchange inside the Boka Kotorska Bay: the general decrease in the outflow currents for the central section (Kumbor Strait) can be due to the anticyclonic patterns seen in the central bay that contribute in lowering the current strength flowing outside.

The Kelvin number computation can help in interpreting the role of the three straits, from a circulation point of view. In fact smaller values for the innermost strait (around 0.3–0.4, Table 3), for both scenarios, define the presence of a thicker buoyant layer there. Higher Kelvin numbers are found for the Kumbor and the outermost straits. This would allow classifying the areas of the bay closer to the sea differently from the Morinj-Kotor Bay. Following the ROFI classification proposed in Garvine (1995), it seems that the Verige strait morphology and the presence of a thick buoyant layer, due to rivers in the maximum discharge scenario and to heating in the minimum discharge scenario, would behave similarly to a narrow river mouth while the rest of the bay would be more similar to a gulf, in its dynamics (Simpson, 1997).

Some final indications on the Bay hydrodynamics are obtained from the residence time that is considered a good estimator of transport time scales inside a semi-enclosed basin. From Fig. 13 two aspects arise. The first is that completely different pictures are seen if the domain is forced with the maximum or the minimum freshwater discharge scenario indicating that this forcing is predominant in driving the transport processes inside the bay. The second aspect is that the bay residence time is highly spatially varying. In the maximum discharge scenario a flushing situation is seen and the large amount of freshwater coming from the eastern Kotor-Morinj branch of the bay allows a faster water renewal (from 8 to 12 days in the vertical integrated picture of Fig. 13). Comparing the surface and the deep layer residence time maps for the maximum discharge scenario (Fig. 13) it is interesting to note that in the surface the highest residence times are in the Tivat Bay, while at the bottom they are in the inner branches. These evidences, together with the current maps shown in Fig. 10, allows the hypothesis that the anticyclonic structure seen in the Tivat Bay is a trapping structure that keeps water inside the bay. In the minimum discharge scenario the interesting aspect is that water in the inner branch seems to be stuck there. That part of the bay needs more than 70 days to renew its water, while the Tivat Bay has a residence time around 15 days. For both scenarios residence times are becoming smaller approaching the outermost branch of the bay where the tidal effects help in mixing and exchanging water.

To conclude, the nested modeling tool that is the first attempt to apply an integrated tool for hydrodynamic studies in the Boka Kotorska area permitted to simulate the hydrodynamics by means of a high resolution unstructured grid, taking into account also the effects due to the exchange with the open sea. The whole study allowed the identification of Boka Kotorska Bay as a ROFI system. Freshwater sources are recognized as driving forcings for the circulation. The lack of freshwater temperature measurements is a crucial aspect for the investigation of the hydrodynamics, stressing the importance of future monitoring to provide realistic imputs for the model. From this model implementation the Boka Kotorska bay can be defined mainly estuarine but evidences from the current and T/S sections in the straits that connect Kotor-Morinj Bay with Tivat Bay and in the channel linked to Herceg Novi Bay suggest that more complex small scale dynamics can be seen. Further studies are needed to investigate the dynamics of the straits with models and measurements.

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