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Exceptional dense water formation on the Adriatic shelf in the winter of 2012

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Abstract

We document dense water formation (DWF) throughout the Adriatic shelf and coastal area in January/February 2012, resulting in record-breaking densities observed during and after the event. The unprecedented dense water generation was preconditioned by a dry and warm year which resulted in a significant reduction of coastal freshwaters, superimposed on a long-term basin-wide salinity increase. The final event that triggered the DWF was an extended period of cold weather with strong and severe winds. Record-breaking potential density anomalies (above 30 $\mathrm{kg\,m^{-3}}$) were measured at several DWF sites. Accumulated surface net heat and water losses in some coastal regions exceeded 1.5 $\mathrm{GJ\,m^{-2}}$ and 250 $\mathrm{kg\,m^{-2}}$ over 21 days, respectively. Excessiveness, importance of shelf-type DWF, effects on the thermohaline circulation and deep aquatic systems, and connection with climate change are discussed.

1 Introduction

Aside from the open-ocean convection type of dense water formation (DWF), which has been early recognized to be substantial in driving thermohaline circulation in global ocean and deep basins, the role of DWF over a shelf in changes of deep basins has not been perceived as important until recently (Ivanov et al., 2004; Allen and Durrieu de Madron, 2009; Pattiaratchi et al., 2011). This applies particularly to mid-latitude large and deep basins, such as the Mediterranean Sea, where deep thermohaline circulation is driven by extensive wintertime heat losses and wind mixing at several DWF sites (Robinson et al., 2003). Although extensively investigated at the Mediterranean subbasin and process scales (Pasqual et al., 2010), the contribution of the shelf-generated dense water has generally been underrated in the Mediterranean-scale studies, especially within long-term and climate studies (Somot et al., 2006). This is partly a result of still too low resolution of coastal bathymetry and strong temporal and spatial variability of the atmospheric forcing in shelf regions (Béranger et al., 2010).

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The Adriatic Sea (Fig. 1) is a scholar example of both open-convection and shelf types of dense-water formation processes, being a result of frequent similar synoptic conditions and wind patterns, mostly related to the blowing of cold and severe bora (ENE or NE) wind (Grisogono and Belušić, 2009). Due to closeness of shelf and open-ocean dense water formation sites, the DWF frequently takes place simultaneously at both places, but not always, as the surface heat losses and preconditioning may differ over the distance of several hundred kilometers (Josey, 2003). The deep-convection site is located in the 1200-m deep circular South Adriatic Pit (SAP) characterized by cyclonic circulation and central doming of isopycnals, where vertical mixing during strong DWF may reach 800 m (Gačić et al., 2002). The shelf DWF site is located in the northernmost part of the wide Adriatic shelf, having depths less than 50 m, where the strong bora cools the entire water column (Pullen et al., 2007; Jeffries and Lee, 2007). Generated dense waters (North Adriatic Dense Water – NAdDW, e.g. Zore-Armanda, 1963; Bergamasco et al., 1999; Vilibić and Supić, 2005) flow as a dense current along the Western Adriatic shelf, replacing old waters in the Middle and South Adriatic depressions (Jabuka Pit and South Adriatic Pit, respectively – Fig. 1). NAdDW partly transforms into Adriatic Dense Water (AdDW) during deep-convection processes in the South Adriatic, and both AdDW and modified NAdDW subsequently flow out of the Adriatic through the Strait of Otranto, sinking to the Ionian deep layers and affecting the whole deep Eastern Mediterranean (Robinson et al., 2003).

The dense water outflow from the Adriatic is compensated by the advection of saltier Levantine Intermediate Water (LIW) from the Ionian Sea, which affects circulation and dense water formation in the Middle and North Adriatic. It is suggested that the interaction between the Ionian and the Adriatic is changing on decadal scale by means of the Bimodal Oscillating System (BiOS) mechanism (Gačić et al., 2010), an internally driven process related to decadal variation of the upper-layer circulation in the Ionian, from cyclonic to anticyclonic and vice versa. The mechanism influences the intrusion of LIW in the Adriatic (stronger intrusions during the cyclonic phase) and affects the dense water properties in the SAP and biogeochemical properties of the whole system (Civitarese

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et al., 2010). Conversely, the changing properties of outflowing AdDW eventually modify the upper-layer circulation in the Ionian and the pathways of water masses, thus impacting the entire Levantine basin (Gačić et al., 2011).

Multi-decadal monitoring efforts along the DWF area and several campaigns that captured very dense bottom currents (Supić and Vilibić, 2006) documented maximum potential density anomaly (PDA – σ_θ) in the Adriatic not exceeding 30 kg m^{-3}. However, it seems that higher densities may be reached quite close to the coast, during severe winters occurring over centurial timescales. Namely, Vatova (1929) documented the temperature of 3.95 °C and salinity equaling 38.15 at 22 m depth off Koper (Gulf of Trieste), during severe winter of 1929, resulting in PDA of 30.30 kg m^{-3}. Harsh winter conditions caused mass mortality of benthic organisms at the time. Still, this almost 100 yr old measurement is the only historical record with such a high density in the North Adriatic. The record was broken during the long and severe bora episode in the winter of 2012, preconditioned by a very dry year. During this recent episode the shelf and coastal DWF occurred not only at the classical DWF site but also in a number of Eastern Adriatic coastal channels and bays, where DWF has not been documented to this day due to the large freshwater load. This paper is the first documentation of the DWF that occurred in the North and Middle Adriatic during the winter of 2012. The study includes an assessment of the preconditioning and atmospheric forcing reproduced by operational atmospheric and ocean models, and it raises a discussion on different aspects of the observed extreme event.

2 Data and methods

2.1 Field campaigns and data processing

A number of oceanographic field campaigns were carried out in the coastal and open Adriatic waters between February and April 2012, taking CTD profiles by different probes (Seabird SBE 19 and SBE 25, Idronaut 316, Sea&Sun MSS90), all of them

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regularly calibrated and having an accuracy of at least ±0.01 °C for temperature and ±0.005 for practical salinity. Also, vertical thermohaline profiles measured by an ARGO float stacked in the Jabuka Pit for almost a year were analysed (code 1900848, available at http://www.coriolis.eu.org). Figure 1 contains the locations and sampling dates of the most interesting vertical profiles, but many other observations and cruise repetitions were taken, in both coastal and open Adriatic.

Continuous sampling of temperature and practical salinity has been conducted off Venice, at the Acqua Alta platform, located in a 16 m deep area (AA in Fig. 1). Hydrolab DS5X multiparameter sensors were located at the surface and near the bottom (at 2 m and 13 m), with a sampling rate of 30 min and an accuracy of ±0.1 °C for temperature and ±0.2 for salinity. The data were quality checked and calibrated by vertical profiles obtained every 30 days with IDRONAUT Ocean Seven 316 CTD probe (accuracy of ±0.003 °C for temperature and ±0.003 for salinity). Wind speed and direction, air pressure, temperature and humidity data were sampled every 30 min, 15 m above the sea level. Latent and sensible fluxes at AA platform were computed using COARE 4.0 algorithm, following the methodology given by Edson (2009). Also, continuous sea temperature measurements were performed in the central part of the Gulf of Trieste (Paloma pillar, located 10 km to the west of station TS), at depths of 3, 15 and 24 m (sea-floor depth is 25 m) with SIAP-MICROS Pt100 sensors (accuracy ±0.1 °C).

Potential temperatures (PT) and potential density anomalies (PDA) were computed from temperature and practical salinity data, following TEOS-10 algorithms and using scripts available at http://www.teos-10.org.

2.2 Operational numerical models

Two operational numerical models were used to quantify the processes at the air-sea interface. The first is the NWP ALADIN/HR model, and the second is the COSMO/ROMS one-way coupled system. NWP ALADIN/HR model is operationally used by the Meteorological and Hydrological Service of Croatia. The model forecast is run in 2 km horizontal resolution on 37 levels in the vertical using non-hydrostatic dynamics and a full set of physics parameterizations (Tudor and Ivatek-Šahdan, 2010). It is initialized daily from the 6 h ALADIN forecast run in 8 km resolution using the scale selective digital filter initialization (Termonia, 2008). SST in the model provided by the global atmospheric model ARPEGE and does not change during the 24 h model run. Turbulent fluxes are computed as turbulent exchange between the lowest model level (around 17 m above the sea surface) and the sea surface. The turbulent exchange coefficients are resolved using prognostic turbulent kinetic energy (TKE) values.

The second COSMO model (www.cosmo-model.org) is a limited-area nonhydrostatic atmospheric prediction model with 7 km horizontal resolution and 72-h forecast range, being operational at Hydro-Meteo-Clima Service (SIMC) of the Emilia Romagna Regional Agency for Protection and Environment (ARPA-EMR). The Regional Ocean Modeling System (ROMS, http://www.myroms.org) is a primitive equation, finite differences, hydrostatic, free surface model, tides included. The utilized Adriatic application (described in Russo et al. (2009) and operational at DISVA in collaboration with SIMC and CNR-ISMAR) has a constant resolution of 2 km across the entire domain and 20 stretched vertical sigma levels. Forty-nine rivers and karstic springs (in the eastern coastal area) were also included as sources of mass and momentum using available daily discharges for the Po River and monthly climatological values for other sources. Radiation condition is imposed at the Strait of Otranto with a nudging of mean daily forecast of temperature, salinity, baroclinic currents from the general circulation model of the Mediterranean Ocean Forecasting System (Oddo et al., 2009). Fluxes through the air-sea interface were calculated using the COARE 3.0 bulk flux algorithms (Fairall et al., 2003), with sea surface temperature (SST) from ROMS and short wave radiation, wind, air temperature, humidity, cloud cover and atmospheric pressure from the COSMO-I7 atmospheric model.

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3 Results and discussion

Maximum PDA records and tabulated respective PTs, salinities and dates of measurements taken in the North and Middle Adriatic between February and April 2012 (during and after the extreme cold event and severe bora outbreak) are shown in Fig. 1. The bora episode lasted for about 3 weeks in coastal Eastern Adriatic region, between 25 January and 14 February 2012. Wind was strong to severe from ENE–NE, blowing occasionally with hurricane force. The maximum PDAs were measured throughout the Gulf of Trieste, with absolute maximum at TS station sampled on 15 February (30.59 kg m^{-3} at 18 m depth; the respective PT and salinity were 4.24 °C and 38.56). During the field study carried out in the Gulf between 14 and 16 February 2012, PDA surpassed 30.50 kg m^{-3} at 25 CTD stations out of 44. The absolute temperature minimum below 20 m was observed at 24 m depth on the Paloma pillar, in the central part of the Gulf (3.9 °C), in the mornings of 13 and 15 February 2012. This temperature record is quite similar to the bottom temperature observed by Vatova (1929) in the winter of 1929 (3.95 °C at 22 m).

Slightly lower PDAs were measured at the AA oceanographic platform on 11 February (30.35 kg m^{-3}). The platform is located at the margin of the bora-driven Northern Adriatic gyre, in which a peak of DWF is normally located (Boldrin et al., 2009). Such densities are much higher than those previously recorded in the area over an extended period of time (Supić and Vilibić, 2006), driven both by extremely high salinities (> 38.5) and very low temperatures (< 6.5 °C). Another PDA maximum was measured at 100-m deep Pag Channel station (PC), located deep inside Croatian inner waters. Exceptionally high salinities (around 38.77) were recorded at the station and these salinities are even higher than the average value documented for the South Adriatic (Artegiani et al., 1997). Finally, extremely high salinities, low PTs and associated high PDAs were recorded along the entire Eastern Adriatic coastal area northwest from Split, all above 29.55 kg m^{-3}. Such values have never been documented before in this part of the Adriatic (e.g. Zore-Armanda et al., 1991).

Vertical profiles at selected stations (Fig. 2) show a variety of processes that occurred during the winter of 2012. The difference between vertical profiles in September 2011 and February 2012 at the Jabuka Pit station (JP) exhibits vertical homogenization and deep convection that occurred at least down to 150 m during the bora event (Fig. 2a). Further on, between February and April 2012 cruises, the temperature below 180 m decreased by more than 2.5 °C, while salinity showed a slight decrease (0.06–0.08), resulting in additional PDA increase by up to 0.45 kg m^{-3}. The changes visible near the bottom in February and below 80 m in April 2012 are footprints of dense water arrival from "classical" North Adriatic DWF site and/or from the Eastern Adriatic inner waters.

The maximum recorded PDAs in the inner Croatian waters (Fig. 2b) largely exceeded those observed in the open Middle Adriatic (Jabuka Pit, Palagruža Sill) just after the event, which ranged around 29.2–29.3 kg m^{-3} (not shown). This implies the existence of a density current flowing through deep connecting channels of the Eastern Adriatic, most of them transporting dense water to the Jabuka Pit (arrows in smaller inset in Fig. 1, showing the Eastern Adriatic area and presumed pathways of dense water). Indeed, a strong drop in temperature and a slight decrease in salinity were observed in the bottom of BL station on 28 February 2012 (Fig. 2b, one should note that BL station is about 200 m deep, while the depression 10 km to the west of BL is 237 m deep, but no measurements were taken there). As there was almost no possibility for dense water to reach BL station from the North Adriatic 15 days after the DWF (Vilibić and Supić, 2005), the most likely explanation is that these waters came from the inner Croatian sea. To confirm this, however, further quantitative analysis and estimation of the DWF rates along the Eastern Adriatic coast should follow through process-oriented numerical modelling exercises.

Particularly interesting is the PDA measured at TL station, located in the middle of 10-km long island embayment connected to the open Adriatic (Telašćica Bay, Dugi Otok Island). Two weeks after the event the majority of the embayment was homogenized, except for the deepest parts, where very cold and slightly less saline waters were observed, with PDA equalling 29.98 kg m^{-3}. As TL station is located in a depression

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within the embayment, which is separated from the outer parts of the bay by an 8-m high ridge, the captured bottom dense waters represent a footprint of DWF that occurred few weeks before. These waters then rapidly left the embayment as a density current over a slope, towards the northern parts of deep Jabuka Pit, and presumably reached its northernmost depression, to the west of BL station (vertical profile similar to TL was observed at DR station).

The highest PDAs were recorded in the Gulf of Trieste (Fig. 3). The potential density anomaly exceeded 30.0 $\mathrm{kg\,m^{-3}}$ throughout the Gulf, except at the very mouth of the Isonzo River. Maximum densities were measured along the bottom slope of the north-western part and in the deepest central part of the Gulf (above 30.5 $\mathrm{kg\,m^{-3}}$), being a result of extremely low temperatures ($< 4.7\,^{\circ}\mathrm{C}$) and high salinities (38.4–38.5).

Time series of PT, salinity and PDAs observed at AA station (Fig. 4) document the severity of the event and also the evolution of characteristics. During the episode the entire water column mixed, water cooled down for about $4\,^{\circ}\mathrm{C}$ (to 5.8–6.5 $^{\circ}\mathrm{C}$), while salinity surpassed 38.5 (since less saline surface waters were restricted to the very coast during the bora), resulting in PDAs higher than 30 $\mathrm{kg\,m^{-3}}$. That was a result of strong cooling at the surface, as turbulent heat flux series computed for AA (Fig. 4a) denote the cooling with two pronounced maxima, the first stronger one occurred on 3 February with maximum heat losses up to 800 $\mathrm{W\,m^{-2}}$, while the second maximum was observed on 11 February, with heat losses reaching 700 $\mathrm{W\,m^{-2}}$. However, the AA station is not positioned in the area with the strongest cooling; heat fluxes at AA are found to be 3–4 times lower than in the bora maximum jets stretching from several locations at the eastern shore (Pullen et al., 2007). Turbulent heat fluxes from both models followed those computed via bulk formulae using meteorological and oceanographic data acquired at the AA tower. During intense heat loss episodes COSMO/ROMS systems overestimated the fluxes by about 10 % while ALADIN/HR model underestimated them by about 14 % on average. Nevertheless, temporal changes and peak values were reproduced well by both models, as can be observed in Fig. 4a.

Spatial distribution of modelled fluxes, represented in Fig. 5 as a cumulative energy and mass loss during the bora episode (25 January–14 February 2012), quantifies the amount of energy and mass taken from the sea and indicates jets with extreme energy losses due to cold and severe bora wind. The energy loss (Fig. 5a) exceeded 1.5 GJ m^{-2} over the maximum bora jet along the eastern shore (off Senj), which is equivalent to a cooling rate of about 4.5 °C over the whole event, if box-model heat balance approach over 80 m deep ocean (average sea depth over the bora jets areas in the inner Croatian waters) is used (Gill, 1982). Naturally, similar energy losses over smaller and shallower embayments, e.g. Pag Bay (40 m average depth), would multiply the cooling of the ocean. Lower cooling rates over shallower Northern Adriatic would yield a similar temperature decrease. The energy loss of 0.7 GJ m^{-2} modelled over 30–40 m deep TL embayment would decrease the temperature for about 5 °C. Similar rates were estimated for the Gulf of Trieste and confirmed by temperature measurements from the buoys in the Gulf. Lower heat losses occurred over the DWF open-convection area in the South Adriatic, where bora did not blow during the whole period and therefore relatively modest cooling and vertical mixing were observed (up to 500 m).

In addition to the cooling, cumulative E-P water loss (Fig. 5b) during the event surpassed 250 kg m^{-2} over the maximum bora jet, being equivalent to a salinity increase of 0.12 over the 80 m deep inner Croatian waters. Cumulative water losses were 2–3 times lower over classical DWF site in the Northern Adriatic, resulting in a slightly lower salinity increase rate (about 0.1). By using a box model, PDA increase can be estimated to around 0.95 kg m^{-3} in the inner Croatian waters.

The volume of the generated NAdDW exceeding the density threshold of 29.5 kg m^{-3} (Artegiani et al., 1997) equalled 4250 km^3, estimated from the COSMO/ROMS numerical model. The NAdDW encompassed the most of the northern and large part of the Middle Adriatic. By assuming that the associated dense water current (flowing southeast) lasts for 3 months, one may reach a preliminary estimate of average transport of 0.55 Sv, which is an order of magnitude larger than during normal DWF years (Vilibić and Supić, 2005).

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As estimated salinity increase due to evaporation is on the order of 0.1, the observed high salinities at all DWF sites, particularly in the inner Croatian waters, should be a result of a preconditioning. Indeed the whole 2011 was characterized by very dry and warm conditions in Western and Southern Europe (NOAA/NCDC and WMO climate reports), especially over the Eastern Adriatic, where the driest year ever was recorded (climate report from Meteorological and Hydrological Service of Croatia, available at http://klima.hr). Also, the monthly runoff of the largest Adriatic river, Po River, was constantly below the respective average (about −25 % overall) throughout a whole year, from April 2011 to March 2012. This is particularly relevant to the inner eastern coastal waters, where the freshwater load coming largely through submarine karstic springs was very low (stations PC, MS, ZD, DR); therefore, high salinity preceded the cooling episode in the winter of 2012.

Simultaneously, the advection of saline waters over Palagruža Sill towards the open Middle and North Adriatic in the summer of 2011 (see station JP in Fig. 2a) increased the salinity at all open DWF sites for about 0.3. As coastal waters were absent, these high salinity waters reached the northernmost Adriatic shelf areas and intruded into coastal Eastern Adriatic.

The preconditioning to the DWF ended with warmer- and saltier-than-average waters, rapidly changing to colder-than-average during the three weeks of bora outbreak, evidencing the severity and uniqueness of the event. The synoptic setting in the atmosphere was persistent for almost three weeks. It included several deep cyclones traversing the Mediterranean, mesoscale cyclones developing over the Middle and South Adriatic and a high pressure system stretching from Scandinavia to Western Europe. This represents a classical blocking situation (Lejenäs, 1989), occurring with such intensity over the Adriatic once in a few decades. Exactly, such persistence in cold outbreaks over the Adriatic was observed previously in 1929 and 1956 (Penzar et al., 2001). The winter of 1929 was so severe that bottom waters in the Gulf of Trieste cooled down to 3.95 °C, with observed salinity equalling 38.15 (Vatova, 1929). Strength of DWF during the winter of 1956 was measured at deep JP station surveyed on 26 April 1956, where PT and salinity at 240 m equalled to 9.27 °C and 38.31, respectively, resulting in a PDA of 29.67 kg m^{-3}. One should note that both past extreme DWFs (in 1929 and 1956) were characterized by much lower salinities, as preconditioning was presumably different, with much higher precipitation rates and river runoffs and cooler climate preceding the DWF.

The observed difference in temperature and salinity over centurial timescales may be associated with ongoing climate changes, observable in a positive trend of the Adriatic salinity and upper-layer temperature (Vilibić et al., 2012), driven by positive E-P-R and heat flux trends observed over the Adriatic. Climate projection for the end of 21st century gives additional warming of surface Adriatic waters by about 2.5° C and salinity increase of about 0.5 (Tsimplis et al., 2008), changing the preconditioning of the DWF. This will presumably result in more saline and warmer dense waters, replacing present deep Adriatic and Mediterranean waters. However, the changes in coastal regions are found and projected to be more rapid: the decrease in freshwater coastal input in the Adriatic, resulting in salinity and density trends higher in coastal regions than in the open Adriatic (Vilibić et al., 2012), may weaken Adriatic-Ionian thermohaline circulation and therefore change the BiOS variability.

On the other hand, atmospheric blocking situations and intensity of cold air outbreaks over Southern Europe are projected to increase in the 21st century (Vavrus et al., 2006). This may result in more frequent occurrence of prolonged DWF episodes like in 2012, which may strengthen BiOS and the Adriatic-Ionian thermohaline cell. It seems that interplay between prolonged DWF during winter blocking situation and "normal" winters in the future climate will determine the strength of the thermohaline circulation, although regional climate models project that the circulation could become shallower (Somot et al., 2006). These changes are quite important, as the DWF brings oxygen to deep ocean layers, necessary especially within biodiversity niches such is Jabuka Pit, but also important for the whole deep Mediterranean. Finally, they will influence internal processes in the Ionian Sea and the BiOS, thus affecting circulation patterns

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and pathways of water masses, and possibly impacting the future interplay in DWF between the Adriatic and Aegean Seas.

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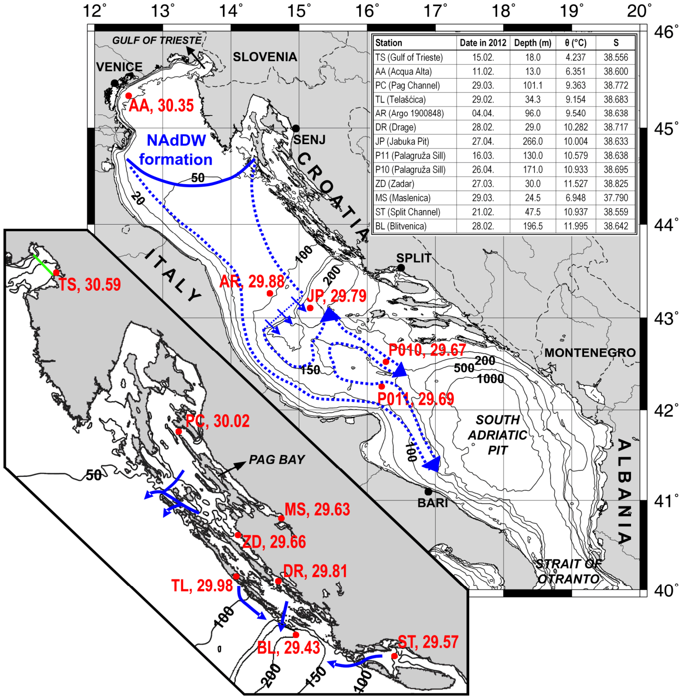

Station	Date in 2012	Depth (m)	θ (°C)	S
TS (Gulf of Trieste)	15.02.	18.0	4.237	38.556
AA (Acqua Alta)	11.02.	13.0	6.351	38.600
PC (Pag Channel)	29.03.	101.1	9.363	38.772
TL (Telašćica)	29.02.	34.3	9.154	38.683
AR (Argo 1900848)	04.04.	96.0	9.540	38.638
DR (Drage)	28.02.	29.0	10.282	38.717
JP (Jabuka Pit)	27.04.	266.0	10.004	38.633
P11 (Palagruža Sill)	16.03.	130.0	10.579	38.638
P10 (Palagruža Sill)	26.04.	171.0	10.933	38.695
ZD (Zadar)	27.03.	30.0	11.527	38.825
MS (Maslenica)	29.03.	24.5	6.948	37.790
ST (Split Channel)	21.02.	47.5	10.937	38.559
BL (Blitvenica)	28.02.	196.5	11.995	38.642

Fig. 1. Adriatic Sea bathymetry, with selected stations at which CTD samplings were carried out between February and April 2012 (main panel – the whole Adriatic; smaller inset – zoom of the Eastern Adriatic coastal area). Maximum values of potential density anomalies (PDA, in $kg\,m^{-3}$) observed at these locations are indicated adjacent to station names. Respective sampling dates, depths, salinities and potential temperatures (PT) are shown in an inserted table. Continuous measurements of meteorological and oceanographic parameters were available at Acqua Alta platform (AA). The green line in smaller inset indicates CTD transect used in Fig. 2c. The main path of the North Adriatic Dense Water (NAdDW) appears within blue dashed lines in the main panel. Presumed pathways of dense water generated along Eastern Adriatic coast are denoted by blue arrows in smaller inset.

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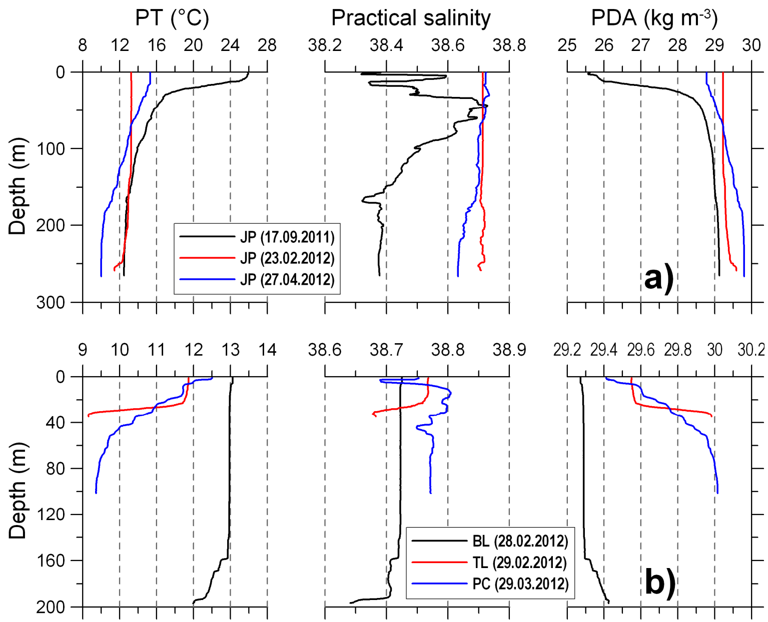

Fig. 2. Vertical profiles of potential temperature, practical salinity and potential density anomaly at selected stations along the Eastern Adriatic coast: **(a)** JP on 17 September 2011, 23 February 2012 and 27 April 2012, **(b)** BL on 28 February 2012, TL on 29 February 2012 and PC on 29 March 2012.

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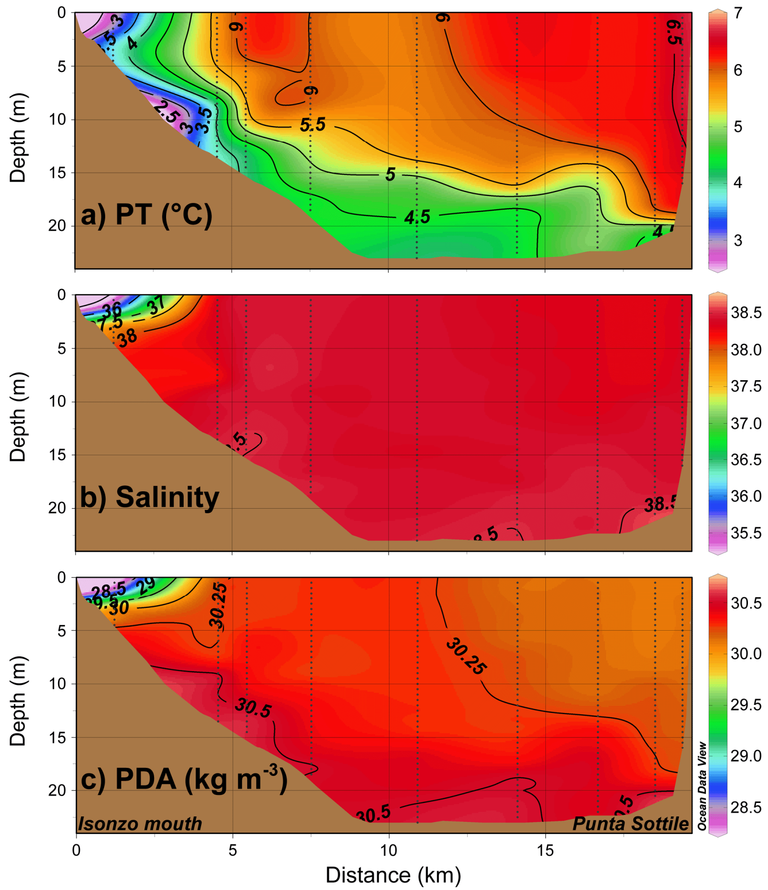

Fig. 3. Distribution of **(a)** potential temperature (PT, in °C), **(b)** practical salinity and **(c)** potential density anomaly (PDA, in $kg\,m^{-3}$) measured in the Gulf of Trieste between 14 and 16 February 2012. The mouth of the Isonzo River is at the northwestern part of the transect. See the smaller inset in Fig. 1 for transect position.

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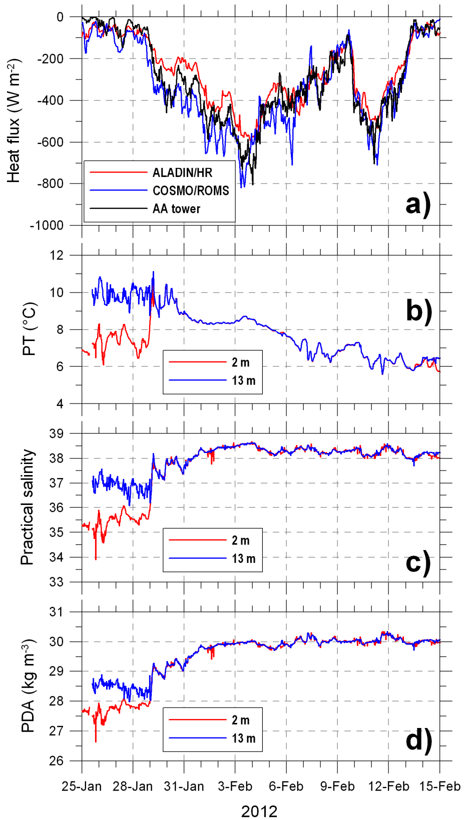

Fig. 4. **(a)** Time series of turbulent heat fluxes estimated for AA, together with modelled ones computed by ALADIN/HR and COSMO/ROMS models at the grid point nearest to AA, for the period between 25 January and 14 February 2012, and time series of surface (2 m) and bottom (13 m) **(b)** potential temperature (PT), **(c)** practical salinity and **(d)** potential density anomaly (PDA) during the same period.

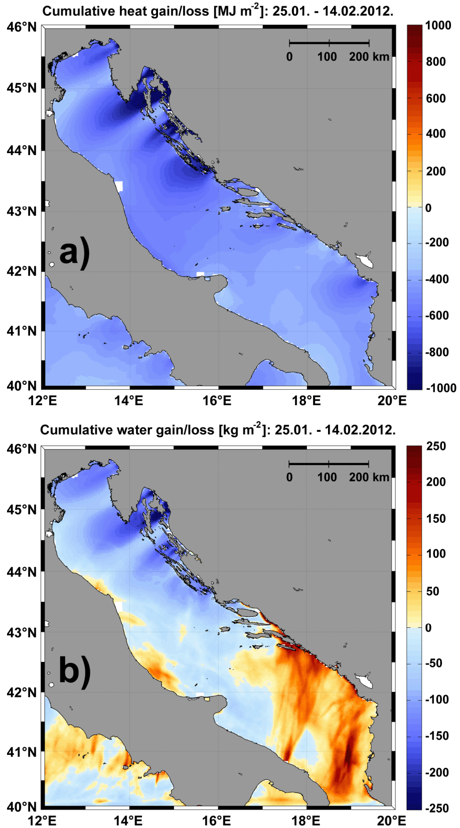

Fig. 5. Cumulative **(a)** heat and **(b)** water gain/loss between 25 January and 14 February 2012 as estimated by ALADIN/HR model.

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