Response to the reviewers' comments on the manuscript "Dense water formation in the coastal northeastern Adriatic Sea: the NAdEx 2015 experiment" by Vilibić and co-authors, submitted to Ocean Science (osd-2017-6)

We thank to both reviewers for their comments which we believe that improved significantly quality of the manuscript.

Reviewer #1 comments:

I still think that the paper needs major work, I find it very confusing, surely because there are a lot of data to be discussed and shown, but the reader needs to be guided through all these information in a more effective way.

- We performed the major revision of the paper following comments raised by the reviewer, whose comments are along the line with comments of Reviewer #1. So, we hope that the new version of manuscript is more coherent, structured and fluid to read.

English must be revised possibly by a native English-speaking person.

- The language is corrected by language-correcting service, American Journal Experts.

The additional section 6.3 that was promised in the answers to the reviewers is not in the new version of the manuscript. I am still not convinced that the DWF occurrence has been demonstrated, and even less that the involved volumes may be relevant for the northern Adriatic system. I think that the model results do not perform very well, especially considering that the authors explicitly show that overall the model did not reproduce properly the observed 2-layer structure as well as under- and overestimation of thermohaline properties. The authors themselves say that the model did not have sufficient resolution to to reproduce the bottom density current (which should be important here, given the aim of the paper)...

- Although we promised new Section 6.3 to lay down the arguments about the DWF in the NAdEx area, we decided not to do so, as Section 6 is solely dedicated to results. Section 6.3 was supposed to contain predominantly the discussion of the results. Therefore, we decided to reformulate and strengthen the argument pro DWF in Section 7. However, these arguments are still not fully recognized as reliable, also raised by Reviewer #2, so that we rewrote the whole discussion part on the DWF, following the suggestions given by Reviewer #2. Also, we agree that the model performance is not a perfect one, particularly for currents at constrictions influenced by rapidly changing bathymetry or narrow channels resolved only by one or two model grid cells, but we provided extended discussion on that. This discussion will hopefully be of great help for others applying ocean models in regions with complex bathymetry and forcing, including future modelling exercises that for sure will be applied to the NAdEx area, as containing really nice and diverse dataset useful for validation of models. We hope that the text and statements placed in the text are reliable now and following the provided results.

To conclude, major revision is required to 1) improve the structure of the paper (paragraphs presenting the dataset and guiding the reader through the information, addressing one by one all questions that you want to answer here), 2) convince the reader how important DWF in this area is respect to DWF outside the area, 3) if possible, improve the model results (maybe not feasible).

- We did the major revision following comments 1) and 2), while for 3) it would be necessary to set up completely new modelling setup, both for atmosphere and ocean. So, we decided to keep the present model, while encouraging further modelling studies in this complex area which might be evaluated on the presented comprehensive observations.

Reviewer #2 comments:

This is the second review of the manuscript «Dense water formation in the coastal northeastern Adriatic Sea: the NAdEx 2015 experiment» by Vilibic et al. The authors have provided a comprehensive response to the previous comments which is highly appreciated. They have convincingly responded to a majority of the major remarks and to most of the minor ones (although new minor concerns arise), which is a significant step forward toward the publication of their work. However, several major issues previously arosen still remain, which either fragilize some of the authors' conclusions or complexify the reading. I therefore recommend a major revision of the manuscript.

The following major concerns still remain:

M1 Although the authors disagreed with me on the too large number of Figures, I believe this remark is even truer now that the manuscript reaches 20 Figures. Some of them provide repetitive informations and others are too raw to support the authors' claims, fragilizing them.

- We reduced the number of figures following suggestions of the reviewer (now we have 17 figures), but also following general comment of the other reviewer, to improve the flow and readability of the manuscript.

The authors should seek to be more synthetic and to add a few (simple) diagnostics to some Figures to be more convincing. In particular:

- I still believe Figures 11 and 12 repeat already-existing informations and the added value of showing statistical distributions is very low as it is presented. Also, as mentioned in former remark m14 (which has not been addressed), I think displaying relative differences (Fig.11c,d and Fig.12d,e,f) is irrelevant, especially for salinity, it gives the misleading impression that the bias is low and it makes it hard to read the actual salinity bias. As mentioned in the previous m14, absolute differences would be easier to read and interpret. For the q-q plots (Fig.11a,b and Fig.12a,b,c), the dashed-dotted line is still not labelled, please explain how it is obtained.

- We removed Figures 11c,d and Figures 12d,e,f, while the rest is merged into the single figure. Also, we added explanation for the dash-dotted line in figure caption.

- As mentioned in the previous review, model-obs Figures could easily be merged with obs-only Figures, which would make the reading much simpler. The authors have already

successfully done it for Figure 6, they could do the same by removing Figures 9 and 10 and putting them aside their observational counterparts.

- Done.

- As already mentioned before, Figure 15 is not insightful as it is now and could also be removed. The SI difference doesn't read well and plotting directly both time differences would have been easier, and most of the domain already has a very low (<0.05m²/s²) stratification before the Bora events occur. Also, displaying the MLD would be very insightful (see comment M3).

- We changed SI to MLD in Fig. 15 (now Fig. 11).

- The new Table 2 is too instantaneous to be insightful and could also be removed. Instead, the intense transports during Bora events could be compared in the text to the winter mean transport (e.g. on average during the 6 Bora events, the T, S and volume transports are respectively X times, Y times and Z times larger than their winter mean value). Also, mass and volume transports are almost identical so that the mass transport could be removed from Table 1.

- We removed Table 2 and provided some data in the text as suggested. Also, we removed mass transport from Table 1.

- The very large number of geographic locations makes the reading very confusing. In particular, the following locations should appear in Figure 1: Istria, Sedmovrace, Senj, Kvarneric (confusion between A4, T4 and Kvarneric transect).

- We tried to remove some locations by replacing them by station/transect codes, to clarify others (e.g. Kvarnerić Channel is used everywhere instead Kvarnerić), while adding the missing locations to Figure 1 (like Senj, Istria was already there, while Istrian Peninsula is changed by Istria).

M3 Although the authors have put forward more explicitely both hypotheses of a DWF occurring locally or dense waters from the open Adriatic shelf, I still find the conclusions confusing, including those stated in the abstract. In addition, as in coastal areas DWF occurs exclusively when the mixed layer reaches the bottom of the water column, the lack of any mixed layer computation is still a major drawback of the paper.

- We cleared up the text, particularly abstract, and added MLD as suggested.

- Regarding the first point, here is the conclusion I have reached, which is clearly stated nowhere in the paper : « Observations at transect T4 and station A9 show the incoming of dense water from the open shelf, and current profiles only show marginal outward transport of dense water from the NADEX area to the open shelf. They support balanced inward-outward dense water exchanges or even a dominating inward transport. However, modelling results show the domination of outward dense water transport, strongly supporting the hypothesis that the NADEX area is a source of dense waters for the open Adriatic. » Please re-formulate more clearly the respective contributions of the local formation, outward and

inward transport in the NADEX area to the DWF phenomenon, in particular in the abstract, the conclusion and section 4 (p.9, L.4-25).

- We reformulated the text following the above suggestions. We hope that it sounds much better and coherent now.

- Regarding the lack of any mixed layer computation: I believe that comments of Figure 13 are not convincing without an MLD being displayed (see also comments m9 and m11), and the color range change obviously didn't fix the issue (it is still impossible to read with the eye a 0.01kg/m³ density variation). I also believe (former M8) that Figure 15 should be removed if no mixed layer is displayed (eg: relevant contours).

- We added mixed layer depth to Figure 13 (now Figure 10), to existing PDA Hovmoller as a thick line. The methodology for MLD computation is also added in the text. Now we present MLD instead of SI in Fig. 15.

Figure 15 would be insightful if the IS time difference map was displayed together with a relevant MLD contour (e.g. 50m depth) before and after the Bora event, so that the reader can objectively identify the regions of DWF created by the Bora event.

- We computed the respective MLD for dates presented in old Fig. 15 (now Fig. 11). MLD has been following the SI distribution, i.e. it is reaching the bottom at the most of the domain. However, following the suggestion of the reviewer, we put MLD instead of SI to the figure (putting both at the same figure will be too messy).

M11 (new) The authors claim in their response to have addressed their general question 4 (What are the associated mesoscale and frontal processes associated?), which I believe is not the case: no actual mesoscale or frontal process has been studied, they have just identified a front. As questions 1 to 3 are enough, I believe question 4 should be removed.

- We removed it as requested.

Here is a list of the new minor concern:

m1 The authors have identified an interesting bottom hydrological trend in observations which is the main signature of DWF: they should evaluate it in the model.

- Done, the model really reproduced the T-S trends at all A stations. We decided not to provide additional figures, as the reviewer comments are asking for their reduction. Some of the text was already in the manuscript, but a few statements are added to the Section 5.

m2 p.6, L.15 Compare year 2015 to the 10-year average rather than to specific years, because the fact that it is lower than 2012 and higher than 2014 doesn't prove that year 2015 was average.

- We also compared it to the average and we kept comparison with specific years.

m3 p.7 L.27 How do you know that this incoming occurred dominantly through T4 connecting passage?

- To be perfectly honest, we really don't know, and it is not perfectly clear from the Leg 2 salinity distribution, hence we omitted the statement.

m4 p.9, L.4-5 Question 2 is not answered to in the whole manuscript (see comment M3).

- We've changed the text, including discussion and conclusions, following the suggestion from M3. It is basically softening our conclusions and put the accent on additional research to get the answer on Question 2.

m5 p.8, L.28 Fig. 5 not Fig. 6.

- Corrected.

m6 p.9, L.5 Fig. 6 not Fig. 7. The orientation of all channel cross-sections would help a lot to interpret Fig. 6 as each section has a different orientation (e.g. just display for instance a horizontal line on top of the current measurements if the section is East-West).

- Done, inserted in Fig. 7.

m7 p.10, L.15-16 Positive bias, not negative.

- Corrected.

m8 p.11, L.11-21 The model evaluation is too qualitative, be more quantitative (e.g. bias in the module and in the angle). For now it is not convincing that the model performs overall well.

- We computed it and added details in the text.

m9 p.11, L30 The water column was not homogeneous all the time from December to early April. Only displaying the MLD in Fig.13 would determine when it occurred (when the MLD reached the bottom). For instance, it is clear that DWF was intermittent in early January and in March.

- We added MLD to the figure, to already existing PDA Hovmoller plot.

m10 p.12 L.3 Also (maybe mostly) the surface radiative forcing restratifies the water column.

- This effect is present but it is of minor importance. We rewrote the sentence.

m11 p.12, L.3-5 I don't agree on the comparison between G1 and G2: the water column looks much more homogeneous throughout the winter in G2 than G1. Once again, displaying the MLD would determine if it is the case or not.

- We added MLD to the figure and rewrote the text accordingly.

m12 p.13 L.14 Why do you expect wind-driven dynamics to induce an energy loss?

- This area has been affected by strong bora wind episodes, which has the maximum there. Yet, we haven't estimated contributions of different processes, in that sense we removed the sentence as unjustified.

m13 p.14 In the formula, rename U vector as Uout for instance to specify that it is only the outward velocity.

- Ok, done.

m14 p.14 L.13-25 There are a series of English and typing mistakes, please correct them.

- The whole manuscript is corrected by professional language-correcting service, American Journal Experts (www.aje.com).

m15 Use the same range of values between Fig.17 and 19.

- Corrected.

m16 p.17 paragraph 1 Also, the lateral boundary conditions for momentum impact highly the level of kinetic energy close to the coastline. Do you have free-slip conditions? If not, this would be a means of improving the modelled velocities in the NADEX area.

- Free-slip conditions have been imposed as the lateral boundary conditions inside the domain (land). Coastline of the eastern side of the Adriatic is complex with many narrow channels and islands acting as lateral friction, similar like stairway effect. If using additional no-slip condition this effect would be even more pronounced. We fully agree that such choice could affect dynamics and currents in channel areas, so it is added to the text.

m17 p.17 L.15 Don't talk about one-way coupling: it is just a forced atmospheric simulation.

- Corrected.

m18 A schematic scheme of the main phenomena evidenced in this field campaign would help the reader to have a general overview of the main results of the study.

- We agree that it might be useful to have some sketching of observed processes, yet this will add extra figure to the paper and we feel that such a figure is better as a graphical abstract and not as a part of the paper.

Manuscript with annotated changes (before AJE correction):

Dense water formation in the coastal northeastern Adriatic Sea: the NAdEx 2015 experiment

Ivica Vilibić[1], Hrvoje Mihanović[1], Ivica Janeković[2,3], Clea Denamiel[1], Pierre-Marie Poulain[4], Mirko Orlić[5], Natalija Dunić[1], Vlado Dadić[1], Mira Pasarić[5], Stipe Muslim[1], Riccardo Gerin[4], Frano Matić[1], Jadranka Šepić[1], Elena Mauri[4], Zoi Kokkini[4], Martina Tudor[6], Žarko Kovač[1], Tomislav Džoić[1]

[1]Institute of Oceanography and Fisheries, Split, Croatia
[2]Ruđer Bošković Institute, Zagreb, Croatia
[3]The University of Western Australia, School of Civil, Environmental and Mining Engineering & UWA Oceans Institute, Crawley WA, Australia
[4]Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS, Trieste, Italy
[5]University of Zagreb, Faculty of Science, Andrija Mohorovičić Geophysical Institute, Zagreb, Croatia
[6]Meteorological and Hydrological Service of Croatia, Zagreb, Croatia

Correspondence to: Ivica Vilibić (vilibic@izor.hr)

Abstract. The paper investigates wintertime dynamics of the coastal northeastern Adriatic Sea, and is based on numerical modelling and in situ data collected through field campaigns executed during the winter and spring of 2015. The data have been collected by a variety of instruments and platforms (ADCPs, CTDs, glider, profiling float), and have been accompanied by atmospheric-ocean ALADIN/ROMS modelling system. Research focus has been put on the dense water formation (DWF), thermal changes and circulation, and water exchange between the coastal and open Adriatic. According to both observations and modelling results, dense waters are formed in the northeastern coastal Adriatic during cold bora outbreaks. However, dense water formed in this coastal region has, due to lower salinities, lower densities than dense water formed at the open Adriatic. Since the sea is deeper in the coastal area than at the open Adriatic, observations show: (i) balanced inward-outward exchanges at deep connecting channels of denser dense waters coming from the open Adriatic DWF site and less dense waters coming from the coastal region, and (ii) outward flow of less dense waters dominated in intermediate and surface layers. The latter has been confirmed by the model - even if it significantly underestimates currents and transports in connecting channels - classifying coastal northeastern Adriatic waters as a secondary site for the DWF. Median residence time of the coastal area is estimated to be about 20 days, indicating that the coastal area may be relatively quickly renewed by the open Adriatic waters. Obtained data represents a comprehensive marine dataset, to be used for calibration of atmosphere and ocean numerical models and pointing to a number of interesting phenomena to be investigated in the future.

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Deleted: Since the sea is deeper in the coastal area than at the open Adriatic, dense waters from the open Adriatic occasionally enter the coastal area near the bottom of the connecting passages, while the surface flow is mostly outward from the coastal area.

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1 Introduction

Due to its geographical position and surrounding orography, the Adriatic Sea - a semi-enclosed 800 x 200 km basin located at the north of the Mediterranean (Fig. 1) - can be considered as a unique testbed where happen a number of processes important for driving the circulation of the Eastern Mediterranean Sea (Malanotte-Rizzoli et al., 2014). Dense water formation (DWF) is one of these processes. In the Adriatic Sea, the DWF occurs through both water column cooling and mixing on the shallow and wide northern Adriatic shelf (Vested et al., 1998) and through deep-convection in the 1200-m deep circular South Adriatic Pit (Gačić et al., 2002). The cooling at both locations is a result of strong bora wind (Grubišić, 2004; Grisogono and Belušić, 2009) which may cause widespread heat losses up to 1000 W/m^2 (Supić and Orlić, 1999) and localised heat losses up to 2000 W/m^2 (Janeković et al., 2014). Although of secondary importance, bora-driven evaporation is also contributing to large densities in the northern Adriatic (Mihanović et al., 2013). Adriatic dense waters are important for: (i) replenishment of deep waters in the Eastern Mediterranean (Roether and Schlitzer, 1991; Bensi et al., 2013), (ii) changing or maintaining internal vorticity of the northern Ionian (Gačić et al., 2010) and (iii) driving decadal oscillations of thermohaline and biogeochemical properties in the Adriatic (Buljan, 1953; Gačić et al., 2010; Civitarese et al., 2010; Batistić et al., 2014).

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Focusing on the northern Adriatic, up to 2012 it has been thought that the DWF occurs over open shelf areas only (Vilibić and Supić, 2005). Therein, a pool of very dense waters is created by a double-gyre circulation driven by spatial inhomogeneity of the bora wind (Zore-Armanda and Gačić, 1987; Kuzmić et al., 2006). The generated dense waters are gravitationally transported towards middle Adriatic depressions though a bottom density current (Nof, 1983), mostly along the western Adriatic slope due to the Coriolis force (Artegiani and Salusti, 1987; Vilibić and Mihanović, 2013). A portion of waters is travelling across the southern Palagruža Sill and, when reaching South Adriatic Pit slope and canyons there, they are being transported downslope to the near-bottom layers (Querin et al., 2013; Langone et al., 2016). This concept has been supported by a number of numerical modelling studies (e.g., Beg-Paklar et al., 2001; Chiggiato and Oddo, 2008). However, this classical northern Adriatic DWF picture has been substantially changed following the exceptional DWF winter of 2012, when formation of dense waters has been observed in the northeastern coastal area as well (Fig. 1) (Mihanović et al., 2013). Subsequent modelling studies implied that up to 40% of the overall dense water generated in the northern Adriatic during winter of 2012 originated from the eastern coastal areas (Janeković et al., 2014), with a significant transport between the coastal and open Adriatic through a number of channels (Vilibić et al., 2016a). It should be emphasized that these two modelling studies were the first ones that used realistic fresh water discharges. Most of previous modelling studies used an old river climatology (Raicich, 1994), which overestimates real river discharges in the eastern Adriatic by an order of magnitude (Janeković et al., 2014), thus preventing numerical reproduction of the DWF in the northeastern coastal areas and also significantly impacting the rates of the DWF over the northern Adriatic shelf areas (Vilibić et al., 2016a).

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Interestingly, atmospheric processes over the northeastern coastal Adriatic area have been thoroughly researched, as the maximum of the cold and dry bora wind and its spatial and temporal variability have been reported there, occasionally reaching hurricane strength (Grubišić, 2004; Grisogono and Belušić, 2009; Kuzmić et al., 2015). As opposed to meteorology,

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less has been known of oceanography of the area. For a long time, the coastal northeastern Adriatic has been considered an area in which significant freshwater fluxes strongly affect thermohaline properties (e.g. Orlić et al., 2000). These freshwater discharges normally come through occasional floods accumulated over the 150-km long and 1600-m high mountain ridge of Velebit (Perica and Orešić, 1997) and a large number of submarine karstic springs (Sekulić and Vertačnik, 1996; Bonacci, 2001; Benac et al., 2003; Surić et al., 2015). Further on, thanks to occasional oceanographic campaigns, the inner area of Velebit Channel has been classified as a two-layer system, with surface salinity exhibiting much lower values (~1.0) than at the open Adriatic (Viličić et al., 2009). Also, it has been known that a strong northern Adriatic thermohaline front (Lee et al., 2005; Poulain et al., 2011) has its starting point in the northeastern coastal Adriatic, specifically in the Kvarner Bay, with coastal waters advected towards the open sea, particularly during strong bora events (Pullen et al., 2003; Lee et al., 2005; Beg Paklar et al., 2008). As it is topographically separated from the open Adriatic by a number of islands (Fig. 1), the northeastern coastal area has not been considered as eligible for wintertime processes such as dense water formation up to winter of 2012, at least not at rates that may impact the overall northern Adriatic dynamics.

Up till now, winter of 2012 remains the only winter for which dense water formation in the northeastern coastal Adriatic has been observed and modelled. Question is whether this is due: (i) to exceptionality of the 2012 winter - implying that this was an extraordinary event, or (ii) to a lack of observational campaigns and poor model performance in the area - pointing to both a possibility of regular dense water formation in the area and an omission in our previous research efforts. To answer this question we have envisioned and carried out the North Adriatic Dense Water Experiment 2015 (NAdEx 2015). A number of different platforms and instrumentations for data collection were engaged (Fig. 1), along-side with a state-of-the-art nested atmosphere-ocean modelling system, all during winter/spring of 2015, i.e. during and post a common Adriatic DWF period. Obtained experimental data and modelling results allow us to: (i) estimate whether the DWF is a common process in the northeastern Adriatic, (ii) if so, to quantify both DWF and thermohaline changes leading to it; and (iii) to estimate rate of exchange between coastal and open Adriatic waters through a number of connecting passages.

Section 2 gives details of the field experiment and data used in this paper, together with a description of the atmosphere-ocean modelling system. Section 3 documents the atmospheric conditions during the winter/spring of 2015. Section 4 describes representative ocean observations, followed by model verification in Section 5. Section 6 displays thermohaline, stratification and buoyancy changes as reproduced by the model, followed by estimates of heat, salt, mass and volume transports at the boundaries of the region, including residence times. A throughout discussion and major conclusions are presented in Section 7.

2 Data and methods

2.1 The studied area

The northeastern Adriatic is a coastal region consisting of a number of elongated channels and bays (Fig. 1). It communicates with the open Adriatic through a number of narrow (from a kilometre to few kilometres) channels. The only

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exception is a wide opening connecting Kvarner Bay to the open Adriatic. Kvarner Bay may thus be considered as a crossing region between coastal and open Adriatic waters. The inner coastal region is deeper (80-100 m) than the the open Adriatic (50-70 m). Only a few small river mouths are located in the area, plus the freshwater input by the hydropower plant near Senj, altogether with average freshwater input rates of about 80 m^3/s (Vilibić et al., 2016a). Yet, there are also tens of submarine springs, which are quite active during and after the prolonged precipitation events, and which may double the freshwater load to the coastal area (Sekulić and Vertačnik, 1996). Furthermore, climate of the region, particularly of Rijeka Bay, is characterized by significant precipitation driven by orography (Gajić-Čapka et al., 2015).

2.2. The field experiment

The NAdEx 2015 experiment was carried out between late autumn 2014 and summer 2015. Primary goal of the experiment was to study the DWF in in the coastal northeastern Adriatic, commonly occurring between January and March (Janeković et al., 2014). Temperature, salinity and current data were collected by a number of instruments and observing platforms deployed in the area (Fig. 1). The whole experiment has been realized through contributions and collaborative work of several research institutions: Institute of Oceanography and Fisheries, Ruđer Bošković Institute, Geophysical Department of the Faculty of Science of the University of Zagreb, Meteorological and Hydrological Service, all from Croatia, and National Institute of Oceanography and Experimental Geophysics, Italy. It thus represents an unique effort for the Adriatic which may serve as a good practice for future research activities in the region.

Currents over the water column were measured at stations A1 to A9 using RDI Acoustic Doppler Current Profilers (ADCPs) between late November 2014 and early August 2015 (A7, A8, A9)/early July (A4) and using Nortek ADCPs between early December 2014 and mid-August 2015 (A1, A5, A6)/late May (A2); ADCP at station A3 malfunctioned after only one week of operation and did not measure any data after that. A Seabird 911 CTD probe accompanied ADCPs at stations A3, A4, A7, A8 and A9, providing the bottom temperature and salinity series between late November 2014 and early August 2015. Vertical profiles of temperature and salinity data have been acquired by Seabird SBE 25 probe at 19 CTD stations during two cruise legs. Leg 1 was carried out between 3 and 6 December 2014 and Leg 2 between 26 and 29 May 2015. A Teledyne–Webb Research Slocum glider was operated along transect off the Kvarner Bay in a campaign lasting from 24 to 26 February 2015, while Arvor-C profiling float was deployed on 19 February in the northern part of Kvarner Bay and recovered on 15 March 2015 on the Istria coast near the entrance of the bay, profiling regularly the whole water column every 3 hours (Gerin et al., 2015). Potential density anomaly (PDA, reference pressure equalling zero) was computed from temperature and practical salinity data, following TEOS-10 algorithms (described at http://www.teos-10.org). Complete setting of the experiment is illustrated in Fig. 1.

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2.3. The modelling system and its setup

The atmospheric-ocean modelling system covering the entire Adriatic Sea has been used as the NAdEx 2015 parent numerical model. Atmospheric part of the system is based on a hydrostatic version of ALADIN numerical weather prediction (NWP) model used by the Meteorological and Hydrological Service of the Republic of Croatia (Tudor et al., 2013, 2015). The model is operationally integrated four times per day, having 37 sigma levels in vertical and 8 km resolution in horizontal, except for winds which are dynamically downscaled to 2 km (Ivatek-Šahdan and Tudor, 2004). All variables have been provided with the time step of 3 h. Although bora wind may have a substantial variability on periods from several minutes to a few hours, previous modelling studies that used 3-h ALADIN/HR forcing provided reliable results (e.g. Janeković et al., 2014). The model is initialized with 3D-Var run, at 8 km resolution, using the data available through Global Telecommunication System (GTS) and local data exchange (Stanešić, 2011). The model uses SST fields coming from the IFS (Integrated Forecast System) operational forecast run in ECMWF (European Centre for Medium Range Forecast). These SSTs have a positive bias towards in situ measurements during the winter, much lower at the open Adriatic when compared to the SST satellite observations, affecting precipitation maxima (Ivatek-Šahdan et al., 2017) but not significantly the wind speed, which is controlled by surrounding topography (Tudor et al., 2017). Wind gusts have been computed following Brožkova et al. (2006) formulation, which has been tuned for oceanographic simulations in the Mediterranean. ALADIN/HR simulations have been verified in the coastal northeastern Adriatic during severe bora events (Tudor and Ivatek-Šahdan, 2010; Tudor et al., 2013).

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For the ocean part, Regional Ocean Modelling System (ROMS) has been used. ROMS is a 3-D hydrostatic, nonlinear, free surface, s-coordinate, time splitting finite difference primitive equation model (Shchepetkin and McWilliams, 2005, 2009). Horizontal resolution of the Adriatic model is 2 km, with 20 sigma layers in vertical, following the studies by Janeković et al. (2014) and Benetazzo et al. (2014) which satisfactorily reproduced the DWF in the northern Adriatic. The open boundary conditions at the Otranto Strait (free surface, temperature, salinity, and velocity) are taken from the Adriatic REGional model (AREG, Oddo et al., 2006), with sponge layer at the boundary. The Flather scheme was used for barotropic velocities and a combination of Orlanski-type radiation boundary conditions with nudging (Marchesiello et al., 2001) for baroclinic velocities and tracers (temperature and salinity). Long-term stability of the model run has been ensured by smoothing bathymetry using a linear programming technique (Dutour Sikirić et al., 2009) that suppresses horizontal pressure gradient errors occurring over complex bathymetries with steep slopes, such as in the Adriatic Sea, and during multiyear integrations (Haidvogel et al., 2000). The ALADIN/HR surface variables were introduced to the ROMS via bulk parameterisation (Fairall et al., 1996). The most recent river discharge climatology has been imposed at the freshwater point sources following Vilibić et al. (2016a) data, without changing the ambient temperature. More details on the modelling system can be found in Janeković et al. (2014) and Vilibić et al. (2016a).

In addition to the Adriatic model, a nested ocean model (ROMS as well) was imposed to the NAdEx 2015 region to properly reproduce its complex bathymetry (Fig. 1). The nested domain has been tilted by 45º to follow the orientation of the area. The nesting has been done using the 1:4 ratio in horizontal - thus nested model had a horizontal resolution of 500 m - and keeping 20 sigma levels in vertical. The nested ocean model was forced with the same ALADIN/HR operational fields as the parent model. Free-slip conditions have been imposed at the boundaries.

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The parent modelling system has been operationally integrated since 1 January 2008, while the nested simulation was run between 1 October 2014 and 30 September 2015, covering the experimental NAdEx 2015 period. Verification of the parent model was performed for the winter of 2012 (Janeković et al., 2014; Vilibić et al., 2016a). Basin-wide negative salinity bias has been found to exist, presumed to come from the AREG model lateral boundaries (Janeković et al., 2014). In the AREG model these boundaries exhibit basin-wide overfreshening coming from old river climatology by Raicich (1994), thus influencing also our parent simulations. Yet, the model was found appropriate for reproduction of thermohaline properties in the area (Vilibić et al., 2016) and quantification of the DWF in both open northern and coastal northeastern Adriatic (DWF sites 1 and 2 in Fig. 1).

3 Atmospheric conditions and air-sea interaction

The winter of 2015 (December through March) was characterized by warmer-than-average temperature conditions over the NAdEx area compared to the baseline climatological period of 1961-1990 (MHS, 2015, 2016). According to these reports, the highest positive anomalies (91-98 percentile) were recorded in December and January, followed by average temperatures in February and warm conditions (75-91 percentile) in March. DJFM precipitation values (measured only above land) were close to climatological values, with highest positive anomalies measured in February. Regarding average January-February net heat fluxes over the NAdEx area (as delimited by nested domain boundaries in Fig. 1) - these two months are chosen as the DWF is dominantly occurring at that time (Beg Paklar et al., 2001; Vilibić and Supić, 2005) - the winter of 2015 may be classified as normal with the respect to other winters between 2008 and 2015. Precisely, cumulative January-February net heat losses equalled to 0.80 MJ/m^2, a bit higher than of average for 2008-2015 period (0.76 MJ/m^2), about 50% less than in the winter of 2012 (1.20 MJ/m^2) and almost two times larger than in the winter of 2014 (0.49 MJ/m^2).

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Several cooling events occurred during the winter of 2015, of which three bora episodes – preceding New Year, in early February and early March – were particularly severe. The first severe bora episode lasted for several days (between 28 December 2014 and 1 January 2015), with gusts stronger than 50 m/s in the Velebit Channel and air temperature falling below 0ºC The bora event between 4 and 7 February 2015 was particularly strong over the NAdEx area, peaking during the night of 5/6 February with measured wind gusts of about 60 m/s in the northern Velebit Channel. A month later, another strong bora event occurred along the eastern Adriatic coast, the latter was however particularly pronounced over the middle Adriatic and southern part of the Velebit Channel, where the wind gusts peaked on 5 March with values of about 55 m/s.

To better understand impact of bora wind on the northeastern coastal Adriatic, we have compared wind stress, net heat flux and water flux variables (all originating from ALADIN model) averaged over all bora events with those averaged between 15 December 2014 and 15 March 2015 (Fig. 2). Herein bora event is defined as a period during which wind blows from ENE and exceeds 15 m/s at the ALADIN grid point off Senj (location G1 in Fig. 1) - ENE represents predominant direction of bora in that area (Zaninović et al., 2008). Maximum wind stress is modelled within the Senj Jet (marked by an arrow in Fig. 2), with area of wind stress stretching from the Kvarner Bay towards the western shore, exactly at the location where major wind jet and ocean frontal zone are commonly found (Pullen et al., 2007; Beg Paklar et al., 2008; Kuzmić et al., 2015). The largest bora-driven heat loss was documented in the Velebit Channel and within the offshore jets, again reaching maximum in the Senj Jet. Heat losses strongly decrease towards the western Adriatic coastline. Such bora driven heat loss distribution largely follows distribution associated with the extreme bora wind outbreak of winter of 2012 (see Fig. 4 in Janeković et al., 2014). The pattern of bora heat losses also resembles average net heat losses between 15 December 2014 and 15 March 2015, indicating that cooling of the northern Adriatic waters dominantly happens during bora episodes.

As it is strongly dependent on wind speed and humidity, the evaporation pattern (not shown) driven by bora wind follows the net heat loss patterns, with maximum rates exceeding 10 mm/day off Senj. Yet, an interesting pattern is found for the water flux (E-P) associated to the bora episodes, with highest negative values at the open Adriatic and particularly at the western coastline. Negative values may be also found in the NAdEx 2015 area. This implies that the bora wind – as defined by using single station at the core of the strongest jet - is associated with precipitation that appears at the back side of a cyclone, decreasing its rates toward the northwest, where maximum water uptake has been modelled.

We can conclude this section on atmospheric conditions by saying that, in spite of three strong bora events, no exceptional cooling events were observed during winter of 2015. This gives us an opportunity to study whether dense water is generated in the northeastern coastal area during average winter conditions.

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4 Ocean observations

Temperature and salinity data measured between 3 and 6 December 2014 (Leg 1 cruise) at the transect stretching over the NAdEx 2015 area (stations 1 to 19) exhibit a predominant two-layer thermohaline structure (Fig. 3a), with warmer (>16ºC) and less saline (<37.0) waters in the surface and intermediate layers - to depths of about 50-60 m. These depths were characterized by a sharp thermocline, under which a pool of colder (13-14ºC) and more saline (~38.0) waters was residing. The pool had a substantially higher density (potential density anomaly, PDA>28.5 kg/m^3) than waters residing above (<27.8 kg/m^3). Thermocline and halocline followed each other in the first third of the transect (up to station 6), after which halocline formed at smaller depths. Maximum in salinity stretching over the whole water column at stations 11 to 13 indicates an inflow of saline open Adriatic waters through connecting channels where A3 and A4 ADCPs have been moored.

Six months later, during Leg 2 cruise executed between 26 and 29 May 2015, two-layer structure was still evident from temperature data (Fig. 3b), but this time was driven by seasonal heating during springtime (Buljan and Zore-Armanda, 1976). Thermocline was positioned at depths between 20 and 30 m. However, salinity was homogenised over the whole transect, with substantially higher values (37.8-38.0) than observed during Leg 1 cruise, peaking again at stations 11 to 13. The salinity changes between Leg 1 and Leg 2 cruises indicate an advection of high salinity waters from the open Adriatic towards the whole NAdEx 2015 area, that may be a result of the DWF-driven thermohaline circulation, as found for the whole Adriatic Sea (Orlić et al., 2006) and for the Gulf of Trieste area (Mihanović et al., 2013). PDA distribution was following temperature distribution, with much higher values present in deep layers (29.0-29.1 kg/m^3) than during the Leg 1 cruise. The latter indicates that, in spite of lack of extreme cooling events, the DWF did occur during wintertime, although observed temperatures were much higher and salinities lower than during the extreme winter of 2012 (Mihanović et al., 2013).

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The thermohaline properties measured at the bottom of connecting channels, over which the transport between the coastal and open Adriatic area is happening, reveal a rate of the wintertime cooling that happened in the northern Adriatic (Fig. 4). A constant decrease in temperature (Fig. 4a) from beginning of the experiment (early December) up to the end of March was recorded at all stations, having a weak step-like structure presumably associated with strong bora events. At station A4, bottom temperatures were higher, not decreasing below 12ºC. Lowest temperature has been observed at the northwestern part of the Kvarner Bay entrance, at station A9, where minimum of about 10.5ºC was reached in early February and remained through March. By contrast, these temperatures were observed at neighbouring stations A8 and A7 a month later, indicating a presence of a complex circulation and a deep thermohaline front within the bay. In support to the existence of the front, the difference between temperature and salinity series measured at A7, A8 and A9 stations between 1 February and 31 March 2015 (in terms of their averages and variability) is significant at the 99% level. Existence of the wintertime thermohaline front through the water column can be clearly seen on glider measurements performed off the Kvarner Bay on late 26 February (Fig. 5), when strong bora conditions were present in the area. However, the front weakened the day after, when the glider returned back over the almost same track. Kokkini et al. (2017) ascribe the variability of the front to the wind forcing, where strong bora wind is in favour of a sharp front. This front has also been observed and investigated during previous wintertime campaigns (Lee et al., 2005; Poulain et al., 2011).

As for bottom salinity (Fig. 4b), it decreased in mean values when going northwestward, from station A4 to station A7, and again across the Kvarner Bay entrance to the station A9. In addition, strong salinity variability at daily and weekly scale was embedded into the series, varying between 37.5 and 38.5 at A7 to A9 stations. Such a pronounced variability indicates presence of a thermohaline front, changing its position over time. The variability was particularly strong during wintertime (January-March 2015), decreasing during the springtime. Although having monthly variations, an overall increase in salinity was recorded at all stations between mid-December 2014 and early February 2015. Temperature and salinity southeast-northwest differences along the outer NAdEx 2015 area are reflected in PDA values (Fig. 4c), which increased from mid-December (~28.0 kg/m^3) to mid and late February (~29.2 kg/m^3). Maximum PDA values were sustained until late March, presumably associated with near-bottom outflow or inflow of dense waters. PDA values slowly decreased during springtime.

Pronounced spatial and temporal changes in thermohaline properties of the Kvarner Bay may be quantified by analysing the profiling float data (Fig. 6). Arvor-C float temperature and salinity profiles obtained at the inner part of the Kvarner Bay show a weak stratification over the water column, except at the very bottom, where a few metres thin layer with substantially higher temperatures (~0.8ºC) and salinities (~0.5) was detected. This thin near-bottom layer was not present over the central western Kvarner Bay where the float was transported between 22 and 25 February (for position of the float see Fig.

1). The layer was however present at the outer western part of the bay where float drifted between 3 and 5 of March. PDA values of this bottom layer reached 29.4 kg/m^3, being larger than PDA measured at the A stations or CTDs for about 0.3 kg/m^3. Similar few metres thin density layer which was found in mid-February 2012 at the western Adriatic shelf was associated with the initial near-bottom outflow of dense waters from the northern Adriatic (Vilibić and Mihanović, 2013). Analogously, our hypothesis is that a small fraction of dense waters generated on the northern Adriatic shelf, having higher densities than waters of the Kvarner Bay (Janeković et al., 2014), spreads towards the deeper Kvarner Bay as a weak bottom density current.

Assessment of wintertime ADCP data (Fig. 7) reveals a substantial baroclinic component atop the barotropic circulation at all stations during and after two strong bora episodes (1 February – 1 April 2015), when the DWF and dense water flow were expected to occur. Weaker currents at station A9 and strong outflow at A7 and A8 stations in the surface layer indicate presence of an anticyclonic curl at the entrance of the Kvarner Bay. The pattern in currents also resembles patterns of local wind stress and wind curl, which are pronounced off the southern tip of Istria (Pullen et al., 2003; Grubišić, 2004). An inflow to the Kvarner Bay may be seen in the bottom layer of the station A9 - part of this inflow might be ascribed to dense waters coming from the northern Adriatic shelf, thus confirming our hypothesis of the origin of the bottom density current seen in Arvor-C data. Near the bottom of stations A7 and A8, the mean flow is weak, yet changeable in time, suggesting an interplay between dense waters coming from the coastal area with those coming from the northern Adriatic shelf in the Kvarner Bay area. At the same time, much stronger currents have been observed in surface and intermediate layers, indicating the predominant outflow of waters from the NAdEx area towards the open Adriatic. Going to the southeast, at station A4, measured currents were parallel to the coastline. However, being deployed too far from the connecting channel, this station was indeed not measuring interchange between coastal and open Adriatic waters but the Eastern Adriatic Current, which may be strong in that region (Orlić et al., 2006). Currents measured at the station A2 exhibit a strong baroclinic pattern, pointing to an exchange of waters between open and coastal Adriatic through a narrow channel: outflow current is present in the surface layer and inflow current near the bottom. Yet, these currents are strongly affected by local bathymetry, probably resembling the effects of both very narrow connecting channel (about 600 m in width) and the Eastern Adriatic Current modulated by the cape of Veli Rat (about 2 km south of station A2). Finally, current data measured at the A1 station document predominant inflow of the open Adriatic waters, mostly in the surface layer. The inflow is likely driven by orientation of the channel and the incoming Eastern Adriatic Current. Interestingly, wintertime baroclinic circulation, with a predominant outflow from Velebit Channel in surface layer and inflow in bottom layer, is also maintained in the inner channels (stations A5 and A6). This particularly refers to the currents measured at the station A6 located near the Senj bora jet, implying that currents at this stations are likely largely wind-driven.

5 Model validation

The modelling system was validated against available observations. Verification on the CTD data collected over the Leg 1 cruise (Fig. 3c) reveals an underestimation of temperature in surface layer and overestimation of temperature in deep

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layers, where a pool of cold and dense waters was observed in reality (Fig. 3a). Oppositely, salinity has been overestimated in surface layers and underestimated in near-bottom layers. An underestimation in salinity in the shallowest southeastern part of the transect (around station 18) is presumably due to submarine springs which are discharging freshwater from neighbouring freshwater lake to the sea and which are not introduced to the model. Altogether, the model did not properly reproduce the observed two-layer structure, but rather much more homogenized water column, without dense water pool in the deepest parts of the NAdEx area. Thermohaline properties during the Leg 2 cruise (Fig. 3d) show better agreement with the observations, particularly salinity, where the bias is about 3 times lower than for the Leg 1 cruise. This particularly refers to the surface layer (Fig. 8). The temperature bias has also been smaller during Leg 2 cruise. However, a drawback was present in reproduction of the thermocline, as the largest root-mean-square error is present exactly at these depths (15-35 m). Nevertheless, model successfully recreated presence of cold and saline bottom layer, as well as a two-layer structure observed during the Leg 2 cruise, keeping both bias and root-mean-square-error pretty low near the bottom. Modelled bottom PDA values at dates corresponding to Leg 2 cruise were higher (around 29.0 kg/m^3) than at dates corresponding to the Leg 1 cruise (around 27.8 kg/m^3), indicating that model was able to reproduce the DWF in the NAdEx area.

Model verification performed on the float and glider data is shown in Figs. 5b and 6b. The float data has been verified on the nested model simulation, while parent model simulation has been used for verification of glider measurements. An inspection of results indicates that the model is able to reproduce observed thermohaline properties inside the Kvarner Bay. There are however several omissions there: (i) both temperature and salinity show an increase in negative bias from inner to outer part of the bay, and (ii) the model is not able to reproduce narrow bottom density current. The latter is because the model does not have sufficient vertical resolution to reproduce such a thin bottom layer. An overestimation of both temperature and salinity of the open Adriatic waters (positive bias) has been visible on the model-to-observation differences along the glider pathway, where the parent model does produce warmer and saltier water northwest from the measured thermohaline front. By contrast, temperature and salinity biases were much lower in absolute values southwest from the front. These results imply two conclusions: (i) the position of the thermohaline front was not properly modelled, and (ii) the strength of the front in the model is much weaker than captured by glider observations.

Model-to-observation Q-Q plots of temperature and salinity constructed by comparing float, glider and CTD data (Fig. 9a, b) indicate that temperature data have been reproduced fairly well over the inner NAdEx area (float and CTD), but not at the open Adriatic, i.e. in the area off Kvarner Bay (glider). As for salinity, model overestimated values below 37.6 compared to the CTD measurements, while higher salinities were successfully reproduced. Salinities measured with the Arvor-C profiler and glider were generally overestimated by the model over most of percentile distribution, except for salinities around 37.6 and for the upper tail of the distribution (>38.1). This particularly holds for salinities measured by the glider, i.e. for salinities modelled with a lower resolution parent model. Summarily, the model best reproduced salinity in the interior of the basin, a bit worse in the Kvarner Bay and much worse off the bay.

Comparison of bottom temperature and salinity, and bottom current speed data, as measured at stations A1 to A9 (Fig. 9c, d, e), indicates that temperature and salinity have been fairly reproduced by the model at all stations, differing by less

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Box-Whiskers plots (Fig. 11c, d) confirms that model reproduced well the temperatures in the Kvarnerić Channel and Kvarner Bays (CTD and float measurements), with a minor portion of relative differences exceeding 10%. However, temperatures measured by the glider off Kvarner Bay were significantly overestimated by the parent model.

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than 1^{o}C and 0.3, respectively, except for some sparse data. That also refers to the reproduction of thermohaline properties and changes in time (not shown), which exhibit low biases - particularly for temperature - at all stations over the whole measuring interval (not shown). The temperature trends have been matching observations pretty well, being negative between December and February, then reaching minimum temperatures in late February and March due to dense water outflow, and after showing a weak positive trend due to mixing and advection of open Adriatic waters. A significant decrease in temperature and salinity properties in the outer Kvarner Bay (stations A7 to A9) has been also reproduced by the model. The biases are slightly larger at A7, A8 and A9 stations, particularly in temperature (0.3-0.6ºC), as the model do not reproduce a thin near-bottom inflow of warmer and saltier waters in the outer part of the Kvarner Bay as seen on the float data (Fig. 6a). Yet, these biases, and also overall temperature, salinity and current biases at most of A stations are smaller than root-mean-square values (not shown). However, current speeds have been strongly underestimated by the model at all stations, between 50% and 80% in average. There may be several reasons for that: (i) too coarse horizontal resolution of ocean model, (ii) insufficient resolution of atmospheric model and inappropriate reproduction of bora-driven mesoscale variability, and (iii) inappropriate boundary conditions. Reasons for this underestimation will be discussed in more detail in Section 7.

Aside underestimation, comparison of mean currents and the associated standard deviation ellipses (Fig. 7) exhibit a number of differences between modelled and observed currents, being largely the result of the complex bathymetry. Model-to-observation current speed differences averaged over the vertical and for the whole period range from -4 cm/s at stations A5, A6, A8 and A9 to -6 cm/s at station A1, while directional biases range from about -5o at A2, through approx. -15^{o} at A4, A6 and A8, reaching approx. -25^{o} at A1, A5 and A7, and 27^{o} at A9. Vertical structure of currents - i.e. a rate of change of current speed over the vertical – has been fairly reproduced at all stations, except A2. The latter is a consequence of the complex bathymetry in the region underrepresented by the model, as connecting channel off which the station A2 has been positioned toward the open sea, is very narrow, about 600 m in its deep section. Also, the station is located a bit off the channel, presumably exhibiting a strong interaction between the Eastern Adriatic Current and the channel current. At all other stations the model reproduce either the surface maximum in currents and a decrease towards the bottom (A1, A4, A7, A8, A9) or maximum currents in the bottom layer (A5) or two-layer circulation (A6). The current direction is fairly reproduced at A1, A4, A5, A6 and A8, but much worse at A7 and A9 (plus A2).

In conclusions, the model is reproducing thermohaline properties and the DWF in the coastal northeastern Adriatic (inner domain) fairly well and may thus be used for quantification of related processes and dynamics there. It should however be taken into account that a restricted (weaker than observed) water mass communication has been reproduced between coastal and open Adriatic through connecting passages.

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6 Model results

6.1 Thermohaline, buoyancy and stratification changes

Modelled temporal changes of thermohaline properties at location G1, positioned in the Velebit Channel at the core of the Senj bora jet, and at location G2, positioned in the outer Kvarnerić Channel, are displayed in Fig. 10. Mixed layer depth (MLD), computed by using de Boyer Montégut et al. (2004) methodology with density increment threshold set to 0.125 kg/m^3, is reaching the bottom all time at G2 till early April, indicating that water column was vertically homogenized over most of the basin from December until early April. Later on, surface thermocline developed, deepening to about 30-40 m in early July. Salinity series at the G1 location exhibit pronounced daily and weekly changes in the upper layer, as being influenced by the nearby freshwater discharge of the Senj hydropower plant. Yet, vertical homogeneity and MLD reaching the bottom have been present there during cooling events around 30 December 2014, 5 February and 5 March 2015 - this is due to its position on the track of the Senj bora jet. Between bora events, the ocean started to relax through horizontal advection and increasing a bit stratification due to radiative forcing.

The most of the coastal area has been vertically homogeneous prior to the early February and early March bora events (Fig. 11), with MLD reaching the bottom in the most of the region. The only exceptions were coastal waters close to river mouths, like eastern Velebit Channel and off Senj power plant (where G1 station is positioned), and areas characterized by strong thermohaline fronts, like Kvarner Bay. However, both boras were substantially strong and mixed even these regions to the bottom, allowing for the DWF to occur in the whole coastal region.

A simple box model (e.g. Gill, 1982) of energy balance has been applied to these locations, relating the decrease of the ocean temperature ΔT in a box to surface heat losses:

$$\Delta T = \frac{1}{Hc\rho_0}\int_{t_1}^{t_2} Q\, dt$$

where Q is the surface heat flux in the time interval between t_1 and t_2, while H is the ocean depth. The specific heat of sea water c and sea water density ρ_0 was approximated by constant values of 3990 J/kg K and 1027.5 kg/m^3. This model assumes no lateral exchange of energy between the box and the adjacent sea, what is a fair approximation for short and transient events like the bora. At station G1 this simplified formula gives ΔT = -0.96ºC, -0.48ºC and -0.03ºC for three bora events (the third bora was very weak at G1), respectively, while the respective cooling rate as provided by the model is -1.04 ºC, -0.51 ºC and -0.07ºC. Given the assumptions of this simple box model, one can conclude that the cooling in the area is dominantly driven by the bora wind.

Density persistently increased at both locations until mid-March, when maximum PDA values were modelled at both G1 and G2 locations. This maximum is a results of the severe bora wind episode that peaked in some parts of the area on 5/6 March (see Section 3). As a consequence, thermohaline circulation strengthened and the open-Adriatic saline waters were advected to the coastal area, particularly to its outer parts (G2 location). An increase in salinity in the coastal area has been

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additionally intensified in May, presumably driven by the lagged thermohaline circulation of the Adriatic-Ionian basin (Orlić et al., 2006).

Buoyancy changes, estimated following Marshall and Schott (1999) over the nested model domain, document buoyancy loss that was dominantly occurring during bora outbreaks (Fig. 12). The most pronounced buoyancy loss occurred around 30 December 2014, being largest in the Velebit Channel inner area, a bit lower along the bora jets (Senj Jet, Pašman Jet, Janeković et al., 2014), and lowest at a wake of the bora wind (e.g. G2 location). Buoyancy loss was predominantly driven by the heat loss, while haline-driven buoyancy changes were of minor importance. Buoyancy losses during bora events decreased stratification of the area, which can be seen clearly through an increase in MLD and areas where MLD reach the bottom (Fig. 11). This particularly applies to the inner Velebit Channel, where maximum buoyancy losses with rates high enough to homogenize the whole water column were modelled. We can conclude by saying that model successfully reproduced DWF during severe bora outbreaks. Knowing this, we can study dense water dynamics in the area and interchange between inner coastal and open Adriatic waters in more detail.

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6.2 Lateral boundary fluxes, residence and flushing times

Heat and salinity fluxes normal to transects T1 to T789 (notation is following numeration of stations A1 to A9) and averaged between 15 December 2014 and 15 May 2015 are shown in Fig. 13. Positive fluxes are considered if directed towards northeast at T2, T3, T4 and T789, and towards northwest at T1, T5 and T6. Heat fluxes indicate that the coastal northeastern Adriatic gained energy mostly over transects T1 and T3. This applies particularly to T1 surface layers and T3 bottom layers, while near-surface heat fluxes were of opposite direction at the T3 transect. Fluxes at T2 transect also show an inward-outward structure, with the strongest outward values modelled near the bottom. Fluxes were predominantly weakly negative along the T4 transect and strongly negative along the T789 transect, indicating that the coastal area was losing energy and salt through the northern connecting passages, in particular through the Kvarner Bay. The predominance of negative fluxes, occurring mostly through the Kvarner Bay, may be perceived through averaging transports over transects and the outer lateral boundary (Table 1) (T_{outer}=T1+T2+T3+T4+T789). In summary, the coastal northeastern Adriatic lost energy through lateral boundaries, and in particular through Kvarner Bay boundary, during the winter and spring of 2015 (15 December 2014 – 15 May 2015), a period which encompasses preconditioning, generation and spreading phase of the DWF in the area.

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Normal modelled fluxes at inner transects (T5 and T6, Fig. 16) were mostly directed nothwestward in the very surface layer, presumably due to bora-driven currents. Fluxes were of opposite direction in the bottom layer, following two-layer circulation in these constrictions. The total inner transports (T_{inner}=T5+T6) show transport of energy, salt and mass towards the inner coastal area of the Velebit Channel (Table 1). However, this transport is much weaker than the transport modelled at the outer boundaries of coastal waters.

Modelled fluxes and transports are highly variable in time (Fig. 14), particularly over the outer lateral boundaries. Average transports during six peak events are larger for about 6 and 2 times than the respective average transports over the outer and inner lateral boundaries, respectively. As they occur over the by far largest transect, transports at the transect T789

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dominate T_{outer} transports. It is interesting that during some peak events, such as 28 December 2014 and 22 February 2015, the T1 inward transport peaks simultaneously as the outward transport at transects T2, T4 and T789. Therefore, the peak inflow at the southern boundary of the NAdEx 2015 area, which is under the influence of the Eastern Adriatic Current (occasionally being directed toward the inner waters southeast of the transect T1), is balanced by the strong outflow at the northwestern lateral boundaries. By contrast, there are situations in which peak transports are localized over smaller parts of the domain. For example, peak outward transports at transects T2 and T3 are balanced by the inward transport at T1 on 5 March 2015. These transports were presumably driven by strong bora which blew severely in the southeastern part of the NAdEx 2015 domain, increasing its speed towards the southeast (central Adriatic). Transports at the lateral boundaries became much weaker after the early March bora, having lower values in April and May.

Dense water average mass flux (Fig. 15), defined as a flow of water with PDA >29.2 kg/m^3 normal to transects (Janeković et al., 2014), was largest at the outer lateral boundaries at transects T3 and T789. As expected, mass flux is directed towards the open Adriatic, but with higher values in the surface layer than near the bottom, as wind-driven transport is stronger there. Also, the near-bottom minima can be a sign of a sporadic penetration of dense waters coming from the open sea, i.e. northern Adriatic shelf, towards the deep coastal area, supported also by the profiling float data (Fig. 6). That dense water flow may reverse, particularly at northern outer transects T4 and T789, is clearly seen in Fig. 16. The strongest dense water outflow event was modelled to occur around 22 February, about two weeks after the early February severe bora events, through all but T3 outer lateral boundary transects. During the peak dense water outflow, the dense water volume transport over outer boundaries reached the maximum value of 0.4 Sv, being comparable with the peak dense water outflow modelled during the extreme winter of 2012 (Janeković et al., 2014). The dense water transport across inner transects is also interesting, as on average it is directed towards the inner coastal area. Yet, the inflow is stronger at transect T5 in late February and late March, while the maximum inflow is occurring at transect T6 during late March and April.

Residence times are computed for both outer and inner coastal areas and for a period between 15 December 2014 and 15 May 2015. Residence time (RT) has been computed by applying the formula:

$$RT = \frac{\iiint_{x,y,z} \rho(x,y,z)\, dx\, dy\, dz}{\oint\!\!\oint_{C,z} \rho\,(x,y,z)\, \vec{u}_{out}(x,y,z).\vec{n}\, dC\, dz}$$

where $\rho(x,y,z)$ is the density of the water at each point (x,y) and for each depth z of the domain, while $\vec{u}_{out}(x,y,z).\vec{n}$ is the normal outward velocity along the contour C of the domain. Such an approach assumes that (i) only the velocities at the border of the domain are used to calculate the residence time, (ii) only the outflow of water at the border is taken into account; the goal here is to only look at how long it would take for the water masses to leave the domain assuming that there is no income of water within the studied domain, and (iii) the residence time is calculating with a time step of 3 h over the period of the studied event, assuming a steady state of the dynamical conditions at each time step. Box-whiskers statistics has been computed for total (RT) and dense water (DWRT) residence times (Fig. 17). The median RT for the whole coastal basin (bordered by outer transects T1, T2, T3, T4 and T789) has been estimated to 19 days, although it appeared much shorter during

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strong wind outbreak episodes (down to 7 days) and much longer during low mass exchange between coastal and open Adriatic waters (up to 40 days). Dense water residence times (DWRT; waters with PDA >29.2 kg/m^3) are much lower, with median value of 11 days and normally not longer than 35 days. DWRT is smaller than RT as the volume of the generated dense waters is much smaller than the volume of the whole coastal area, while the dense water outflow was substantial ad occurring over a large portion of the transects, not just at the bottom.

7 Discussion and conclusions

The coastal northeastern Adriatic is one of the Adriatic regions so far least investigated. There have been several reasons for this: (i) it has been considered to have no substantial influence to the overall Adriatic dynamics, as it is separated from the open Adriatic by several long islands, physically restricting water exchange, (ii) the area is positioned far away from research institutes, whose monitoring activities have thus not encompassed the area (see e.g. published data catalogues by Buljan and Zore-Armanda (1966, 1979) and Zore-Armanda et al. (1991)), and (iii) satellite remote sensing does not perform well in the region, as numerous channels and complex topography impair quality of data (Klemas, 2011). In addition, this area has wrongly been treated as a basin with strong freshwater fluxes, particularly of riverine origin (Raicich, 1994). Recently, it has been found that this old climatology of river discharge overestimates real river discharges by almost an order of a magnitude (Janeković et al., 2014; Vilibić et al., 2016a). Only limited parts of the coastal northeastern Adriatic were investigated previously (e.g. Rijeka Bay in early 1980s, Gačić et al., 1983, outer Kvarner Bay during the winter of 2002/2003, Lee et al., 2005; Poulain et al., 2011). The NAdEx 2015 experiment is the first and up-to-now the only experiment that systematically approached monitoring of the northeastern coastal Adriatic, including communication between the open Adriatic and the coastal area through connecting channels. The NAdEx 2015 was realized through a strong collaboration and engagement of different institutions, resulting in a multiplatform marine dataset which can serve as a baseline for future investigations in the area. That also includes introduction of state-of-the-art measuring platform providing an insight to processes not documented in the Adriatic, like Arvor-C profiling float deployed in the Adriatic Sea for the very first time. The choice of the experimental area – the coastal northeastern Adriatic - emerged from its role in the winter of 2012, when it exhibited an unprecedented heat loss (up to 2000 W/m^2) and DWF rates that strongly contributed to the overall Adriatic dense water dynamics (Mihanović et al., 2013; Janeković et al., 2014).

We have overviewed observations and estimated rates of selected basic processes, using both an extensive set of measured data and a coupled atmosphere-ocean model. Our main intention was to answer two questions: (i) whether or not the DWF is common in the northeastern coastal Adriatic, and (ii) if so, what is DWF-related dynamics behaviour, in particular regarding water exchange with the open Adriatic. To answer these questions we reached the following conclusions: (i) CTD data show that the DWF does occur in the coastal northeastern Adriatic during normal winters in terms of wintertime heat losses, as was the case of 2015; (ii) observations at connecting channels show a marginal bottom outward transport of dense waters to the open shelf and a balanced near-bottom inward-outward dense water exchange, while the outward transport of dense waters is mostly concentrated in intermediate and surface layers, (iii) modelling results show the domination of outward dense water transport, supporting the hypothesis that the NAdEx area is a source of dense waters for the open Adriatic, and (iv) exchange of waters between coastal and open Adriatic waters through a number of connecting passages has been quantified, with residence time varying from a week to a few weeks and being shorter during strong wind conditions.

These results are also in line with previous modelling results by Janeković et al. (2014), who also modelled outflow dense water transports in connecting passages during the winter of 2012. Yet, the density of these waters has been much higher and almost equalling the density of waters coming from the open Adriatic DWF site due to different preconditioning and DWF setup in the winter of 2012, so that the DWF outflow from the NAdEx area happened also in the bottom layers of the connecting passages. Precisely, there are several reasons for this: (i) preconditioning did not include a prolonged period of dry conditions (MHS, 2014, 2015), which may increase salinity of inner coastal waters to values equal to those observed in the open Adriatic (Mihanović et al., 2013), and (ii) wintertime cooling and heat losses were not as pronounced as in 2012, although there were several strong bora events. Although weaker, the DWF of 2015 excited thermohaline circulation in the basin, being detected through an increase of salinity in time (Orlić et al., 2006). Still, the question is whether or not intrusion of the open Adriatic saline waters to the coastal northeastern Adriatic during late winter and spring of 2015 was the result of the open Adriatic thermohaline circulation driven by the DWF in the coastal northeastern Adriatic, or a consequence of the broader open-Adriatic thermohaline circulation.

Aside from documentation of processes by measurements, these data may be particularly useful for fine tuning of numerical models, which is a foreseen direction of future investigations in the Adriatic, in both coastal and open ocean areas – particularly as model strongly underestimated measured currents, especially in narrowest connecting passages (Fig. 10). The tuning should include also a densification of sigma layers near the bottom, where bottom density currents may appear (Vilibić and Mihanović, 2013). For sure, 20 sigma layers in our modelling system were not able to satisfactorily reproduce the observations in the near-bottom layers, like these of Arvor-C profiling float, yet such a number of layers were found to satisfactorily reproduce overall dense water dynamics over the northern Adriatic shelf (e.g. Benetazzo et al., 2014). Estimated variables proportional to currents were also underestimated (e.g. heat, salt, mass and volume fluxes at connecting passages), while residence times were likely overestimated. Yet, thermohaline properties of the coastal area are fairly well reproduced, pointing to the fairness of the model results in reproducing DWF processes and associated dynamics.

Underestimation of water exchange between the coastal and the open Adriatic waters may be a result of several factors. The first and the most obvious one is the horizontal resolution of the ocean model. A resolution of 500 m may not be high enough to reproduce cross-channel processes occurring in a few kilometres wide channels, such as those approximated by the T2 and T3 transects. This hypothesis is supported by the fact that currents were least underestimated in wider channels and areas, e.g. at T4 and T789 transects. However, as they were still underestimated at latter transects (i.e. corresponding ADCP points), part of the misrepresentation must be due to other factors within the modelling system, like parameterisation of wind effects, vertical diffusivity, lack of wave models, slip conditions at the coastline, etc. Surface forcing is the next culprit

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in the list, since an 8-km mesoscale ALADIN model with a 2-km dynamical downscaling of surface wind might not be sufficient for realistic ocean forcing in such a complex area. This applies to both ocean and atmospheric processes, considering that the bora wind in the area is driven by an interaction of the synoptic flow with complex orography of the Velebit Mountain, while being modified by topography of islands (Grisogono and Belušić, 2009).

Recent investigations of different types of bora by the TerraSAR-X images (Kuzmić et al., 2015) conclude that different bora types embed a number of small spatial structures in its flow at the kilometre and event sub-kilometre spatial scales. The structures are particularly developed during severe bora outbreaks when large differences between relatively high sea surface temperature (SST) and overflowing very cold air are present. These differences can trigger secondary bora jets and extensive orographic breaking waves that propagate over the entire coastal northeastern area and over much of the open Adriatic, as was the case during the winter of 2012. Last but not least, the role of air-sea feedback during bora events is not negligible, as was shown through comparison of two-way coupled atmosphere-ocean models vs. uncoupled simulations (Pullen et al., 2006, 2007; Ličer et al., 2016): air-sea feedback influences position and strength of jet-like structures, it decreases heat losses in the area, and it reduces ocean current in a jet for about 10-20% during bora events, therefore suppressing ocean mixing. In summary, an improvement in reproducing wintertime dynamics in a complex area such as the coastal northeastern Adriatic should be based on: (i) an increase in horizontal resolution of an ocean model, (ii) implementation of high-resolution (1 km horizontal resolution at maximum) non-hydrostatic atmosphere model, and (iii) their two-way coupling. This concept does not include the effects of waves, which are known to affect the DWF at the open Adriatic (Benetazzo et al., 2014); yet, no sensitivity modelling study of waves has been performed for the complex coastal regions, which are characterized by a quite limited fetch and strong deformation of waves due to strong gustiness of bora wind.

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To emphasize the importance of the NAdEx 2015 experiment, we should add that preliminary analyses of observations (Vilibić et al., 2016b) reveal a number of interesting phenomena and processes other than those presented in this paper. For example, it seems that dynamics of the thermohaline front that stretches from Kvarner Bay towards the open Adriatic (Lee et al., 2005; Kuzmić et al., 2006; Poulain et al., 2011) is highly variable in time, resembling a near-diurnal wave-like oscillations. A question is if these oscillations are driven by diurnal tides (Cushman-Roisin and Naimie, 2002), Adriatic seiches (Cerovečki et al., 1997), inertial oscillations (Orlić, 1987) or some other phenomena that may induce significant oscillatory currents in the region (Kokkini et al., 2017). In addition, as seen from glider measurements, the front may completely change and even vanish over a daily timescale, and may have a strong impact on the thermohaline and dense water dynamics in the region. Last but not least, high-frequency phenomena have been observed in coastal waters, presumably being a result of inertial, tidal (barotropic and baroclinic), topographic (the Adriatic seiche of 21.5 h) and advective processes strongly influenced by the complex coastal topography. These processes may influence the Adriatic-scale phenomena, similarly as the exchange between the Venice Lagoon and the Adriatic modulates the Adriatic diurnal tides (Ferrarin et al., 2015). Further investigations of all these processes are envisaged through in-depth analyses of the collected NAdEx 2015 dataset and process-oriented atmosphere-ocean modelling at high resolutions.

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Table 1. Average heat, salt and volume transports at transects T1 to T789, as well as sum of transports at the outer (T1+T2+T3+T4+T789) and inner (T5+T6) boundaries of coastal waters.

	T_1	T_2	T_3	T_4	T_5	T_6	T_{789}	T_{outer}	T_{inner}
Salt transport (10^8 kg s^{-1})	1.7	-0.6	0.5	-4.6	-0.6	-0.2	-21.8	-24.8	-0.8
Heat transport (10^{11} J s^{-1})	2.4	-0.8	0.7	-6.3	-0.8	-0.2	-28.4	-32.4	-1.0
Volume transport (10^3 m^3 s^{-1})	4.4	-1.6	0.9	-11.0	-1.6	-0.4	-56.6	-63.2	-2.1

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Table 2. Temperature, salinity mass and volume sum transports at the outer (T1+T2+T3+T4+T789) and inner (T5+T6) boundaries for peak outer transports.¶
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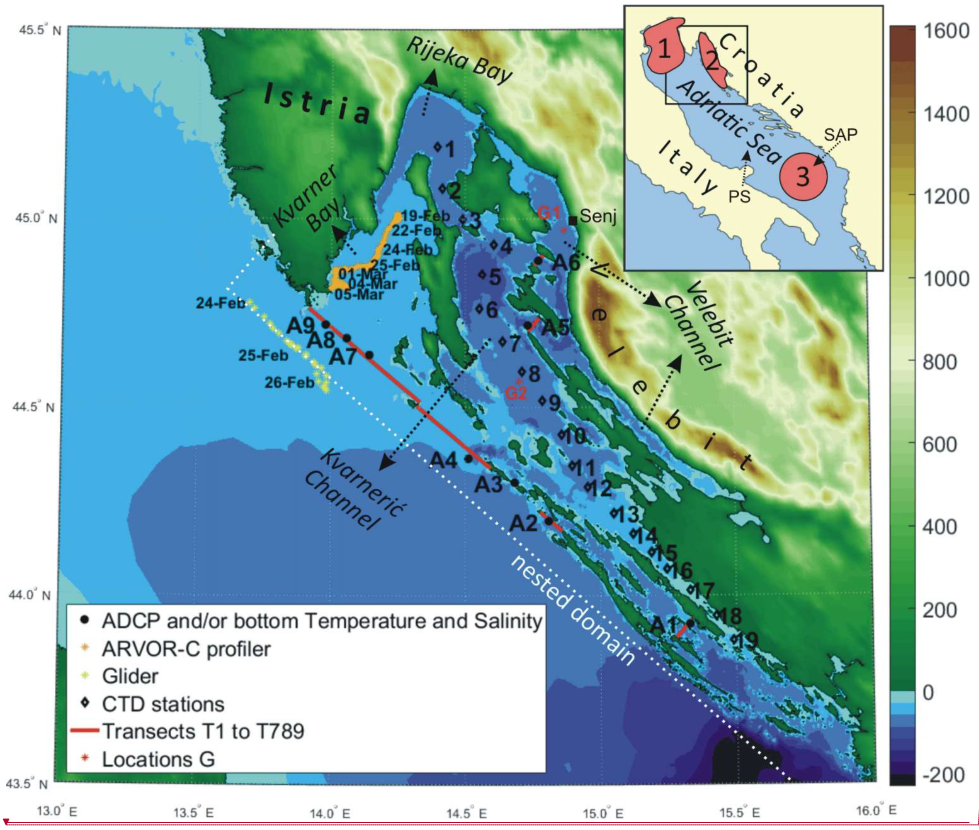

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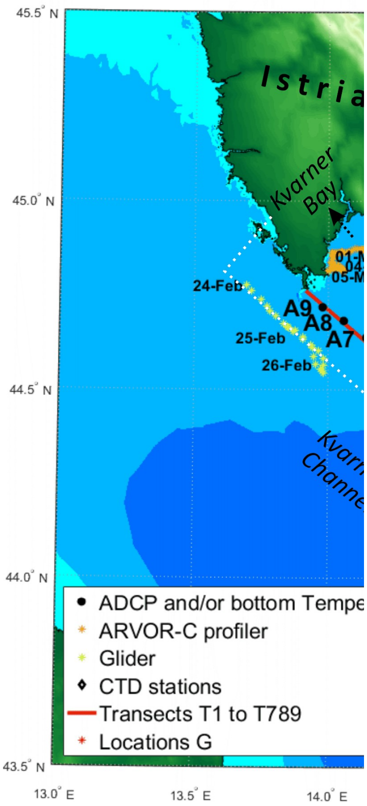

Figure 1. Geographical position and bathymetry of the coastal northeastern Adriatic, with indicated measurements conducted through the NAdEx 2015 experiment: stations A1 to A9 (black circles) where ADCP/SBE911 were moored at the bottom, stations 1 to 19 (black diamonds) where CTD probe profiling has been executed, Arvor-C profiling (orange stars) and glider profiling (yellow stars). Locations G1 and G2 (red stars) have been used for computation of temporal changes in heat losses, buoyancy changes and thermohaline properties from the modelling system, while the definition of the bora episode has been based on ALADIN/HR wind modelled at G1 location. Transects T1 to T6 and T789 are marked by red lines on which the fluxes and transports have been estimated; the transect labels are associated to the equivalent A station labels. Nested ROMS domain boundary is indicated by dashed white line. Inset numbers 1, 2 and 3 denote the areas where dense water formation is documented in the Adriatic Sea, while PS and SAP stand for Palagruža Sill and South Adriatic Pit, respectively.

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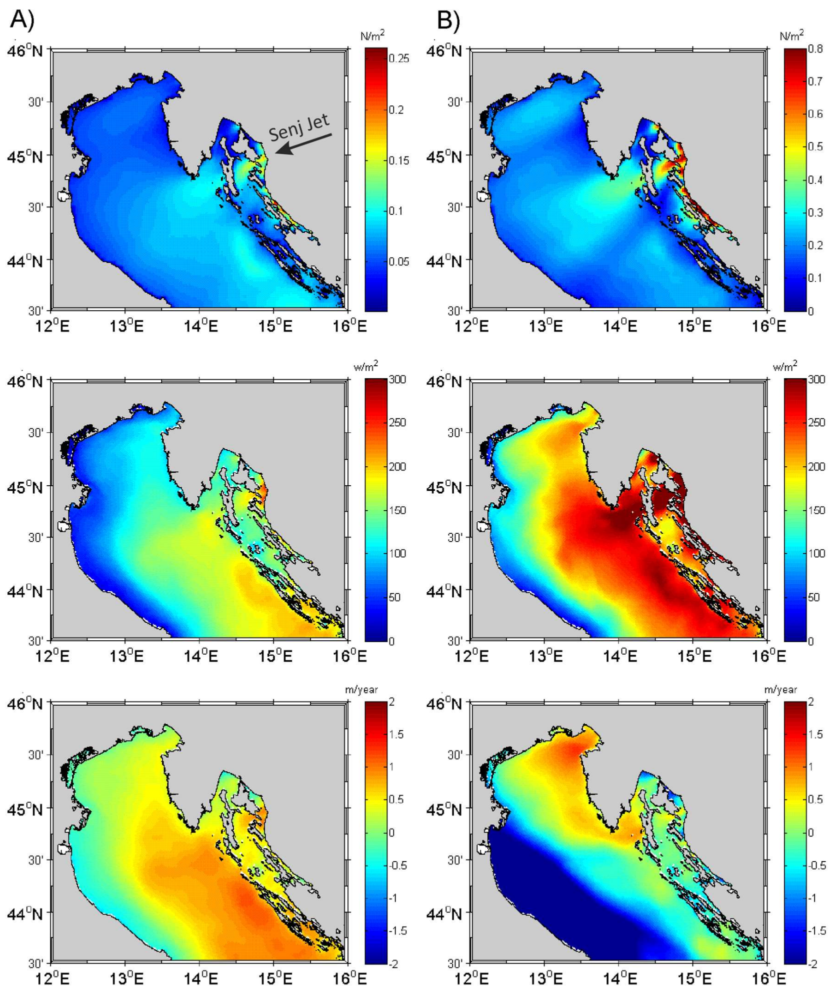

A)
B)
Senj Jet
N/m2
w/m2
m/year
46°N
45°N
44°N
30'
12°E
13°E
14°E
15°E
16°E

Figure 2. Wind stress module (top), net heat flux (middle) and water (E-P) flux (bottom) in the middle and northern Adriatic averaged (a) between 15 January and 15 March 2015, and (b) over all bora episodes occurring between 15 January and 15 March 2015. Bora episodes are defined by the wind speed higher than 15 m/s blowing along the major wind axis (from ENE) at G1 location.

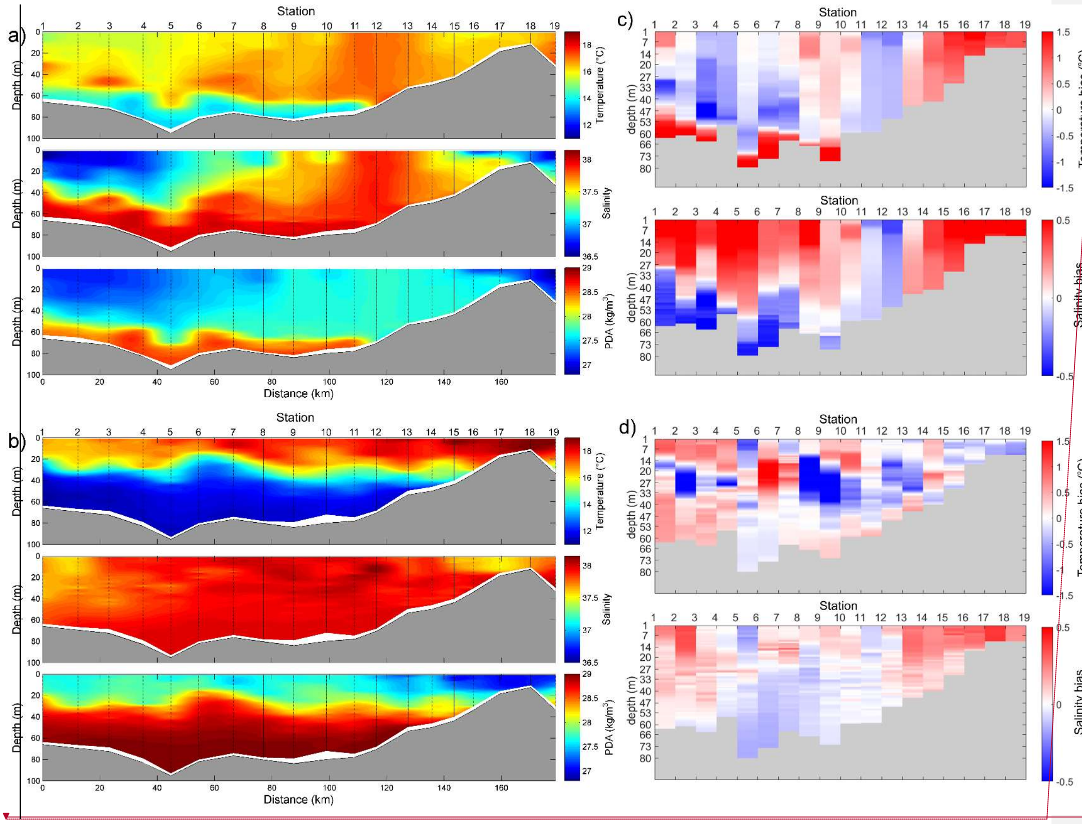
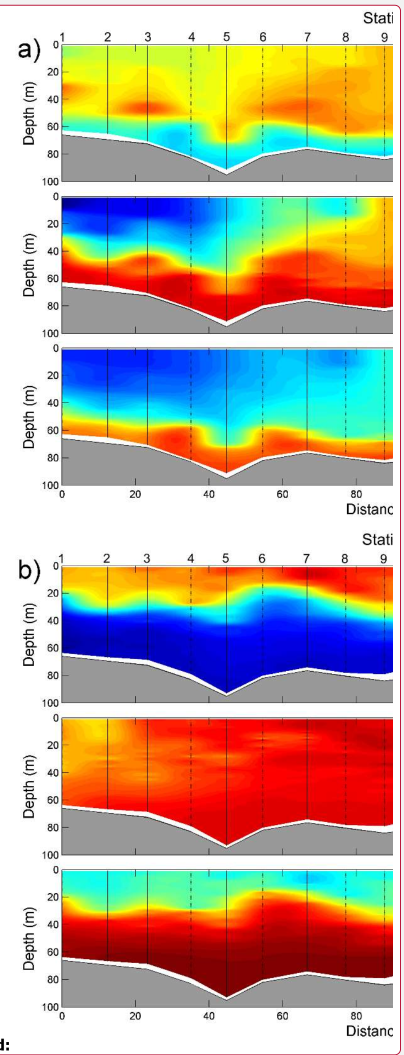


Figure 3. Temperature, salinity and PDA values measured at the Kvarnerić Channel transect during (a) Leg 1 cruise between 3 and 6 December 2014, and (b) Leg 2 cruise between 26 and 29 May 2015, together with model-to-observation difference (bias) in temperature and salinity estimated for (c) Leg 1 and (d) Leg 2 cruises.



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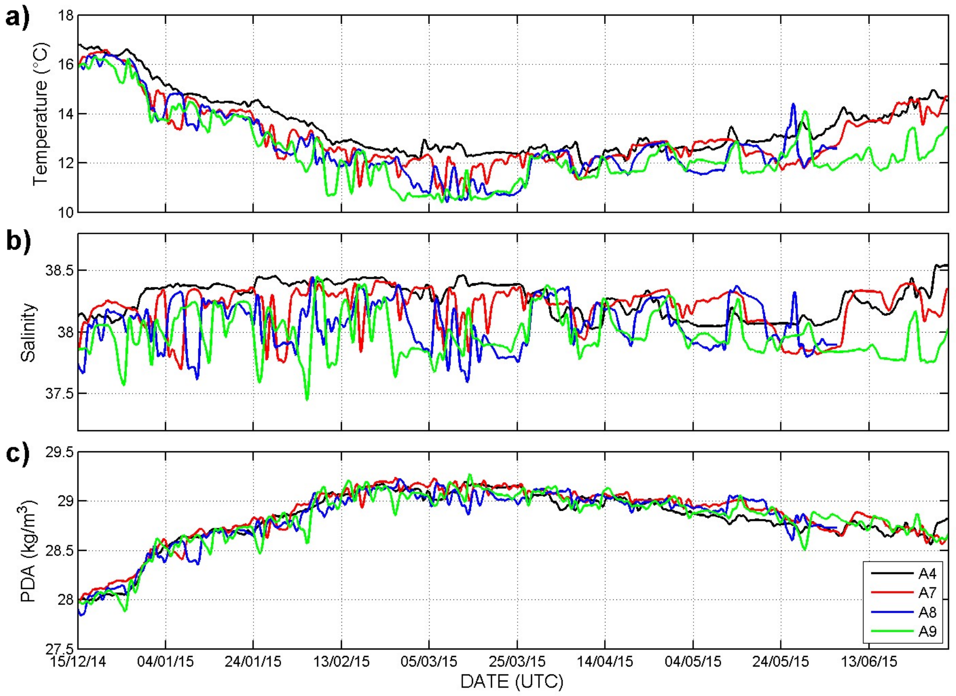

Figure 4. (a) Temperature, (b) salinity and (c) PDA series measured at the bottom of stations A4, A7, A8 and A9. The series are filtered by low-pass Kaiser-Bessel filter with cut-off period at 33 h.

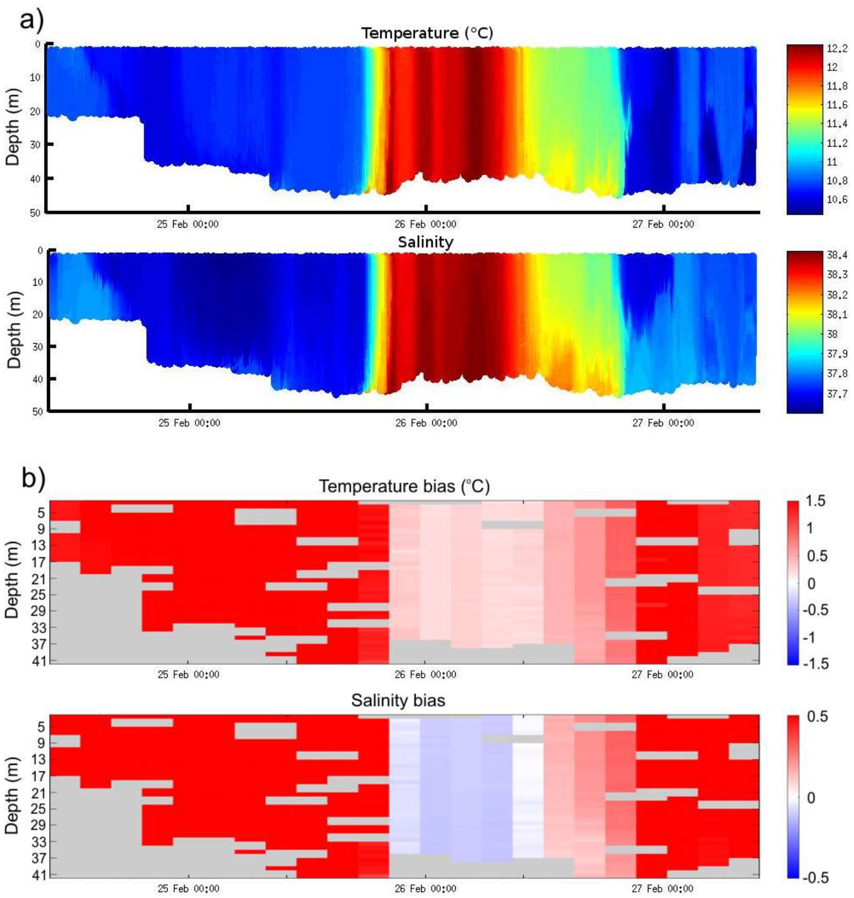

Figure 5. (a) Temperature and salinity profiles measured by Slocum glider between 24 and 27 February 2015 in front of the Kvarner Bay, together with (b) model-to-observation difference (bias). Glider trajectory is plotted in Fig. 1.

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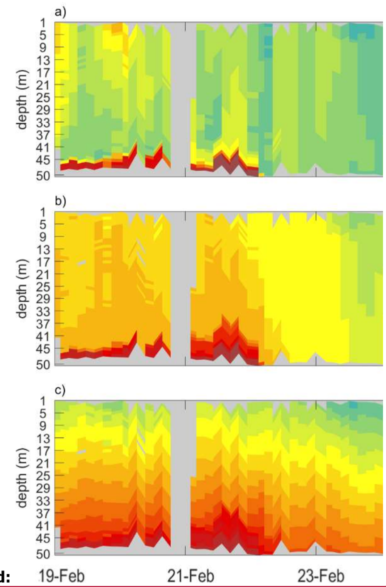

Deleted: **Figure 5. Temperature, salinity and density values measured between 19 February and 5 March 2015 by Arvor-C profiling float in the Kvarner Bay.¶**

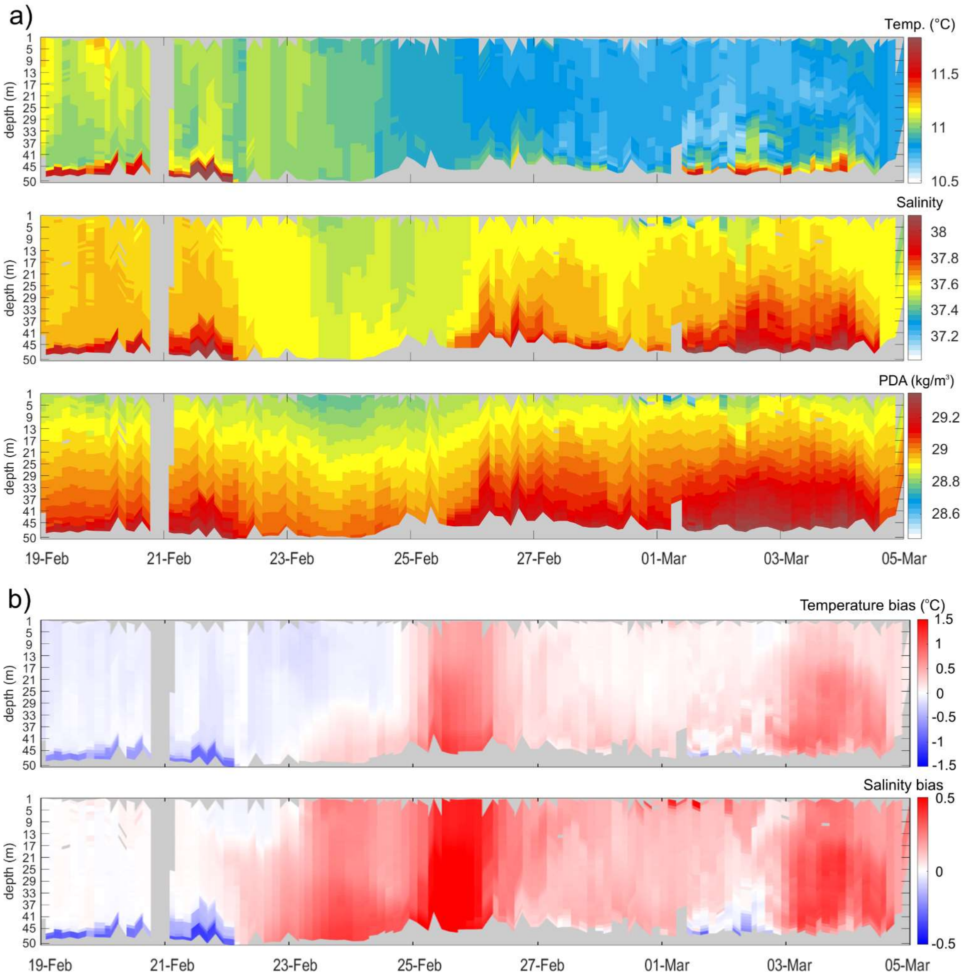

Figure 6. (a) Temperature, salinity and PDA values measured between 19 February and 5 March 2015 by Arvor-C profiling float in the Kvarner Bay, together with with (b) model-to-observation difference (bias). Profiling float trajectory is plotted in Fig. 1.

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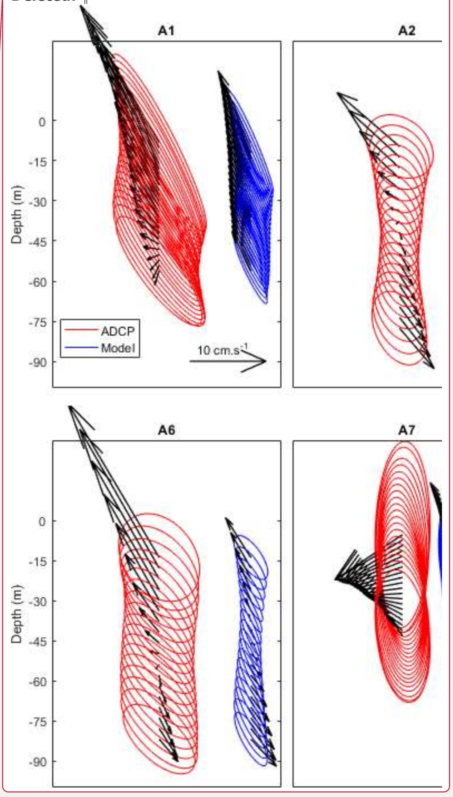

Deleted: Figure 6. Mean residual currents and ellipses of standard deviations measured (red) and modelled (blue) at A1 to A9 stations between 1 February and 1 April 2015.¶
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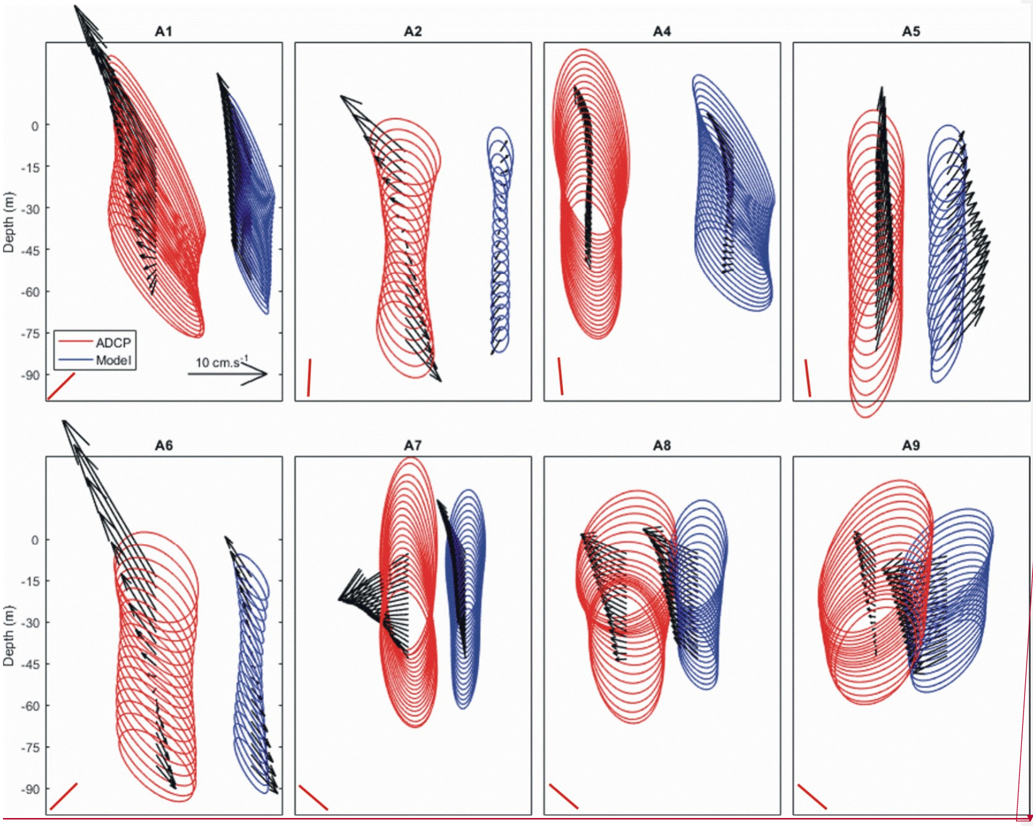
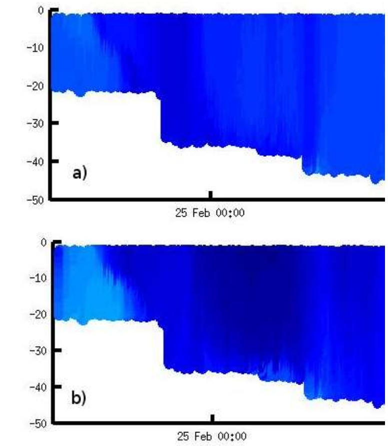


Figure 7. Mean residual currents and ellipses of standard deviations measured (red) and modelled (blue) at A1 to A9 stations between 1 February and 1 April 2015. Orientation of all channel cross-sections in which stations have been moored is indicated by red line in left lower corner.



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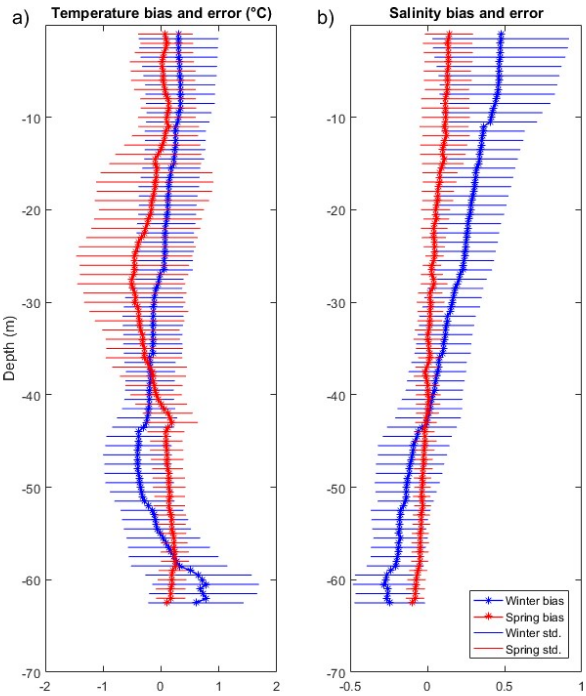

Figure 8. Vertical profiles of the bias and root-mean-square-error during Leg 1 (winter) and Leg 2 (spring) cruises.

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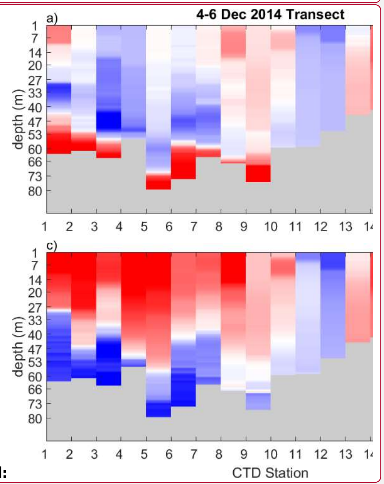

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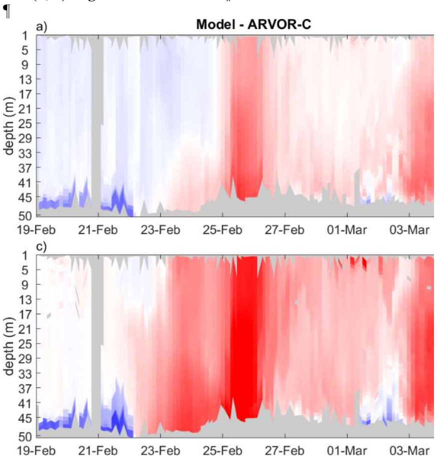

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Figure 10. Model-to-observation difference in (a, b) temperature and (c, d) salinity estimated for (a, c) Arvor-C float and (b, d) glider measurements.¶

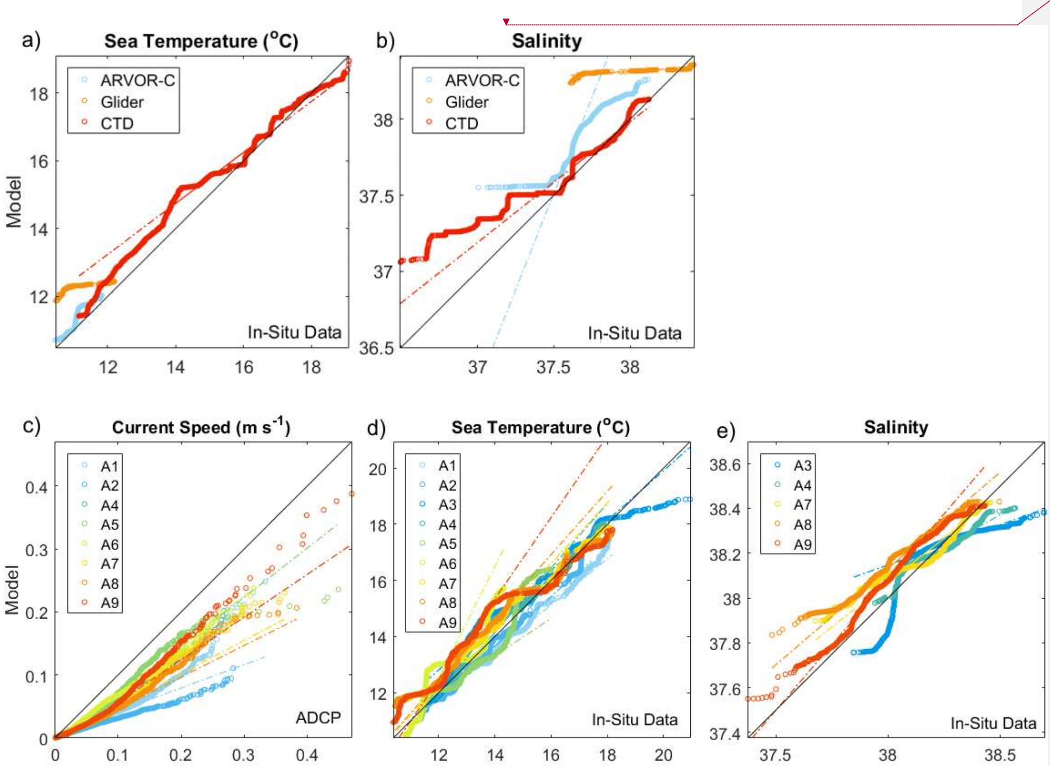
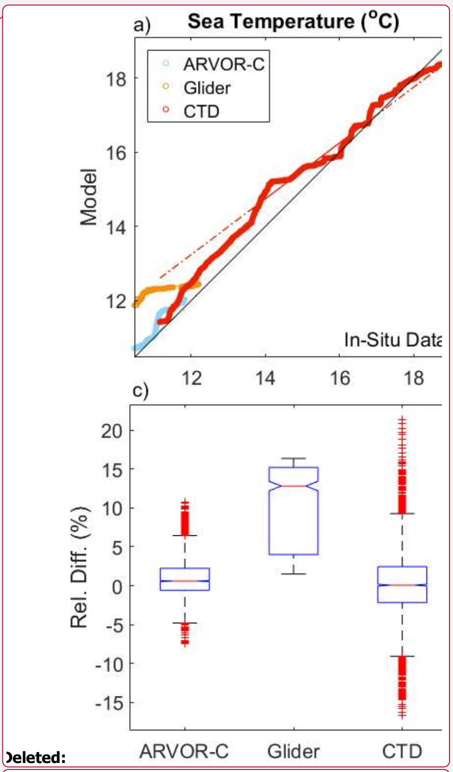


Figure 9. Model-to-observation Q-Q plots of (a) temperature and (b) salinity measured by CTD, Arvor-C profiling float and glider, and (c) current speed, (d) temperature and (e) salinity measured at the bottom of stations A1 to A9. Each dash-dot line represent the Q-Q slope of a particular dataset.



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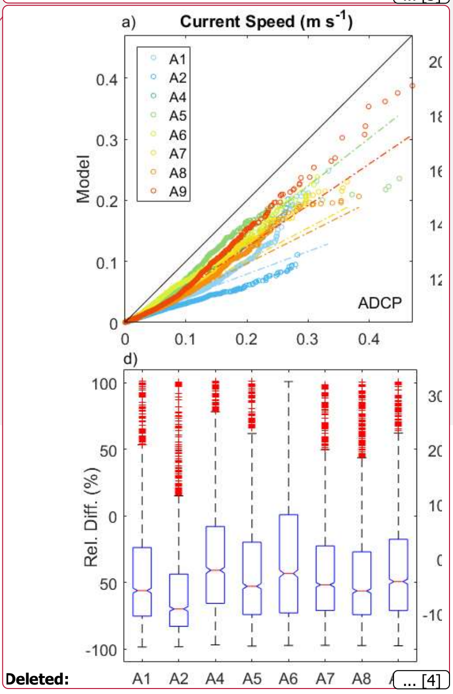

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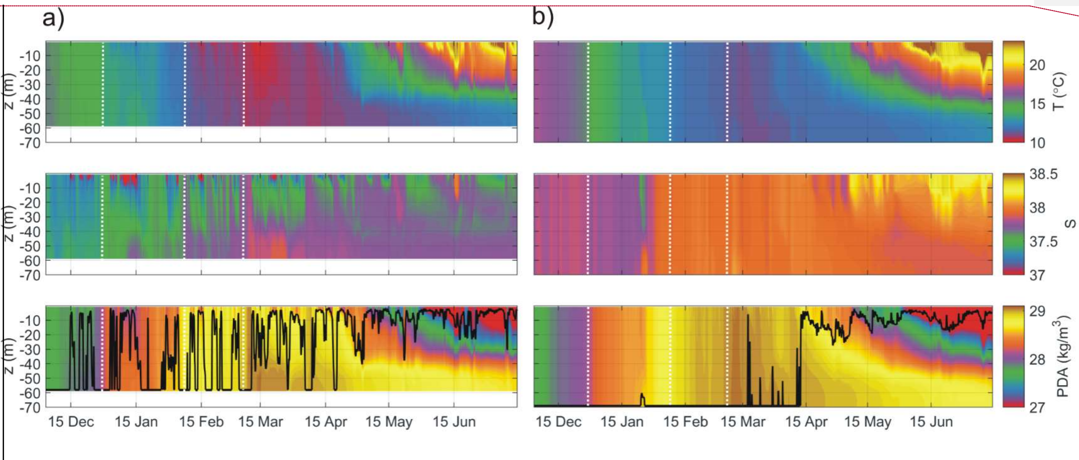

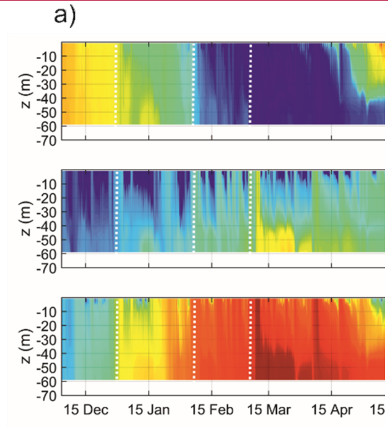

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Figure 10. Hovmöller plot of modelled temperature, salinity and PDA values at grid points (a) G1 and (b) G2. Vertical dashed lines indicate three severe bora episodes discussed in Section 3, while thick black line in PDA plot shows mixed layer depth.

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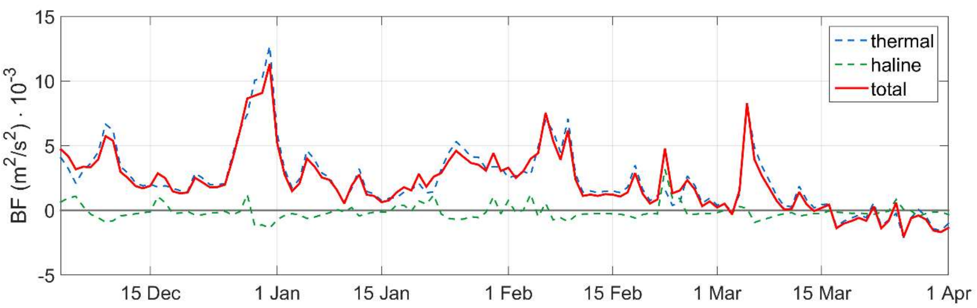

Figure 11. Daily values of surface buoyancy fluxes (BF) and its components averaged over the nested model domain.

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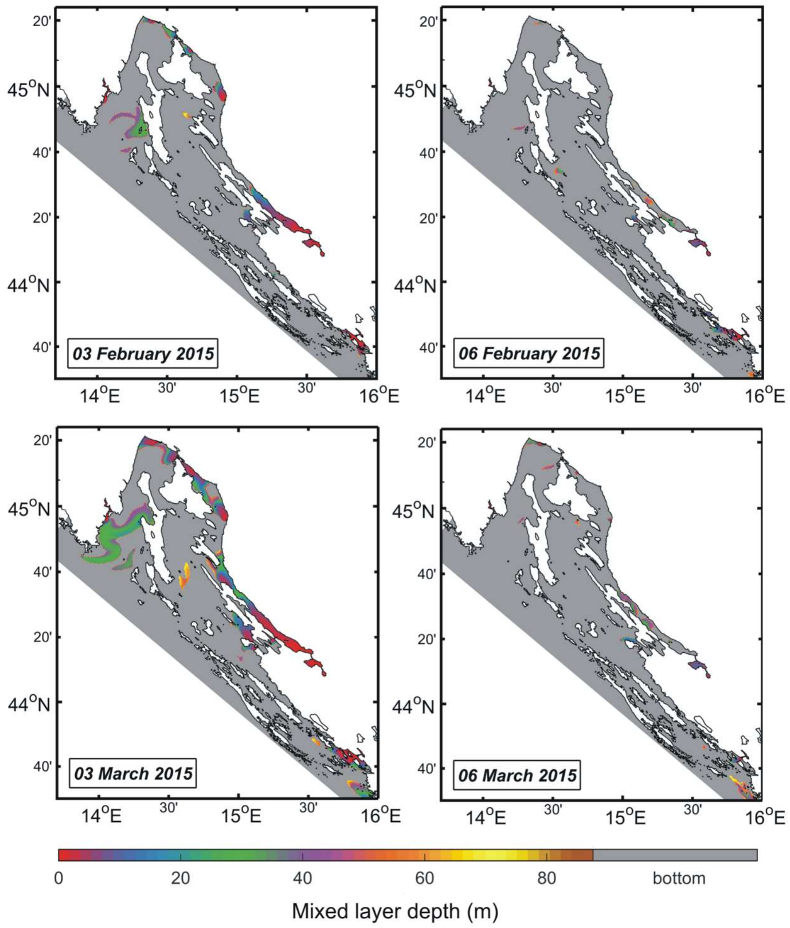

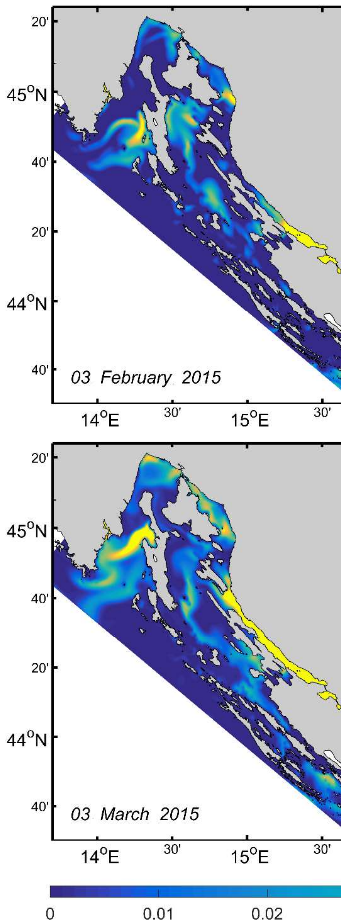

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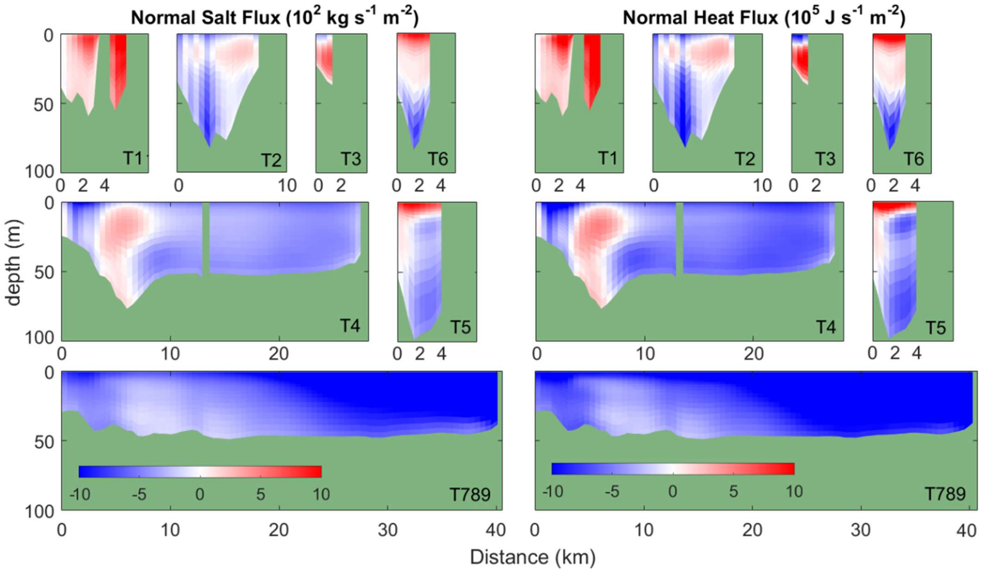
Figure 12. Mixed layer depth (MLD) computed for the nested model domain prior and after the major bora episodes: 3 and 6 February 2015, and 3 and 6 March 2015. Grey colour stand for MLD reaching the bottom.



5 **Figure 13. Modelled heat and salinity fluxes normal to transects T1 to T789 and averaged between 15 December 2014 and 15 May 2015. Positive fluxes are oriented northeastward over the T2, T3, T4 and T789 transects and northwestwards over the T1, T5 and T6 transects. Green areas denote the bathymetry.**

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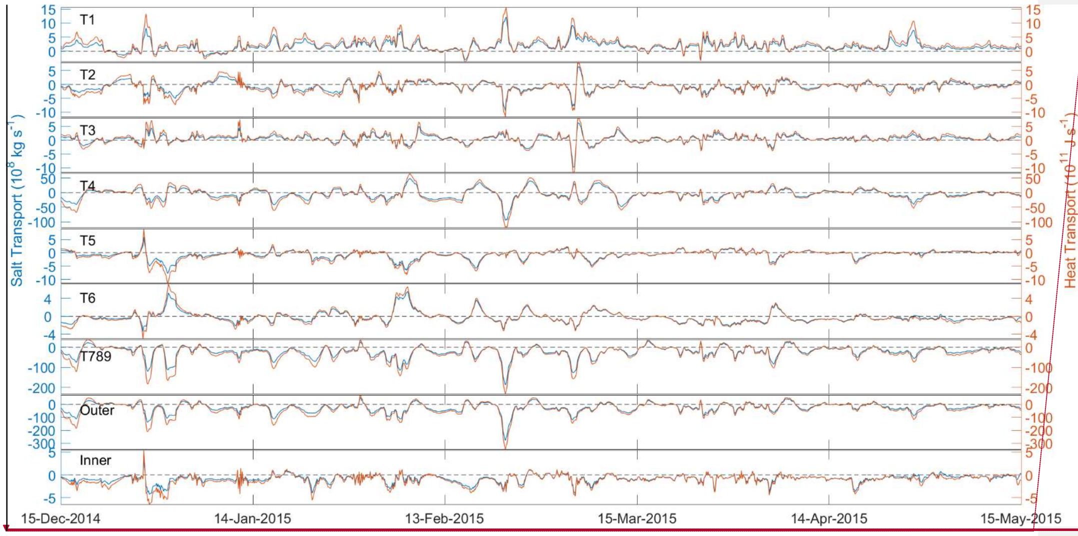

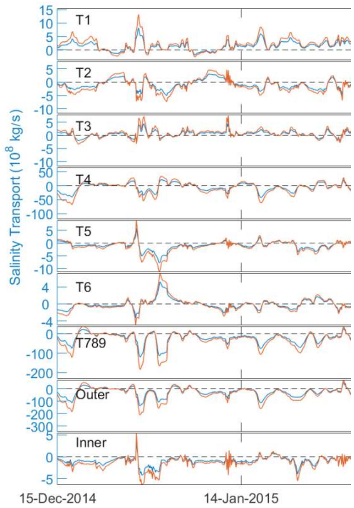

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Figure 14. Time series of heat and salt transports normal to and integrated over transects T1 to T789 between 15 December 2014 and 15 May 2015. Transports across the outer (T1+T2+T3+T4+T789) and inner (T5+T6) domains are plotted too.

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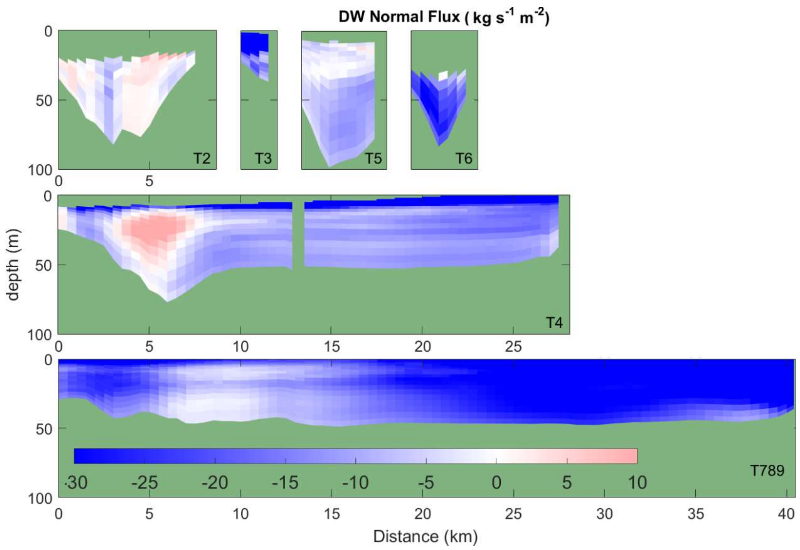

Figure 15. As in Fig. 13, but for dense water mass fluxes. Green areas denote the bathymetry and model cells where no dense water is modelled. T1 is omitted from the figure, as almost no dense water transport occurred there.

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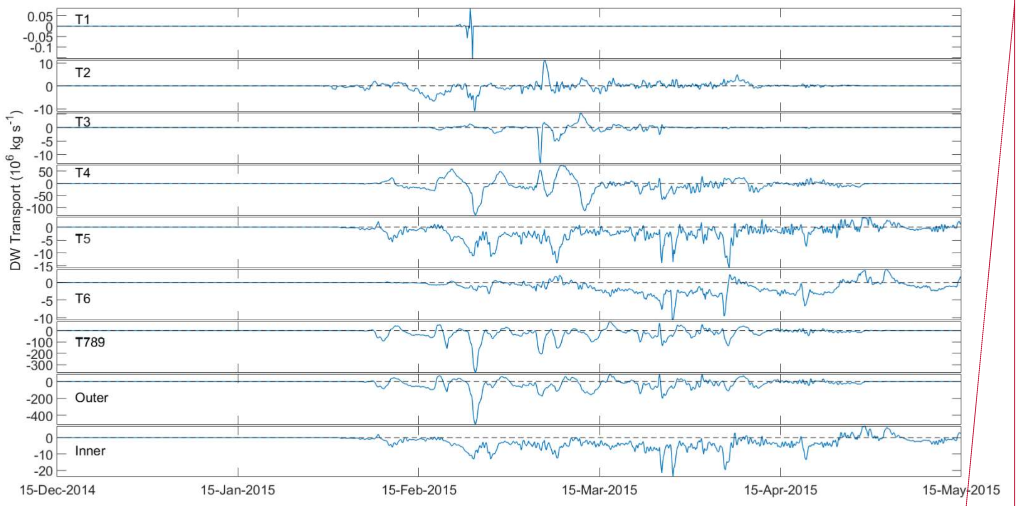

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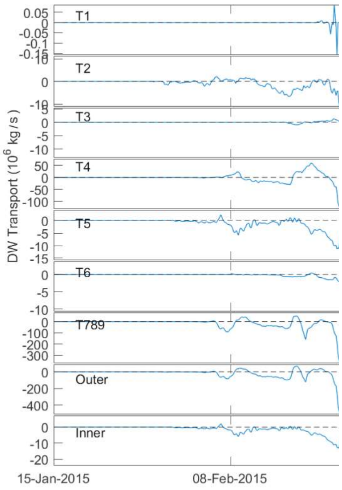

Figure 16. As in Fig. 14, but for dense water mass transports.

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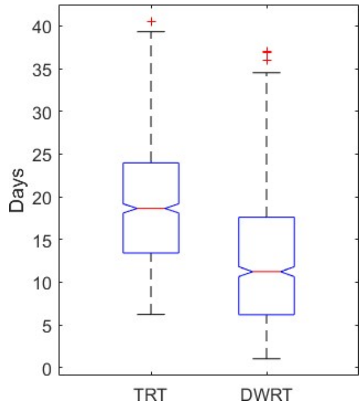

Figure 17. Box-whiskers statistics of total (RT) and dense water (DWRT) residence times for the coastal northeastern Adriatic bordered by transects T1, T2, T3, T4, and T789.

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Mass (10^6 kg s^{-1})	4.6	-1.7	1.0	-11.3	-1.7	-0.5	-58.2	-65.0	-2.1

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Table 2. Temperature, salinity mass and volume sum transports at the outer (T1+T2+T3+T4+T789) and inner (T5+T6) boundaries for peak outer transports.

	T_{outer} Salinity 10^8 kg s^{-1}	T_{outer} Temp. 10^{11} J s^{-1}	T_{outer} Mass 10^6 kg s^{-1}	T_{outer} Volume 10^3 $m^3 s^{-1}$	T_{inner} Salinity 10^8 kg s^{-1}	T_{inner} Temp. 10^{11} J s^{-1}	T_{inner} Mass 10^6 kg s^{-1}	T_{inner} Volume 10^3 m^3 s^{-1}
17/12/14 09:00:00	-113.9	-186.5	-299.5	-291.3	-1.6	-1.3	-4.4	-4.3
28/12/14 15:00:00	-137.4	-211.4	-362.3	-352.4	-3.8	-0.4	-10.1	-9.8
17/01/15 09:00:00	-112.9	-160.9	-295.6	-287.3	0.7	-1.9	1.7	1.6
06/02/15 12:00:00	-113.8	-142.1	-298.2	-289.8	0.7	4.9	1.9	1.8
22/02/15 21:00:00	-279.3	-347.2	-728.6	-707.9	-1.5	-1.5	-3.9	-3.8
05/03/15 09:00:00	-118.6	-145.0	-310.1	-301.3	-2.1	-1.1	-5.6	-5.4

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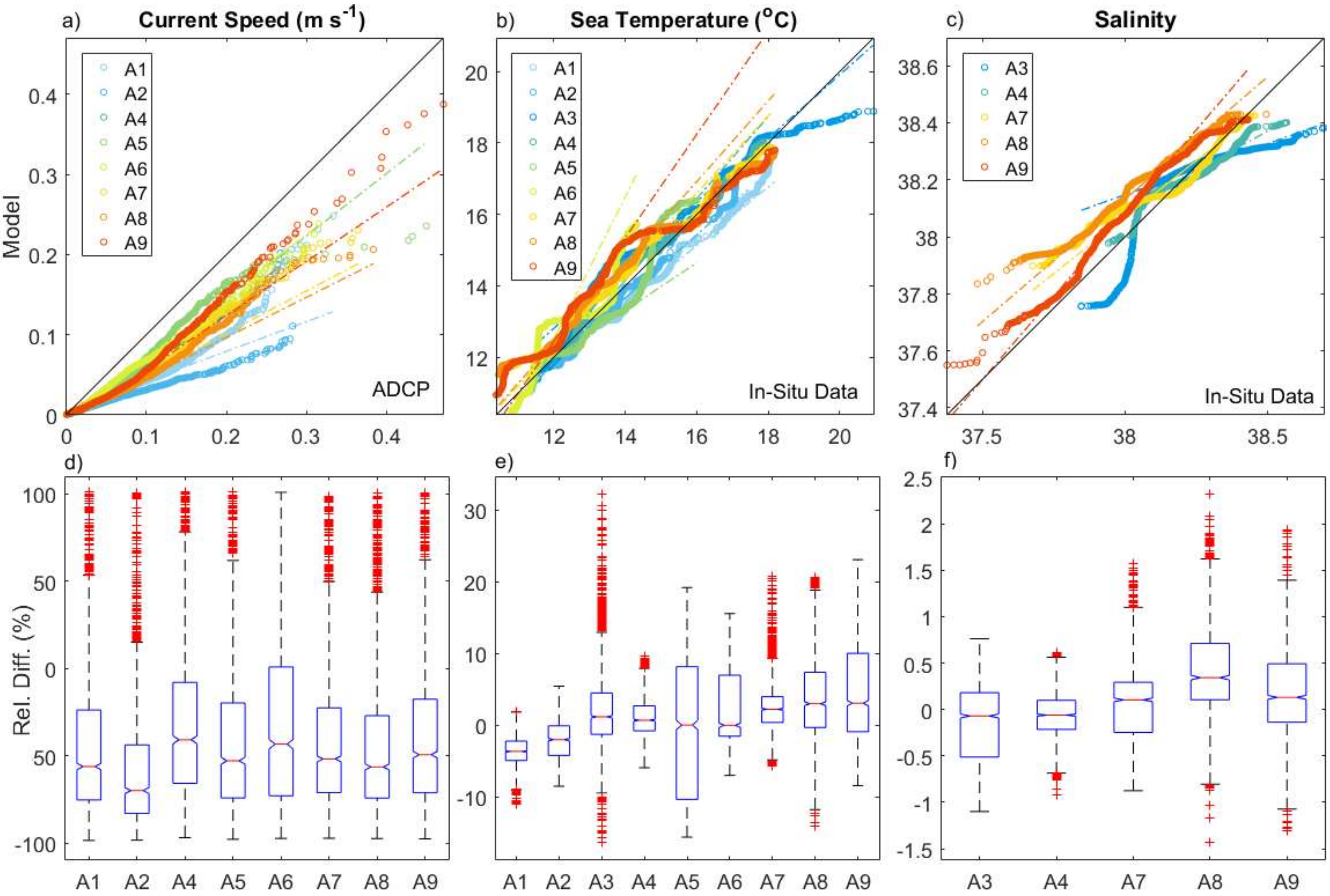

Figure 12. Model-to-observation (a, b, c) Q-Q plots and (d, e, f) Box-Whiskers plots of (a, d) current speed, and (b, e) temperature and (c, f) salinity measured at the bottom of stations A1 to A9. Dash-dot lines represent the Q-Q slope.

Corrections by American Journal Experts:

Dense water formation in the coastal northeastern Adriatic Sea: the NAdEx 2015 experiment

Ivica Vilibić[1], Hrvoje Mihanović[1], Ivica Janeković[2,3], Clea Denamiel[1], Pierre-Marie Poulain[4], Mirko Orlić[5], Natalija Dunić[1], Vlado Dadić[1], Mira Pasarić[5], Stipe Muslim[1], Riccardo Gerin[4], Frano Matić[1], Jadranka Šepić[1], Elena Mauri[4], Zoi Kokkini[4], Martina Tudor[6], Žarko Kovač[1], Tomislav Džoić[1]

[1]Institute of Oceanography and Fisheries, Split, Croatia
[2]Ruđer Bošković Institute, Zagreb, Croatia
[3]The University of Western Australia, School of Civil, Environmental and Mining Engineering & UWA Oceans Institute, Crawley WA, Australia
[4]Istituto Nazionale di Oceanografia e di Geofisica Sperimentale — OGS, Trieste, Italy
[5]University of Zagreb, Faculty of Science, Andrija Mohorovičić Geophysical Institute, Zagreb, Croatia
[6]Meteorological and Hydrological Service of Croatia, Zagreb, Croatia

Correspondence to Ivica Vilibić (vilibic@izor.hr)

Abstract. The paper investigates the wintertime dynamics of the coastal northeastern Adriatic Sea and is based on numerical modelling and in situ data collected through field campaigns executed during the winter and spring of 2015. The data were collected by a variety of instruments and platforms (ADCPs, CTDs, glider, profiling float) and are accompanied by the atmospheric-ocean ALADIN/ROMS modelling system. The research focused on the dense water formation (DWF), thermal changes, circulation, and water exchange between the coastal and open Adriatic. According to both observations and modelling results, dense waters are formed in the northeastern coastal Adriatic during cold bora outbreaks. However, the dense water formed in this coastal region has lower densities than the dense water formed in the open Adriatic due to lower salinities. Since the coastal area is deeper than the open Adriatic, the observations indicate (i) balanced inward-outward exchange at the deep connecting channels of denser waters coming from the open Adriatic DWF site and less dense waters coming from the coastal region and (ii) outward flow of less dense waters dominating in the intermediate and surface layers. The latter phenomenon was confirmed by the model — even if it significantly underestimates the currents and transports in the connecting channels — classifying the coastal northeastern Adriatic waters as a secondary site for DWF. The median residence time of the coastal area is estimated to be approximately 20 days, indicating that the coastal area may be renewed relatively quickly by the open Adriatic waters. The data that were obtained represent a comprehensive marine dataset that can be used to calibrate atmospheric and oceanic numerical models and point to several interesting phenomena to be investigated in the future.

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1 Introduction

Due to its geographical position and surrounding orography, the Adriatic Sea — a semi-enclosed 800 x 200 km basin located north of the Mediterranean (Fig. 1) — can be considered a unique testbed where a number of processes important for driving the circulation of the Eastern Mediterranean Sea occur (Malanotte-Rizzoli et al., 2014). Dense water formation (DWF) is one of these processes. In the Adriatic Sea, DWF occurs through both water column cooling and mixing on the shallow and wide northern Adriatic shelf (Vested et al., 1998) and through deep-convection in the 1200-m deep circular South Adriatic Pit (Gačić et al., 2002). The cooling at both locations is a result of strong bora wind (Grubišić, 2004; Grisogono and Belušić, 2009), which may cause widespread heat losses up to 1000 W/m^2 (Supić and Orlić, 1999) and localized heat losses up to 2000 W/m^2 (Janeković et al., 2014). Although of secondary importance, bora-driven evaporation also contributes to high densities in the northern Adriatic (Mihanović et al., 2013). Adriatic dense waters are important for (i) replenishing deep waters in the Eastern Mediterranean (Roether and Schlitzer, 1991; Bensi et al., 2013), (ii) changing or maintaining the internal vorticity of the northern Ionian (Gačić et al., 2010) and (iii) driving decadal oscillations of thermohaline and biogeochemical properties in the Adriatic (Buljan, 1953; Gačić et al., 2010; Civitarese et al., 2010; Batistić et al., 2014).

Until 2012, it was thought that DWF in the northern Adriatic occurred only over open shelf areas (Vilibić and Supić, 2005). Therein, a pool of very dense waters is created by the double-gyre circulation driven by the spatial inhomogeneity of the bora wind (Zore-Armanda and Gačić, 1987; Kuzmić et al., 2006). The dense waters that are generated are gravitationally transported towards middle Adriatic depressions though a bottom density current (Nof, 1983), mostly along the western Adriatic slope due to the Coriolis force (Artegiani and Salusti, 1987; Vilibić and Mihanović, 2013). A portion of the water travels across the southern Palagruža Sill and, when it reaches the slope and canyons of the South Adriatic Pit, it is transported down the slope to the near-bottom layers (Querin et al., 2013; Langone et al., 2016). This concept has been supported by a number of numerical modelling studies (e.g., Beg-Paklar et al., 2001; Chiggiato and Oddo, 2008). However, this classical northern Adriatic DWF picture has been substantially changed following the exceptional DWF that occurred in the winter of 2012, when the formation of dense waters was also observed in the northeastern coastal area (Fig. 1) (Mihanović et al., 2013). Subsequent modelling studies implied that up to 40% of the overall dense water that was generated in the northern Adriatic during the winter of 2012 originated from the eastern coastal areas (Janeković et al., 2014), and there was significant transport between the coastal and open Adriatic through a number of channels (Vilibić et al., 2016a). It should be emphasized that these two modelling studies were the first to use realistic freshwater discharges. Most of previous modelling studies used old river climatology (Raicich, 1994), which overestimates real river discharges in the eastern Adriatic by an order of magnitude (Janeković et al., 2014), thus preventing the numerical reproduction of the DWF in the northeastern coastal areas and significantly impacting the rates of DWF over the northern Adriatic shelf areas (Vilibić et al., 2016a).

Interestingly, atmospheric processes over the northeastern coastal Adriatic areas have been thoroughly researched. The maximum of the cold and dry bora wind and its spatial and temporal variability have been reported to occasionally reach hurricane in this area (Grubišić, 2004; Grisogono and Belušić, 2009; Kuzmić et al., 2015). As opposed to the meteorology,

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less is known about the oceanography of the area. For a long time, the coastal northeastern Adriatic has been considered an area where significant freshwater fluxes strongly affect the thermohaline properties (e.g., Orlić et al., 2000). These freshwater discharges normally come through occasional floods that accumulate over the 150-km long and 1600-m high mountain ridge of Velebit (Perica and Orešić, 1997) and a large number of submarine karstic springs (Sekulić and Vertačnik, 1996; Bonacci, 2001; Benac et al., 2003; Surić et al., 2015). Further, thanks to occasional oceanographic campaigns, the inner area of the Velebit Channel has been classified as a two-layer system, and the surface salinity exhibits much lower values (~1.0) than that in the open Adriatic (Viličić et al., 2009). Additionally, it has been identified that a strong northern Adriatic thermohaline front (Lee et al., 2005; Poulain et al., 2011) has its starting point in the northeastern coastal Adriatic, specifically in Kvarner Bay, with coastal waters advecting towards the open sea, particularly during strong bora events (Pullen et al., 2003; Lee et al., 2005; Beg Paklar et al., 2008). As it is topographically separated from the open Adriatic by a number of islands (Fig. 1), the northeastern coastal area was considered to be eligible for wintertime processes such as dense water formation before the winter of 2012, at least not at rates that may impact the overall dynamics of the northern Adriatic.

Until now, the winter of 2012 remains the only winter when dense water formation was observed and modelled in the northeastern coastal Adriatic. The question remains whether this is due to (i) the exceptionality of the 2012 winter — implying that this was an extraordinary event, or (ii) a lack of observational campaigns and poor model performance in the area — pointing to both a possibility of regular dense water formation in the area and omissions in previous research efforts. To answer this question, we envisioned and carried out the North Adriatic Dense Water Experiment 2015 (NAdEx 2015). A number of different platforms and instrumentations for data collection were utilized (Fig. 1), along with a state-of-the-art nested atmosphere-ocean modelling system, all during the winter/spring of 2015, i.e., during and after a common Adriatic DWF period. The experimental data and modelling results that were obtained allowed us to (i) estimate whether the DWF is a common process in the northeastern Adriatic; (ii) if so, quantify both DWF and the thermohaline changes leading up to it; and (iii) estimate the rate of exchange between the coastal and open Adriatic waters through several connecting passages.

Section 2 provides the details of the field experiment and data used in this paper, together with a description of the atmosphere-ocean modelling system. Section 3 documents the atmospheric conditions during the winter/spring of 2015. Section 4 describes the representative ocean observations, which is followed by a description of model verification in Section 5. Section 6 displays the thermohaline, stratification and buoyancy changes as reproduced by the model, which are followed by estimates of heat, salt, mass and volume transports at the boundaries of the region, including residence times. A thorough discussion and major conclusions are presented in Section 7.

2 Data and methods

2.1 The study area

The northeastern Adriatic is a coastal region consisting of many elongated channels and bays (Fig. 1). It interacts with the open Adriatic through several narrow (from one kilometre to few kilometres) channels. The only exception is a wide

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opening that connects Kvarner Bay to the open Adriatic. Thus, Kvarner Bay may be considered as a crossing region between coastal and open Adriatic waters. The inner coastal region is deeper (80–100 m) than the open Adriatic (50–70 m). Only a few small river mouths are located in the area, and there is freshwater input from the hydropower plant near Senj. These input combined result in average freshwater input rates of approximately 80 m^3/s (Vilibić et al., 2016a). However, there are also many of submarine springs that are quite active during and after prolonged precipitation events, which may double the freshwater load to the coastal area (Sekulić and Vertačnik, 1996). Furthermore, the climate of the region, particularly of Rijeka Bay, is characterized by significant precipitation driven by orography (Gajić-Čapka et al., 2015).

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2.2. The field experiment

The NAdEx 2015 was carried out between late autumn 2014 and summer 2015. The primary goal of the experiment was to study the DWF in the coastal northeastern Adriatic, which commonly occurs between January and March (Janeković et al., 2014). The temperature, salinity and current data were collected by several instruments and observing platforms deployed in the area (Fig. 1). The entire experiment was accomplished through the contributions and collaborative work of several research institutions: Institute of Oceanography and Fisheries, Ruđer Bošković Institute, Geophysical Department of the Faculty of Science of the University of Zagreb, Meteorological and Hydrological Service, all from Croatia, and National Institute of Oceanography and Experimental Geophysics, Italy. Thus, this study represents a unique effort in the Adriatic that may serve as a good example for future research activities in the region.

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Currents over the water column were measured at stations A1 to A9 using RDI Acoustic Doppler Current Profilers (ADCPs) between late November 2014 and early August 2015 (A7, A8, A9)/early July (A4). Currents were measured using Nortek ADCPs between early December 2014 and mid-August 2015 (A1, A5, A6)/late May (A2). The ADCP at station A3 malfunctioned after only one week of operation and did not measure any data after that. A Seabird 911 CTD probe accompanied the ADCPs at stations A3, A4, A7, A8 and A9 and provided the bottom temperature and salinity series between late November 2014 and early August 2015. Vertical profiles of temperature and salinity data were acquired by a Seabird SBE 25 probe at 19 CTD stations during two cruise legs. Leg 1 of the cruise was carried out between 3 and 6 December 2014, and leg 2 was carried out between 26 and 29 May 2015. A Teledyne-Webb Research Slocum glider was operated along the transect off Kvarner Bay in a campaign lasting from 24 to 26 February 2015, while an Arvor-C profiling float was deployed on 19 February in the northern part of Kvarner Bay and was recovered on 15 March 2015 on the Istria coast near the entrance of the bay. The Arvor-C profiling float regularly profiled the entire water column every 3 hours (Gerin et al., 2015). The potential density anomaly (PDA, reference pressure equalling zero) was computed from the temperature and practical salinity data following TEOS-10 algorithms (described at http://www.teos-10.org). The complete setting of the experiment is illustrated in Fig. 1.

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2.3. The modelling system and its setup

The atmospheric-ocean modelling system covering the entire Adriatic Sea was used as the NAdEx 2015 parent numerical model. The atmospheric part of the system is based on a hydrostatic version of the ALADIN numerical weather prediction (NWP) model used by the Meteorological and Hydrological Service of the Republic of Croatia (Tudor et al., 2013, 2015). The model is operationally integrated four times per day, has 37 vertical sigma levels and 8 km horizontal resolution except for winds, which are dynamically downscaled to 2 km (Ivatek-Šahdan and Tudor, 2004). All variables were provided with a time step of 3 h. Although the bora wind may have substantial variability on periods from several minutes to a few hours, the previous modelling studies that used 3-h ALADIN/HR forcing provided reliable results (e.g., Janeković et al., 2014). The model is initialized with a 3D-Var run at 8 km resolution using the data available through the Global Telecommunication System (GTS) and local data exchange (Stanešić, 2011). The model uses SST fields from the IFS (Integrated Forecast System) operational forecast run in the ECMWF (European Centre for Medium Range Forecast). These SSTs have a positive bias towards in situ measurements during the winter, which are much lower in the open Adriatic when compared to the SST satellite observations. This bias affects the precipitation maxima (Ivatek-Šahdan et al., 2017) but does not significantly affect the wind speed, which is controlled by the surrounding topography (Tudor et al., 2017). Wind gusts were computed following the formulas in Brožkova et al. (2006), which have been tuned for oceanographic simulations in the Mediterranean. The ALADIN/HR simulations have been verified in the coastal northeastern Adriatic during severe bora events (Tudor and Ivatek-Šahdan, 2010; Tudor et al., 2013).

For the ocean part of the model, the Regional Ocean Modelling System (ROMS) was used. ROMS is a 3-D hydrostatic, nonlinear, free surface, s-coordinate, time splitting finite difference primitive equation model (Shchepetkin and McWilliams, 2005, 2009). The horizontal resolution of the Adriatic model is 2 km, and there are 20 sigma layers in the vertical, following the studies by Janeković et al. (2014) and Benetazzo et al. (2014), which satisfactorily reproduced the DWF in the northern Adriatic. The open boundary conditions at the Otranto Strait (free surface, temperature, salinity, and velocity) are taken from the Adriatic Regional model (AREG, Oddo et al., 2006), with a sponge layer at the boundary. The Flather scheme was used for the barotropic velocities, and a combination of Orlanski-type radiation boundary conditions with nudging (Marchesiello et al., 2001) was used for the baroclinic velocities and tracers (temperature and salinity). The long-term stability of the model run has been ensured by smoothing the bathymetry using a linear programming technique (Dutour Sikirić et al., 2009) that suppresses the horizontal pressure gradient errors that occur over complex bathymetries with steep slopes, such as in the Adriatic Sea, and during multiyear integrations (Haidvogel et al., 2000). The ALADIN/HR surface variables were introduced to the ROMS via bulk parameterisation (Fairall et al., 1996). The most recent river discharge climatology was imposed at the freshwater point sources following Vilibić et al. (2016a) data, without changing the ambient temperature. More details on the modelling system can be found in Janeković et al. (2014) and Vilibić et al. (2016a).

In addition to the Adriatic model, a nested ocean model (also ROMS) was imposed on the NAdEx 2015 region to properly reproduce its complex bathymetry (Fig. 1). The nested domain was tilted by 45° to follow the orientation of the area.

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The nesting was done using a 1:4 ratio in the horizontal — thus the nested model had a horizontal resolution of 500 m — and 20 sigma levels were maintained in the vertical. The nested ocean model was forced with the same ALADIN/HR operational fields as the parent model. Free-slip conditions were imposed at the boundaries.

The parent modelling system has been operationally integrated since 1 January 2008, while the nested simulation was run between 1 October 2014 and 30 September 2015, covering the experimental NAdEx 2015 period. Verification of the parent model was performed for the winter of 2012 (Janeković et al., 2014; Vilibić et al., 2016a). Basin-wide negative salinity bias has been found to exist and was presumed to come from the lateral boundaries of the AREG model (Janeković et al., 2014). In the AREG model, these boundaries exhibit basin-wide overfreshening coming from the old river climatology by Raicich (1994), thus also influencing our parent simulations. However, the model was found to be appropriate for the reproduction of thermohaline properties in the area (Vilibić et al., 2016) and quantification of the DWF in both the open northern and coastal northeastern Adriatic (DWF sites 1 and 2 in Fig. 1).

3 Atmospheric conditions and air-sea interactions

The winter of 2015 (December through March) was characterized by warmer-than-average temperature conditions over the NAdEx area compared to the baseline climatological period of 1961–1990 (MHS, 2015, 2016). According to these reports, the highest positive anomalies (91–98 percentile) were recorded in December and January, followed by average temperatures in February and warm conditions (75–91 percentile) in March. The DJFM precipitation values (measured only above land) were close to the climatological values, with the highest positive anomalies measured in February. Regarding the average January–February net heat fluxes over the NAdEx area (as delimited by the nested domain boundaries in Fig. 1) — these two months are chosen as the DWF dominant occurs at that time (Beg Paklar et al., 2001; Vilibić and Supić, 2005) — the winter of 2015 may be classified as normal with respect to the other winters between 2008 and 2015. Precisely, the cumulative January–February net heat losses equalled 0.80 MJ/m^2, which is slightly higher than the average for the 2008–2015 period (0.76 MJ/m^2), approximately 50% less than in the winter of 2012 (1.20 MJ/m^2) and almost two times greater than that in the winter of 2014 (0.49 MJ/m^2).

Several cooling events occurred during the winter of 2015, of which three bora episodes — preceding the New Year, in early February and in early March — were particularly severe. The first severe bora episode lasted for several days (between 28 December 2014 and 1 January 2015), with gusts stronger than 50 m/s in the Velebit Channel and air temperatures falling below 0°C. The bora event between 4 and 7 February 2015 was particularly strong over the NAdEx area, peaking during the night of 5/6 February with measured wind gusts of approximately 60 m/s in the northern Velebit Channel. One month later, another strong bora event occurred along the eastern Adriatic coast. However, the latter event was particularly pronounced over the middle Adriatic and southern part of the Velebit Channel, where the wind gusts peaked on 5 March with values of approximately 55 m/s.

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To better understand the impact of bora wind on the northeastern coastal Adriatic, we compared wind stress, net heat flux and water flux variables (all originating from the ALADIN model) averaged over all bora events with those averaged between 15 December 2014 and 15 March 2015 (Fig. 2). Herein, a bora event is defined as a period during which the wind blows from the ENE and exceeds 15 m/s at the ALADIN grid point off Senj (location G1 in Fig. 1). ENE represents the predominant direction of bora in that area (Zaninović et al., 2008). The maximum wind stress is modelled within the Senj Jet (marked by an arrow in Fig. 2), and the area of wind stress stretches from Kvarner Bay towards the western shore, which is the exact location where the major wind jet and frontal ocean zones are commonly found (Pullen et al., 2007; Beg Paklar et al., 2008; Kuzmić et al., 2015). The largest bora-driven heat loss was documented in the Velebit Channel and within the offshore jets, again reaching maximum in the Senj Jet. Heat losses strongly decrease towards the western Adriatic coastline. Such bora-driven heat loss distribution largely follows the distribution associated with the extreme bora wind outbreak of the winter of 2012 (see Fig. 4 in Janeković et al., 2014). The pattern of bora heat losses also resembles the average net heat losses between 15 December 2014 and 15 March 2015, indicating that cooling of the northern Adriatic waters dominantly occurs during bora episodes.

As it is strongly dependent on wind speed and humidity, the evaporation patterns (not shown) driven by bora wind follow the net heat loss patterns, with maximum rates exceeding 10 mm/day off Senj. However, an interesting pattern is found in the water flux (E-P) associated with the bora episodes, with the highest negative values in the open Adriatic and particularly along the western coastline. Negative values may also be found in the NAdEx 2015 area. This implies that the bora wind — as defined using a single station at the core of the strongest jet — is associated with precipitation that appears at the back side of a cyclone, decreasing its rates towards the northwest, where maximum water uptake has been modelled.

We can conclude this section on atmospheric conditions by saying that, despite three strong bora events, no exceptional cooling events were observed during the winter of 2015. This gives us an opportunity to study whether dense water is generated in the northeastern coastal area during average winter conditions.

4 Ocean observations

The temperature and salinity data measured between 3 and 6 December 2014 (leg 1 of the cruise) along the transect stretching over the NAdEx 2015 area (stations 1 to 19) exhibit a predominant two-layer thermohaline structure (Fig. 3a), with warmer (>16°C) and less saline (<37.0) waters in the surface and intermediate layers to depths of approximately 50–60 m. These depths were characterized by a sharp thermocline, under which a pool of colder (13–14°C) and more saline (~38.0) waters resided. The pool had a substantially higher density (potential density anomaly, PDA>28.5 kg/m^3) than the waters residing above (<27.8 kg/m^3). The thermocline and halocline followed each other in the first third of the transect (up to station 6), after which the halocline formed at shallower depths. The salinity maximum that stretched over the entire water column at stations 11 to 13 indicates an inflow of saline open Adriatic waters through connecting channels where the A3 and A4 ADCPs were moored.

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Six months later, during leg 2 of the cruise, which was executed between 26 and 29 May 2015, the two-layer structure was still evident from the temperature data (Fig. 3b), but this time it was driven by seasonal heating during the spring (Buljan and Zore-Armanda, 1976). The thermocline was positioned at depths between 20 and 30 m. However, the salinity was homogenized over the entire transect, with substantially higher values (37.8–38.0) than observed during leg 1 of the cruise, peaking again at stations 11 to 13. The salinity changes between legs 1 and 2 of the cruise indicate an advection of high salinity waters from the open Adriatic towards the entire NAdEx 2015 area, which may be a result of the DWF-driven thermohaline circulation, as found throughout the Adriatic Sea (Orlić et al., 2006) and in the Gulf of Trieste (Mihanović et al., 2013). The PDA distribution followed the temperature distribution, with much higher values present in deep layers (29.0–29.1 kg/m^3) than during leg 1 of the cruise. The latter indicates that, despite the lack of extreme cooling events, DWF did occur during the winter, although the observed temperatures were much higher and the salinities were lower than during the extreme winter of 2012 (Mihanović et al., 2013).

The thermohaline properties measured at the bottom of connecting channels, over which the transport between the coastal and open Adriatic area is happening, reveal the rate of the wintertime cooling that occurred in the northern Adriatic (Fig. 4). A constant decrease in temperature (Fig. 4a) from the beginning of the experiment (early December) to the end of March was recorded at all stations, having a weak step-like structure presumably associated with strong bora events. At station A4, the bottom temperatures were higher and did not decrease below 12°C. The lowest temperature was observed in the northwestern part of the entrance to Kvarner Bay, at station A9, where a minimum of approximately 10.5°C was reached in early February and remained through March. By contrast, these temperatures were observed at the neighbouring stations A8 and A7 one month later, indicating a presence of a complex circulation and a deep thermohaline front within the bay. In support of the existence of the front, the differences between the temperature and salinity series measured at A7, A8 and A9 between 1 February and 31 March 2015 (in terms of their averages and variability) are significant at the 99% level. The existence of the wintertime thermohaline front through the water column can be clearly seen from the late glider measurements performed off Kvarner Bay on 26 February (Fig. 5), when strong bora conditions were present in the area. However, the front weakened the day after, when the glider returned over approximately the same track. Kokkini et al. (2017) ascribed the variability of the front to wind forcing, where strong bora wind favours a sharp front. This front has also been observed and investigated during previous wintertime campaigns (Lee et al., 2005; Poulain et al., 2011).

The Mean bottom salinity (Fig. 4b) values decreased northwestward, from station A4 to station A7, and again across the entrance to Kvarner Bay to station A9. In addition, strong salinity variability at the daily and weekly scales was embedded into the series, varying between 37.5 and 38.5 at stations A7 to A9. Such a pronounced variability indicates the presence of a thermohaline front that changes position over time. The variability was particularly strong during the winter (January–March 2015), decreasing during the spring. Although there were monthly variations, an overall increase in salinity was recorded at all stations between mid-December 2014 and early February 2015. The southeast-northwest differences in temperature and salinity along the outer NAdEx 2015 area are reflected in the PDA values (Fig. 4c), which increased from mid-December (~28.0 kg/m^3) to mid and late February (~29.2 kg/m^3). The maximum PDA values were sustained until late March, which is

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presumably associated with the near-bottom outflow or inflow of dense waters. The PDA values slowly decreased during the spring.

Pronounced spatial and temporal changes in the thermohaline properties of Kvarner Bay may be quantified by analysing the profiling float data (Fig. 6). The Arvor-C float temperature and salinity profiles obtained from the inner part of Kvarner Bay show a weak stratification over the water column, except at the very bottom, where a thin layer of a few metres with substantially higher temperatures (~0.8°C) and salinities (~0.5) was detected. This thin, near-bottom layer was not present over western central Kvarner Bay where the float was transported between 22 and 25 February (for the position of the float, see Fig. 1). The layer was, however, present at the outer western part of the bay where the float drifted between 3 and 5 March. The PDA values of this bottom layer reached 29.4 kg/m^3, which were greater than the PDA measured at the A stations or by the CTDs by approximately 0.3 kg/m^3. A similar high density layer of a few metres that was found in mid-February 2012 on the western Adriatic shelf was associated with the initial near-bottom outflow of dense waters from the northern Adriatic (Vilibić and Mihanović, 2013). Analogously, our hypothesis is that a small fraction of dense waters generated on the northern Adriatic shelf, these waters had higher densities than the waters of Kvarner Bay (Janeković et al., 2014) and spread towards deeper Kvarner Bay as a weak bottom density current.

The assessment of the wintertime ADCP data (Fig. 7) revealed a substantial baroclinic component atop the barotropic circulation at all stations during and after two strong bora episodes (1 February – 1 April 2015) when the DWF and dense water flow were expected to occur. Weaker currents at station A9 and strong outflow in the surface layers at stations A7 and A8 indicate the presence of an anticyclonic curl at the entrance of Kvarner Bay. The pattern in currents also resembles the patterns of the local wind stress and wind curl, which are pronounced off the southern tip of Istria (Pullen et al., 2003; Grubišić, 2004). Inflow to Kvarner Bay may be seen in the bottom layer of station A9; part of this inflow might be ascribed to dense waters coming from the northern Adriatic shelf, thus confirming our hypothesis of the origin of the bottom density current seen in the Arvor-C data. Near the bottom of stations A7 and A8, the mean flow is weak, yet changeable over time, suggesting an interplay between dense waters coming from the coastal area with those coming from the northern Adriatic shelf in the Kvarner Bay area. At the same time, much stronger currents were observed in the surface and intermediate layers, indicating the predominant outflow of waters from the NAdEx area towards the open Adriatic. Going to the southeast, at station A4, the measured currents were parallel to the coastline. However, as it was deployed too far from the connecting channel, this station was indeed not measuring the interchange between the coastal and open Adriatic waters but the Eastern Adriatic Current, which may be strong in that region (Orlić et al., 2006). The currents measured at station A2 exhibit a strong baroclinic pattern, pointing to an exchange of waters between the open and coastal Adriatic through a narrow channel: an outflow current is present in the surface layer, and an inflow current is present near the bottom. However, these currents are strongly affected by local bathymetry, probably resembling the effects of both a very narrow connecting channel (approximately 600 m in width) and the Eastern Adriatic Current modulated by the cape of Veli Rat (approximately 2 km south of station A2). Finally, the current data measured at station A1 document the predominant inflow of the open Adriatic waters, mostly in the surface layer. The inflow is likely driven by the orientation of the channel and the incoming Eastern Adriatic Current. Interestingly, the

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wintertime baroclinic circulation, with a predominant outflow from the Velebit Channel in the surface layer and inflow in the bottom layer, is also maintained in the inner channels (stations A5 and A6). This particularly refers to the currents measured at station A6 located near the Senj bora jet, implying that the currents at this station are likely principally wind-driven.

5 Model validation

The modelling system was validated against available observations. The verification of the CTD data collected over leg 1 of the cruise (Fig. 3c) reveals an underestimation of the temperature in the surface layer and an overestimation of the temperature in deep layers, where a pool of cold and dense waters was observed (Fig. 3a). Oppositely, the salinity was overestimated in the surface layers and underestimated in the near-bottom layers. An underestimation in salinity in the shallowest southeastern part of the transect (around station 18) is presumably due to submarine springs that discharge freshwater from the neighbouring freshwater lake to the sea and are not introduced to the model. Altogether, the model did not properly reproduce the observed two-layer structure, but rather reproduced a much more homogenized water column, without a dense water pool in the deepest parts of the NAdEx area. The thermohaline properties that were modelled during leg 2 of the cruise (Fig. 3d) show better agreement with the observations, particularly salinity, where the bias is approximately 3 times lower than that for leg 1 of the cruise. This result is particularly applicable to the surface layer (Fig. 8). The temperature bias was also smaller during leg 2 of the cruise. However, a drawback was present in the reproduction of the thermocline, as the largest root-mean-square error is present at the exact depths of the thermocline (15–35 m). Nevertheless, the model successfully recreated the presence of a cold and saline bottom layer, as well as a two-layer structure observed during leg 2 of the cruise, and both the bias and root-mean-square-error remained low near the bottom. The bottom PDA values that were modelled on the dates corresponding to leg 2 of the cruise were higher (approximately 29.0 kg/m^3) than those on the dates corresponding to leg 1 of the cruise (approximately 27.8 kg/m^3), indicating that model was able to reproduce the DWF in the NAdEx area.

The results of the model verification performed on the float and glider data are shown in Figs. 5b and 6b. The float data were verified by the nested model simulation, while the parent model simulation was used to verify the glider measurements. An inspection of the results indicates that the model is able to reproduce the thermohaline properties observed inside Kvarner Bay. There are, however, several omissions there: (i) both temperature and salinity show an increase in negative bias from the inner to the outer parts of the bay, and (ii) the model is not able to reproduce the narrow bottom density current. The latter omission is because the model does not have sufficient vertical resolution to reproduce such a thin bottom layer. Overestimation of both the temperature and salinity of the open Adriatic waters (positive bias) is visible on the model-to-observation differences along the glider pathway, where the parent model produces warmer and saltier water northwest from the measured thermohaline front. By contrast, the temperature and salinity biases were much lower in absolute values southwest of the front. These results imply two conclusions: (i) the position of the thermohaline front was not properly modelled, and (ii) the strength of the front in the model is much weaker than that captured by the glider observations.

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The model-to-observation Q-Q plots of temperature and salinity that were constructed by comparing float, glider and CTD data (Fig. 9a, b) indicate that the temperature data were adequately reproduced over the inner NAdEx area (float and CTD), but not in the open Adriatic, i.e., in the area off Kvarner Bay (glider). The model overestimated salinity values less than 37.6 compared to the CTD measurements, while higher salinities were successfully reproduced. The salinities measured by the Arvor-C profiler and glider were generally overestimated by the model over most of the percentile distribution, except for salinities of approximately 37.6 and the upper tail of the distribution (>38.1). This particularly holds for salinities measured by the glider, i.e., for the salinities modelled by a lower resolution parent model. In summary, the model reproduced the salinity in the interior of the basin best, and the reproductions were slightly worse in Kvarner Bay and much worse outside the bay.

The comparison of the bottom temperature and salinity and the bottom current speed data as measured at stations A1 to A9 (Fig. 9c, d, e) indicates that the temperature and salinity were adequately reproduced by the model at all stations, differing by less than 1°C and 0.3, respectively, except for a few observations. That also refers to the reproduction of thermohaline properties and changes in time (not shown), which exhibit low biases — particularly for temperature — at all stations over the entire measurement interval (not shown). The temperature trends matched the observations well; they were negative between December and February, then reached minimum temperatures in late February and March due to dense water outflow, and finally showed a weak positive trend due to mixing and advection of open Adriatic waters. A significant decrease in the temperature and salinity properties in outer Kvarner Bay (stations A7 to A9) was also reproduced by the model. The biases are slightly larger at stations A7, A8 and A9, particularly in temperature (0.3–0.6°C), as the model do not reproduce the thin near-bottom inflow of warmer and saltier waters in the outer part of Kvarner Bay as observed on the float data (Fig. 6a). However, these biases and the overall temperature, salinity and current biases at most of the A stations are smaller than the root-mean-square values (not shown). However, the current speeds were strongly underestimated by the model at all stations, between 50% and 80% on average. There may be several reasons for those underestimations: (i) the horizontal resolution of the ocean model was too coarse, (ii) the resolution of the atmospheric model was insufficient and the bora-driven mesoscale variability was inappropriately reproduced, and (iii) the boundary conditions were inappropriate. The reasons for this underestimation will be discussed in more detail in Section 7.

Aside from the underestimation, the comparison of the mean currents and the associated standard deviation ellipses (Fig. 7) exhibit a number of differences between the modelled and observed currents, and these differences are largely the result of the complex bathymetry. The model-to-observation current speed differences averaged over the vertical and the entire period range from -4 cm/s at stations A5, A6, A8 and A9 to -6 cm/s at station A1, while the directional biases range from approximately -5° at A2 to approximately -15° at A4, A6 and A8 and reach approximately -25° at A1, A5 and A7, and 27° at A9. The vertical structures of the currents, i.e., the rate of change of the current speed over the vertical, was adequately reproduced at all stations except A2. The latter is a consequence of the complex bathymetry in the region, which is underrepresented by the model. The connecting channel off which station A2 was positioned towards the open sea is very narrow and is approximately 600 m in its deep section. Additionally, the station is located slightly off the channel, and a strong interaction between the Eastern Adriatic Current and the channel current presumably exists. At all other stations, the model

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reproduced either a surface maximum in the currents and a decrease towards the bottom (A1, A4, A7, A8, A9) or the maximum currents in the bottom layer (A5) or two-layer circulation (A6). The current direction is adequately reproduced at A1, A4, A5, A6 and A8, but the reproduction is much worse at A7 and A9 (plus A2).

In conclusion, the model reproduces the thermohaline properties and DWF in the coastal northeastern Adriatic (inner domain) fairly well and may thus be used to quantify the related processes and dynamics in the area. It should, however, be considered that a restricted (weaker than observed) water mass communication was reproduced between the coastal and open Adriatic through connecting passages.

6 Model results

6.1 Thermohaline, buoyancy and stratification changes

The modelled temporal changes of the thermohaline properties at location G1, which is positioned in the Velebit Channel at the core of the Senj bora jet, and at location G2, which is positioned in outer Kvarnerić Channel, are displayed in Fig. 10. The mixed layer depth (MLD), which was computed using the methodology from de Boyer Montégut et al. (2004) with the density increment threshold set to 0.125 kg/m^3, continuously reaches the bottom at G2 until early April, indicating that the water column was vertically homogenized over most of the basin from December until early April. Later, a surface thermocline developed, deepening to approximately 30–40 m in early July. The salinity series at the G1 location exhibited pronounced daily and weekly changes in the upper layer, as it was influenced by the nearby freshwater discharge from the Senj hydropower plant. However, the vertical homogeneity and MLD reaching the bottom were present in this area during the cooling events on approximately 30 December 2014, 5 February and 5 March 2015 — this is due to the position of this station on the track of the Senj bora jet. Between bora events, the ocean began to relax through horizontal advection and slightly increasing stratification due to radiative forcing.

Most of the coastal area was vertically homogeneous prior to the early February and early March bora events (Fig. 11), and MLD reached the bottom in most of the region. The only exceptions were the coastal waters near river mouths, such as the eastern Velebit Channel and off the Senj power plant (where station G1 is positioned), and the areas characterized by strong thermohaline fronts, such as Kvarner Bay. However, both boras were substantially strong and evenly mixed these regions to the bottom, allowing for DWF to occur throughout the coastal region.

A simple box model (e.g., Gill, 1982) of energy balance was applied to these locations, relating the decrease of the ocean temperature ΔT in a box to surface heat losses:

$$\Delta T = \frac{1}{Hc\rho_0}\int_{t_1}^{t_2} Q\,dt$$

where Q is the surface heat flux in the time interval between t_1 and t_2 and H is the ocean depth. The specific heat of seawater, c, and seawater density, ρ_0, were approximated by constant values of 3990 J/kg K and 1027.5 kg/m^3, respectively. This model

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Formatted: Not Superscript/ Subscript assumes no lateral exchange of energy between the box and the adjacent sea, which is a fair approximation for short and transient events, such as the bora. At station G1, this simplified formula gives ΔT = -0.96°C, -0.48°C and -0.03°C for the three bora events (the third bora was very weak at G1), respectively, while the respective cooling rates provided by the model are -1.04°C, -0.51°C and -0.07°C. Given the assumptions of this simple box model, one can conclude that the cooling in the area is dominantly driven by the bora wind.

The density persistently increased at both locations until mid-March, when the maximum PDA values were modelled at both the G1 and G2 locations. This maximum is a result of the severe bora wind episode that peaked in some parts of the area on 5/6 March (see Section 3). As a consequence, the thermohaline circulation strengthened, and the open-Adriatic saline waters were advected to the coastal area, particularly to the outer parts (G2 location). An increase in salinity occurred in the coastal area and intensified in May, which was presumably driven by the lagging thermohaline circulation of the Adriatic-Ionian basin (Orlić et al., 2006).

Buoyancy changes, which were estimated following Marshall and Schott (1999) over the nested model domain, document buoyancy loss that dominantly occurred during bora outbreaks (Fig. 12). The most pronounced buoyancy loss occurred on approximately 30 December 2014 and was largest in the inner areas of the Velebit Channel, slightly lower along the bora jets (Senj Jet, Pašman Jet, Janeković et al., 2014), and lowest in the wake of the bora wind (e.g., G2 location). Buoyancy loss was predominantly driven by heat loss, while the haline-driven buoyancy changes were of minor importance. Buoyancy losses during the bora events decreased the stratification of the area, which can be clearly seen through an increase in the MLD and in the areas where the MLD reached the bottom (Fig. 11). This particularly applies to the inner Velebit Channel, where maximum buoyancy losses with rates high enough to homogenize the entire water column were modelled. We can conclude by saying that the model successfully reproduced the DWF during severe bora outbreaks. Knowing this, we can study dense water dynamics in the area and the interchange between inner coastal and open Adriatic waters in more detail.

6.2 Lateral boundary fluxes, residence and flushing times

The heat and salinity fluxes normal to transects T1 to T789 (notation follows the numeration of stations A1 to A9) and averaged between 15 December 2014 and 15 May 2015 are shown in Fig. 13. Positive fluxes are considered if directed towards the northeast at T2, T3, T4 and T789, and towards the northwest at T1, T5 and T6. The heat fluxes indicate that the coastal northeastern Adriatic gained energy mostly over transects T1 and T3. This particularly applies to the surface layers of T1 and the bottom layers of T3, while the near-surface heat fluxes were in the opposite direction at the T3 transect. The fluxes at the T2 transect also show an inward-outward structure, with the strongest outward values modelled near the bottom. The fluxes were predominantly weakly negative along the T4 transect and strongly negative along the T789 transect, indicating that the coastal area was losing energy and salt through the northern connecting passages, particularly through Kvarner Bay. The predominance of negative fluxes, occurring mostly through Kvarner Bay, may be perceived through averaging the transports over the transects and the outer lateral boundary (Table 1) (T_{outer}=T1+T2+T3+T4+T789). In summary, the coastal northeastern Adriatic lost energy through lateral boundaries, and particularly through the boundary of Kvarner Bay, during the

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winter and spring of 2015 (15 December 2014 – 15 May 2015), a period that encompasses the preconditioning, generation and spreading phases of the DWF in the area.

The normal modelled fluxes at the inner transects (T5 and T6, Fig. 16) were mostly directed northwestward in the surface layer, presumably due to bora-driven currents. The fluxes were in the opposite direction in the bottom layer, following two-layer circulation in these constructions. The total inner transports (T_{inner}=T5+T6) show the transport of energy, salt and mass towards the inner coastal area of the Velebit Channel (Table 1). However, this transport is much weaker than the transport modelled at the outer boundaries of the coastal waters.

The modelled fluxes and transports are highly variable with time (Fig. 14), particularly over the outer lateral boundaries. The average transports during six peak events are approximately 6 and 2 times larger than the average transports over the outer and inner lateral boundaries, respectively. As they occur over the largest transect by far, the transports at the T789 transect dominate the T_{outer} transports. It is interesting that during some peak events, such as those on 28 December 2014 and 22 February 2015, the T1 inward transport peaks simultaneously as the outward transport at transects T2, T4 and T789. Therefore, the peak inflow at the southern boundary of the NAdEx 2015 area, which is under the influence of the Eastern Adriatic Current (occasionally directed towards the inner waters southeast of the transect T1), is balanced by the strong outflow at the northwestern lateral boundaries. By contrast, there are situations when the peak transports are localized over smaller parts of the domain. For example, the peak outward transports at transects T2 and T3 are balanced by the inward transport at T1 on 5 March 2015. These transports were presumably driven by strong bora that strongly blew in the southeastern part of the NAdEx 2015 domain, increasing its speed towards the southeast (central Adriatic). The transports at the lateral boundaries became much weaker after the early March bora, and the values were lower in April and May.

The average dense water mass flux (Fig. 15), defined as a flow of water with a PDA >29.2 kg/m^3 normal to the transects (Janeković et al., 2014), was largest at the outer lateral boundaries at transects T3 and T789. As expected, the mass flux is directed towards the open Adriatic, but the values were higher in the surface layer than near the bottom, as wind-driven transport is stronger there. Additionally, the near-bottom minima can be a sign of a sporadic penetration of dense waters coming from the open sea, i.e., the northern Adriatic shelf, towards the deep coastal area, which is also supported by the profiling float data (Fig. 6). That dense water flow may reverse, particularly at the northern outer transects T4 and T789, which is clearly seen in Fig. 16. The strongest dense water outflow event was modelled to occur on approximately 22 February, approximately two weeks after the early February severe bora events, through all outer lateral boundary transects except T3. During the peak dense water outflow, the dense water volume transport over the outer boundaries reached the maximum value of 0.4 Sv, which is comparable with the peak dense water outflow modelled during the extreme winter of 2012 (Janeković et al., 2014). The dense water transport across the inner transects is also interesting, as it is directed towards the inner coastal area on average. However, the inflow is stronger at transect T5 in late February and late March, while the maximum inflow occurred at transect T6 during late March and April.

Residence times are computed for both outer and inner coastal areas and for a period between 15 December 2014 and 15 May 2015. The residence time (RT) was computed by applying the formula:

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$$RT = \frac{\iiint_{x,y,z} \rho(x,y,z)\, dx\, dy\, dz}{\oint\!\!\oint_{C,z} \rho\,(x,y,z)\, \vec{u}_{out}(x,y,z).\vec{n}\, dC\, dz}$$

where *ρ(x,y,z)* is the density of the water at each point *(x,y)* and for each depth z of the domain, while $\vec{u}_{out}(x,y,z).\vec{n}$ is the normal outward velocity along the contour *C* of the domain. Such an approach assumes that (i) only the velocities at the border of the domain are used to calculate the residence time, (ii) only the outflow of water at the border is taken into account; the goal here is to only look at how long it would take for the water masses to leave the domain assuming that there is no incoming water within the studied domain, and (iii) the residence time is calculated with a time step of 3 h over the period of the studied event, assuming a steady state of the dynamic conditions at each time step. Box-whisker statistics were computed for the total (RT) and dense water (DWRT) residence times (Fig. 17). The median RT for the entire coastal basin (bordered by the outer transects T1, T2, T3, T4 and T789) was estimated to be 19 days, although it appeared to be much shorter during strong wind outbreak episodes (down to 7 days) and much longer during the low mass exchange between the coastal and open Adriatic waters (up to 40 days). The dense water residence times (DWRT; waters with PDA >29.2 kg/m^3) are much lower, with a median value of 11 days and normally not longer than 35 days. The DWRT is smaller than the RT as the volume of the generated dense waters is much smaller than the volume of the entire coastal area, while the dense water outflow was substantial and occurred over a large portion of the transects, not just at the bottom.

7 Discussion and conclusions

The coastal northeastern Adriatic is one of the least-investigated Adriatic regions. There are several reasons for this (i) it is considered to not have a substantial influence on the overall dynamics of the Adriatic, as it is separated from the open Adriatic by several long islands that physically restrict water exchange, (ii) the area is positioned far away from research institutes, whose monitoring activities have not encompassed the area (see published data catalogues by Buljan and Zore-Armanda (1966, 1979) and Zore-Armanda et al. (1991)), and (iii) satellite remote sensing does not perform well in the region, as numerous channels and complex topography impair the quality of the data (Klemas, 2011). In addition, this area has wrongly been treated as a basin with strong freshwater fluxes, particularly of riverine origin (Raicich, 1994). Recently, it has been found that this old climatology of river discharge overestimates the real river discharges by almost an order of a magnitude (Janeković et al., 2014; Vilibić et al., 2016a). Only limited parts of the coastal northeastern Adriatic have been previously investigated (e.g., Rijeka Bay in the early 1980s, Gačić et al., 1983, outer Kvarner Bay during the winter of 2002/2003, Lee et al., 2005; Poulain et al., 2011). The NAdEx 2015 is the first and the only current experiment that systematically approached the monitoring of the northeastern coastal Adriatic, including the communication between the open Adriatic and the coastal area through connecting channels. The NAdEx 2015 was accomplished through a strong collaboration and engagement between different institutions, resulting in a multiplatform marine dataset that can serve as a baseline for future investigations in the area. The experiment also includes the introduction of a state-of-the-art measuring platform that provides insight into the

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processes not previously documented in the Adriatic, such as the first deployment of an Arvor-C profiling float in the Adriatic Sea. The choice of the experimental area — the coastal northeastern Adriatic — emerged from the events in the winter of 2012, when it exhibited an unprecedented heat loss (up to 2000 W/m^2) and DWF rates that strongly contributed to the overall Adriatic dense water dynamics (Mihanović et al., 2013; Janeković et al., 2014).

We have provided an overview of the observations and estimated rates of selected basic processes using both an extensive set of measured data and a coupled atmosphere-ocean model. Our main intention was to answer two questions: (i) whether or not DWF is common in the northeastern coastal Adriatic, and (ii) if so, what is the behaviour of the DWF-related dynamics, particularly regarding water exchange with the open Adriatic. To answer these questions we reached the following conclusions: (i) CTD data show that DWF does occur in the coastal northeastern Adriatic during normal winters in terms of wintertime heat losses, as was the case in 2015; (ii) observations at connecting channels show a marginal bottom outward transport of dense waters to the open shelf and a balanced near-bottom inward-outward dense water exchange, while the outward transport of dense waters is mostly concentrated in the intermediate and surface layers, (iii) the modelling results show the domination of outward dense water transport, supporting the hypothesis that the NAdEx area is a source of dense waters for the open Adriatic, and (iv) the exchange of waters between the coastal and open Adriatic waters through a number of connecting passages was quantified, and the residence time was found to vary from one week to a few weeks and was shorter during strong wind conditions.

These results are also in line with the previous modelling results by Janeković et al. (2014), who also modelled the outflow of dense water transports in connecting passages during the winter of 2012. However, the densities of these waters were much higher and almost equal to the densities of the waters coming from the open Adriatic DWF site due to the different preconditioning and DWF setups in the winter of 2012. Thus, the DWF outflow from the NAdEx area also occurred in the bottom layers of the connecting passages. There are several reasons for this result: (i) preconditioning did not include a prolonged period of dry conditions (MHS, 2014, 2015), which may increase the salinity of the inner coastal waters to values equal to those observed in the open Adriatic (Mihanović et al., 2013), and (ii) the wintertime cooling and heat losses were not as pronounced as in 2012, although there were several strong bora events. Although weaker, the DWF of 2015 excited the thermohaline circulation in the basin, which was detected by an increase in salinity over time (Orlić et al., 2006). Still, the question remains if the intrusion of the open Adriatic saline waters to the coastal northeastern Adriatic during the late winter and spring of 2015 was the result of the open Adriatic thermohaline circulation driven by the DWF in the coastal northeastern Adriatic, or a consequence of the broader open-Adriatic thermohaline circulation.

Aside from documenting the processes by measurements, these data may be particularly useful for fine tuning numerical models, which is a foreseen direction of future investigations in the Adriatic, in both coastal and open ocean areas — particularly as the model in this study strongly underestimated the measured currents, especially in the narrowest connecting passages (Fig. 10). The tuning should also include a densification of the sigma layers near the bottom, where bottom density currents may appear (Vilibić and Mihanović, 2013). Twenty sigma layers in our modelling system were not able to satisfactorily reproduce the observations in the near-bottom layers, such as those from the Arvor-C profiling float; yet, this

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number of layers was previously found to satisfactorily reproduce the overall dense water dynamics over the northern Adriatic shelf (e.g., Benetazzo et al., 2014). The estimated variables proportional to currents were also underestimated (e.g., heat, salt, mass and volume fluxes at connecting passages), while the residence times were likely overestimated. However, the thermohaline properties of the coastal area were reproduced fairly well, pointing to the fairness of the model results in reproducing the DWF processes and associated dynamics.

The underestimation of the water exchange between the coastal and open Adriatic waters may be a result of several factors. The first and the most obvious factor is the horizontal resolution of the ocean model. A resolution of 500 m may not be high enough to reproduce the cross-channel processes that occur in channels that are only a few kilometres wide, such as those approximated by the T2 and T3 transects. This hypothesis is supported by the fact that currents were least underestimated in wider channels and areas, e.g., at the T4 and T789 transects. However, as currents were still underestimated at the latter transects (i.e., corresponding ADCP points), part of the misrepresentation must be due to other factors within the modelling system, such as the parameterisation of wind effects, vertical diffusivity, lack of wave models, and slip conditions at the coastline. Surface forcing is the next culprit in the list since an 8-km mesoscale ALADIN model with a 2-km dynamical downscaling of surface wind might not be sufficient for realistic ocean forcing in such a complex area. This constraint applies to both ocean and atmospheric processes, considering that the bora wind in the area is driven by an interaction of the synoptic flow with the complex orography of Velebit Mountain while being modified by the topography of the islands (Grisogono and Belušić, 2009).

Recent investigations of different types of bora by TerraSAR-X images (Kuzmić et al., 2015) conclude that different bora types embed several small spatial structures in its flow at the kilometre and even sub-kilometre spatial scales. The structures are particularly developed during severe bora outbreaks when large differences between relatively high sea surface temperature (SST) and very cold overflowing air are present. These differences can trigger secondary bora jets and extensive orographic breaking waves that propagate over the entire coastal northeastern area and over much of the open Adriatic, as was the case during the winter of 2012. Last but not least, the role of air-sea feedback during bora events is not negligible, as was shown through the comparison of two-way coupled atmosphere-ocean models vs. uncoupled simulations (Pullen et al., 2006, 2007; Ličer et al., 2016): air-sea feedback influences the position and strength of jet-like structures, it decreases the heat losses in the area, and it reduces the ocean currents in a jet by approximately 10–20% during bora events, therefore suppressing ocean mixing. In summary, an improvement in the reproduction of wintertime dynamics in a complex area such as the coastal northeastern Adriatic should be based on (i) an increase in the horizontal resolution of an ocean model, (ii) the implementation of a high-resolution (1 km horizontal resolution at maximum) non-hydrostatic atmospheric model, and (iii) two-way coupling of ocean and atmospheric models. This concept does not include the effects of waves, which are known to affect the DWF in the open Adriatic (Benetazzo et al., 2014); yet, sensitivity modelling studies of waves have not been performed in complex coastal regions, which are characterized by limited fetch and strong deformation of waves due to strong gustiness of bora wind.

To emphasize the importance of the NAdEx 2015, we should add that the preliminary analyses of the observations (Vilibić et al., 2016b) revealed a number of interesting phenomena and processes other than those presented in this paper. For

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example, it seems that the dynamics of the thermohaline front that stretches from Kvarner Bay towards the open Adriatic (Lee et al., 2005; Kuzmić et al., 2006; Poulain et al., 2011) are highly variable over time, resembling near-diurnal wave-like oscillations. A question remains if these oscillations are driven by diurnal tides (Cushman-Roisin and Naimie, 2002), Adriatic seiches (Cerovečki et al., 1997), inertial oscillations (Orlić, 1987) or some other phenomena that may induce significant oscillatory currents in the region (Kokkini et al., 2017). In addition, as seen from glider measurements, the front may completely change and even vanish over a daily timescale and may have a strong impact on the thermohaline and dense water dynamics in the region. Last but not least, high-frequency phenomena were observed in coastal waters, which are presumably the result of inertial, tidal (barotropic and baroclinic), topographic (the Adriatic seiche of 21.5 h) and advective processes that are strongly influenced by the complex coastal topography. These processes may influence the Adriatic-scale phenomena, similar to how the exchange between the Venice Lagoon and the Adriatic modulates the Adriatic diurnal tides (Ferrarin et al., 2015). Further investigations of all these processes are envisaged through in-depth analyses of the collected NAdEx 2015 dataset and process-oriented atmosphere-ocean modelling at high resolutions.

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