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Multi-model analysis of the Adriatic dense-water dynamics

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S1 Introduction

In this supplementary material, a detailed description of the numerical models used in the article titled "Multi-model analysis of the Adriatic dense-water dynamics" is presented. Also, in order to quantify the differences between the results of four simulations several additional analyses were performed. The supplementary results (Fig. S1 to S4 and text), complementing the results of the main article, include spatial distributions of minimum bottom temperature and maximum bottom salinity and the corresponding timing of the extremes as well as time series of daily bottom temperature and salinity in four subdomains.

S2 Numerical models

S2.1 Mediterranean Sea reanalysis

The Mediterranean Sea reanalysis (hereafter referred as MEDSEA) is distributed within the Copernicus Marine Environment Monitoring Service (CMEMS) framework (Escudier et al., 2020). MEDSEA covers the whole Mediterranean Sea and a part of the Atlantic Ocean for the 1987-2019 period.

Nucleus for European Modelling of the Ocean (NEMO; Madec et al., 2017) is a non-linear, free surface, z-coordinate hydrodynamic model which solves the primitive equations using time-splitting techniques. The model has a horizontal resolution of 1/24° (4.5 km) and 141 unevenly distributed vertical levels (thickness varies from 2 m in the upper layers to 100 m in the deeper layers). The atmospheric forcing of the ocean model is provided by the European Centre for Medium-range Forecasts (ECMWF) ERA5 reanalysis with 0.25° (31 km) horizontal resolution and 1 h temporal resolution (Hersbach et al., 2020). The initial conditions are taken from the SeaDataNet (https://www.seadatanet.org/, last access: 24 February 2023) climatology.

Further, the three-dimensional variational (3D-Var) data assimilation scheme OceanVAR (Dobricic and Pinardi, 2008) is used to assimilate the in-situ data from CTD, Argo profiling floats (ARGO; https://argo.ucsd.edu, last access: 1 May 2022) and expendable bathythermograph (XBT) measurements, into the model along with satellite altimetry observations. Furthermore, a modified GEBCO 30arc-second grid (Weatherall et al., 2015) is used for topography. Nudging schemes are used to constrain heat and freshwater fluxes towards sea surface temperature (SST) and salinity observations. Also, a large-scale bias correction scheme is added to correct the model tendencies. The runoff of the 39 rivers is obtained from monthly mean climatological datasets. Further, SST fields are used for the correction of surface heat fluxes with a Gaussian relaxation coefficient dQ/dSST.

Finally, MEDSEA reanalysis, assessed through a comparison against in situ and satellite observations as well as climatologies, showed a better representation of the main dynamics of the Mediterranean region than the previous, lower-resolution (1/16°) reanalysis (Simoncelli et al., 2016, 2019). A more detailed description of the state-of-the-art MEDSEA product and all the components of the model used to produce it, can be found in Escudier et al. (2021).

S2.2 ROMS and ALADIN/HR modelling system

ROMS-ALADIN/HR has been operationally integrated since 2008 and has already been evaluated in several studies (e.g., Janeković et al., 2014; Vilibić et al., 2016, 2018). Regarding the ocean component, ROMS (Regional Ocean Modelling System) is a 3-D, free surface, bathymetry following, s-coordinate model in which primitive equations are solved with a finite-difference approximation and a time-splitting method (Shchepetkin and McWilliams, 2005, 2009). In this model, the horizontal ROMS grid resolution is 2 km and there are 20 vertically spaced sigma levels controlled by the following parameters: $Vtransform = 2$ and $Vstretching = 2$ with $\theta_s = 7$ (increased resolution at the surface), $\theta_b = 0.5$, and $h_c = 30$ (critical depth of 30 m). Daily averaged lateral boundary conditions are imposed north of the Otranto Strait from the Adriatic Forecasting System (AREG, Oddo et al., 2006). AREG is nested within the larger Mediterranean Forecasting System (MFS) which uses 3D-Var data assimilation (Pinardi et al., 2003; Pinardi and Coppini, 2010; Tonani et al., 2014). Furthermore, a bathymetry smoothing achieved with a linear programming (LP) technique (Dutour Sikirić et al., 2009) is used to reduce numerical instabilities. A river discharge climatology is imposed at the freshwater point sources following Vilibić et al. (2016) data.

Concerning the atmospheric model, a hydrostatic version of the ALADIN/HR (Aire Limitée Adaptation dynamique Développement InterNational; Tudor et al., 2013, 2015) model is used for the atmospheric forcing at the sea surface. The model is operationally run by the Croatian Meteorological and Hydrological Service four times a day with initial conditions computed using mesoscale data assimilation. It has a horizontal resolution of 8 km while the winds are dynamically downscaled to a horizontal resolution of 2 km (Ivatek-Šahdan and Tudor, 2004). In the vertical, 37 sigma layers are used in the model while the temporal resolution of all variables is 3 h. Lateral boundary conditions are obtained from the operational forecast runs of the Integrated Forecast System (IFS) in the ECMWF, where the global analysis is performed using the 4D-Var data assimilation technique. The transfer of the surface variables into the ocean model is done via bulk parametrization (Fairall et al., 1996).

In the study of Janeković et al. (2020), a year-long (1 October 2014 – 30 September 2015) 4D-Var data assimilation experiment has been applied to the Adriatic Sea. Three model simulations were integrated but only two of them are used in this study: (1) a non-assimilative, hindcast simulation, hereafter referred as ROMS-hind and (2) a fully assimilative simulation that used all available observations during the 4-days assimilation cycle – hereafter referred as ROMS-full. During the ROMS-full simulation, the physical-space statistical analysis system (PSAS) approach (Moore et al., 2011a) was applied, splitting the one-year simulation into 91 4-day assimilation cycles, each restarting from the previous cycle using saved initial conditions. This window cycling was necessary to ensure the validity of the Tangent Linear model assumption (Powell et al., 2008) within the 4-day window. Concerning the Adjoint model, clamped boundary conditions were used instead of radiation-nudging of 3D fields. High-resolution multi-platform observations were assimilated into the model, including SST measured by satellites, in situ temperature and salinity data measured by various moving (Argo floats, shipborne CTDs, sea glider, towed CTD profiler) and moored platforms, ocean current profiles measured by moored Acoustic Doppler Current Profilers (ADCPs), and 30-

minute de-tided surface currents from high-frequency (HF) radars. More information about the observations, experiments and skill assessment of the model can be found in the study of Janeković et al. (2020).

S2.3 Adriatic Sea and Coast (AdriSC) climate model

The AdriSC climate module has been developed with the aim to study long-term kilometre-scale processes in the Adriatic region (e.g., Denamiel et al., 2022). The performance of the atmospheric (Denamiel et al., 2021) and ocean (Pranić et al., 2021; Denamiel et al., 2022) components of the climate module has been thoroughly evaluated.

The ocean component is the ROMS model (hereafter referred as AdriSC-ROMS) with a larger 3 km grid and a nested 1 km grid covering the Adriatic and northern Ionian Sea (Fig. 1a). Regarding the vertical resolution, it uses 35 sigma layers transformed ($Vtransform = 2$) and stretched ($Vstretching = 4$) following Shchepetkin and McWilliams (2009) with increased resolution at the surface ($\theta_s = 6$) and bottom ($\theta_b = 2$) as well as a thickness of 50 m ($h_c = 50$). The high-resolution bathymetry data is provided for both grids by a Digital Terrain Model (DTM; Denamiel et al., 2018). The bathymetry smoothing (with the minimum depth of 2 m) was done with a LP method (Dutour Sikirić et al., 2009) which minimized the roughness factors (rx0 = 0.2) and kept the DTM bathymetric features while the horizontal pressure gradient errors were reduced. The initial conditions and boundary forcing of the AdriSC-ROMS 3 km model (sea-surface height, barotropic and baroclinic currents, baroclinic temperature and salinity) are provided daily by the Mediterranean Forecasting System (MFS) MEDSEA v4.1 reanalysis (resolution of 1/16°; Simoncelli et al. 2016, 2019) within the Copernicus Marine Environment Monitoring Service (CMEMS). The river forcing consists of 54 river flows in total (only 49 for the 1 km grid). The river flows are vertically distributed between the first 20 sigma levels and monthly climatologies of the river flows are acquired from various databases and studies. Additionally, a dQ/dSST procedure, described in the study by Denamiel et al. (2019), is used to minimize the corrections of the heat fluxes produced by Weather Research and Forecasting (WRF v3.9.1.1) model (Skamarock et al., 2005), while making sure that no artificial SST trends are generated in the shallow parts of the ROMS grids.

The atmospheric component is the WRF model (hereafter referred as AdriSC-WRF) with a grid resolution of 15 km and a nested 3 km grid (Fig. 1a). The model is nonhydrostatic and consists of 58 vertical levels refined in the surface layer (Laprise, 1992). The physics and parameterisations rely on the optimal configuration of Adriatic high-resolution WRF models (Kehler-Poljak et al., 2017). For the climate simulation, initial conditions and boundary forcing of the WRF 15 km grid are provided by the 6-hourly ERA-Interim reanalysis fields at 0.75° resolution (Dee et al., 2011; Balsamo et al., 2015). In addition, the sea surface temperature (SST) from the ROMS grids is not prescribed to the WRF models since the spatial extension of the ocean grids does not fully cover the WRF 15 km domain. Hence, the SST forcing is provided by the Mediterranean Forecasting System (MFS) reanalysis with 1/16° resolution distributed in the CMEMS (Simoncelli et al., 2019). Finally, the data exchange between the WRF grid and the ROMS models is achieved with the Model Coupling Toolkit (MCT v2.6.0; Larson et al., 2005).

S3 Results

S3.1 Analysis of the extremes

Spatial distributions of minimum bottom temperature and the corresponding timing of the minimums for the four simulations are shown on Fig. S1. In general, lowest temperatures are produced in the northern Adriatic down to 5 °C, along the western coast and in Kvarner Bay, while highest minimums are found in shallower parts of southern Adriatic up to 15 °C. MEDSEA minimums mostly occurred in winter, in the western part of middle Adriatic during spring, whereas in Jabuka Pit minimum temperatures were produced in autumn 2014 (Fig. S1a and b). For ROMS-hind, the main difference is in the Jabuka Pit where the minimums occurred in summer (Fig. S1c and d). ROMS-full minimums mostly happened in winter but also in spring in a part of Kvarner Bay and in the middle Adriatic (Fig. S1e and f). It can be seen that ROMS-full produced smallest temperatures in a patch in the northern Adriatic. For AdriSC-ROMS, temperature minimums are also present mostly in winter while in parts of the middle Adriatic including Jabuka Pit they occurred in spring (Fig. S1g and h). In the SAP, minimums are mostly produced in autumn and partly in winter and spring by all models.

Fig. S2 shows the spatial distributions of maximum bottom salinity with the corresponding timing of the maximums for all simulations. Smallest maximum salinities are obtained in the northern Adriatic, in Kvarner Bay and along the western coast with values reaching down to 38.2, while the largest salinities are produced in the southern Adriatic up to 39.2. MEDSEA results are characterized by the biggest contrast between these areas. Maximums occurred in summer mainly in the coastal areas whereas in the middle Adriatic they happened mostly in autumn (Fig. S2a and b). ROMS-hind results resemble MEDSEA results but with slightly smaller maximums in the middle and southern Adriatic. The timing of the maximum salinities is mostly in late autumn and winter as well as in summer in parts of northern Adriatic and some coastal areas (Fig. S2c and d).

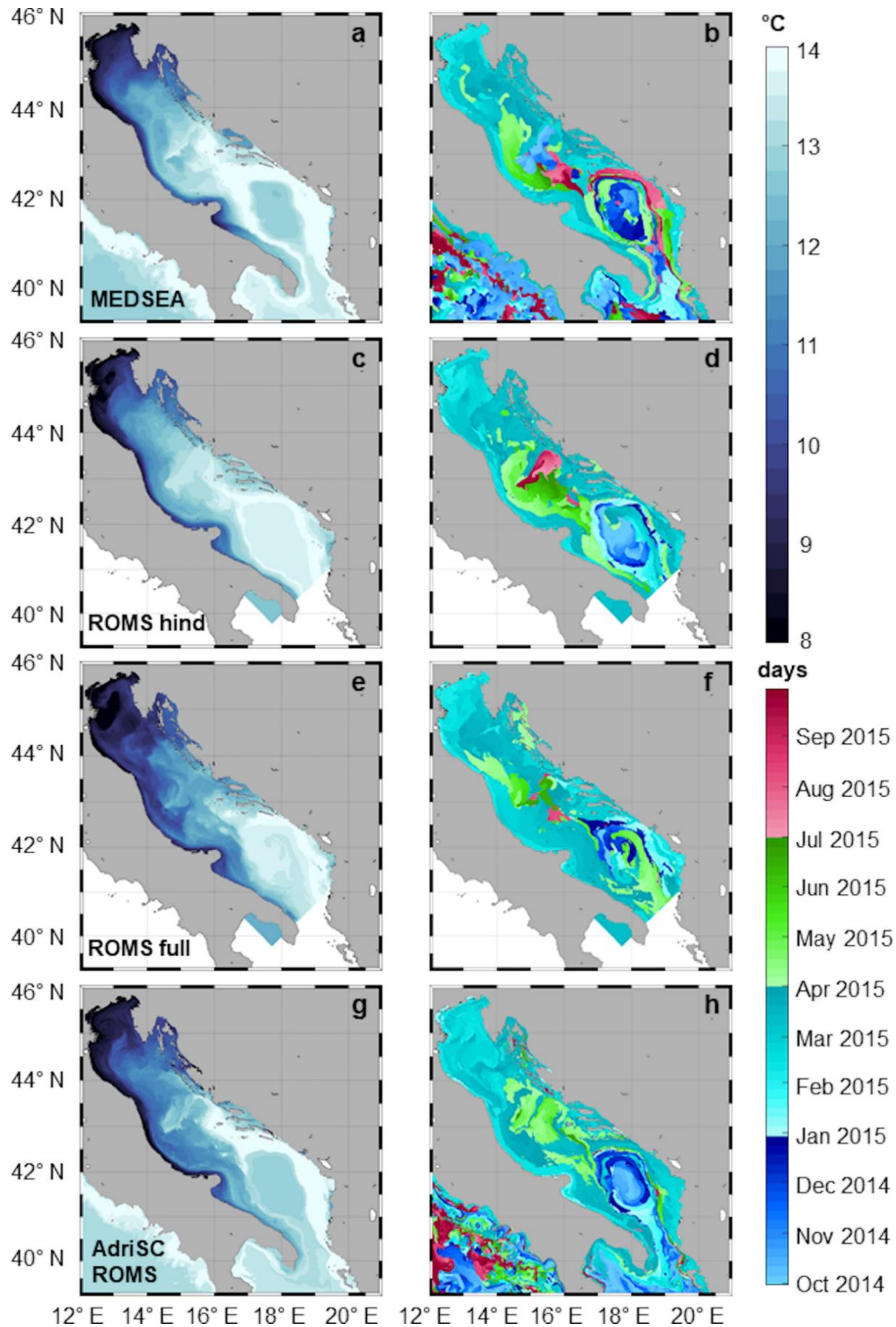

Figure S1. Spatial distribution of minimum bottom temperature and corresponding time of the minimums for (a, b) MEDSEA, (c, d) ROMS-hind, (e, f) ROMS-full and (g, h) AdriSC-ROMS.

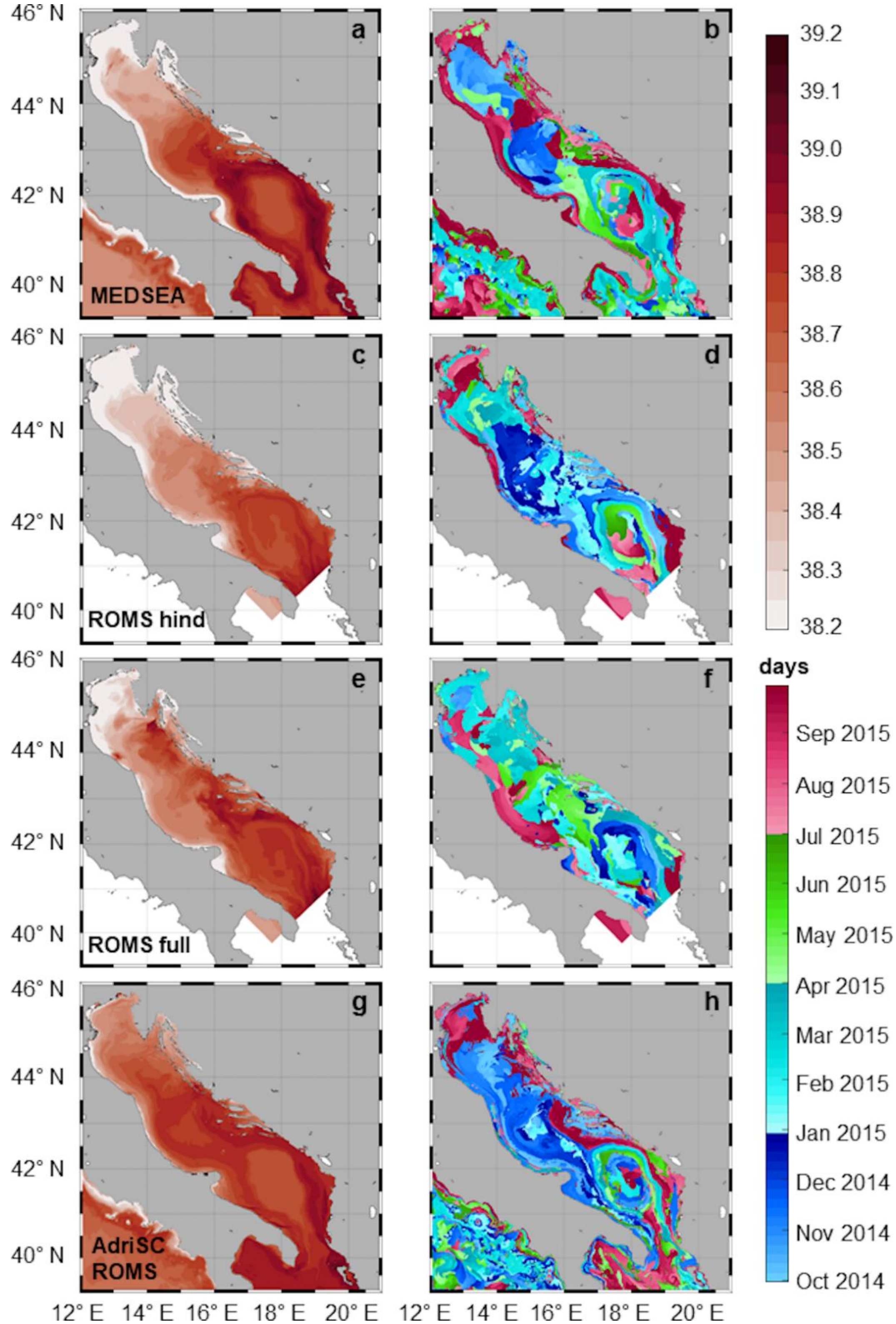

Figure S2. Spatial distribution of maximum bottom salinity and corresponding time of the maximums for (a, b) MEDSEA, (c, d) ROMS-hind, (e, f) ROMS-full and (g, h) AdriSC-ROMS.

Overall, ROMS-full produced slightly larger maximums than ROMS-hind with the biggest differences offshore of Kvarner Bay. Also, maximums are mostly produced in winter in the northern Adriatic and Kvarner Bay, in summer along the western coast and in spring in the middle Adriatic (Fig. S2e and f). Lastly, AdriSC-ROMS results revealed high maximum salinities (above 38.5) over the whole Adriatic except in very narrow coastal parts. The timing of the maximums is mostly in summer for the northern and north-eastern Adriatic as well as along the eastern coast, whereas the rest of the Adriatic reached maximum salinity in autumn (Fig. S2g and h).

S3.2 Dense-water dynamics

Time series of daily bottom temperature and salinity in four subdomains for all simulations are shown on Fig. S3 and S4, respectively. First, in the northern Adriatic subdomain (Fig. S3a), the largest differences in modelled temperature occurred in autumn 2014 and summer 2015 when MEDSEA gives the highest mean temperatures reaching 20.8 °C in October and 20.3 °C in September while the other modelled temperatures are around 1-1.5 °C lower. In contrast, winter and spring temperatures have better matching between simulations with smaller differences. The northern Adriatic mean temperature minimum occurs in the end of February and beginning of March for all simulations. However, ROMS-full is standing out with uneven temperature curve near the minimum and lowest values. The mean salinity results (Fig. S4a) reveal a large positive bias in AdriSC-ROMS results ranging from 0.3 – 1.1 with respect to other simulations.

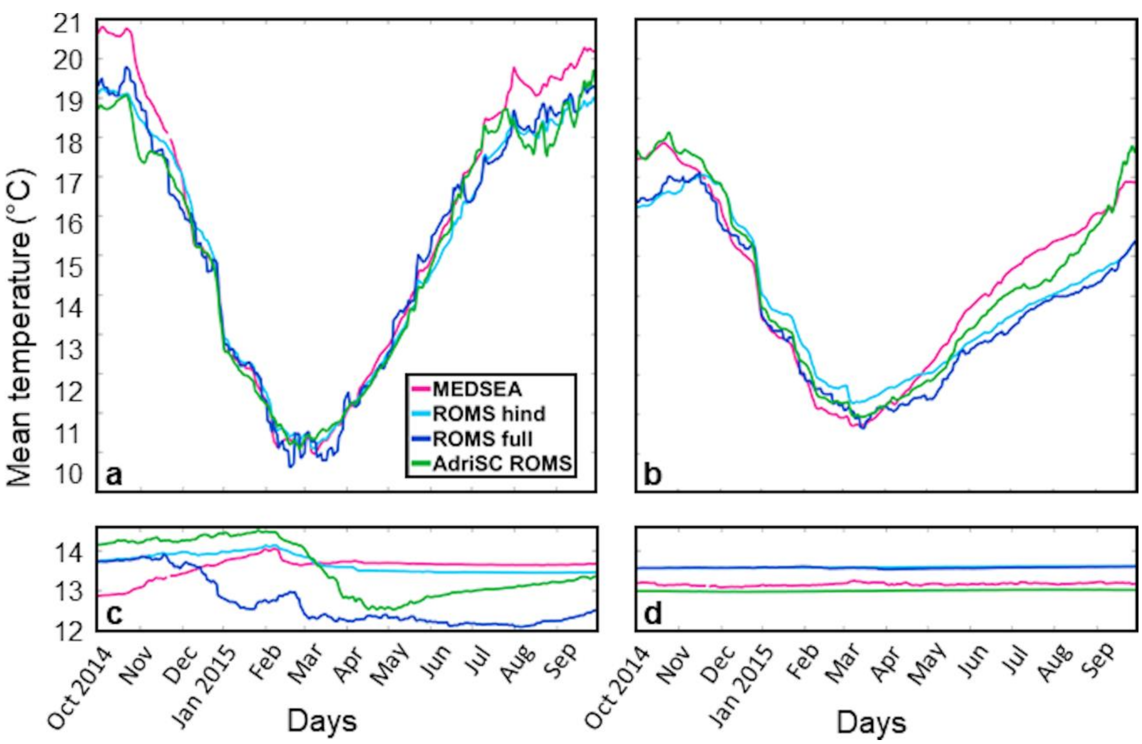

Figure S3. Time series of daily bottom temperature averaged over four subdomains: (a) northern Adriatic, (b) Kvarner Bay, (c) Jabuka Pit and (d) deep Adriatic for the 2014-2015 period and four simulations.

All models produce maximum mean salinity in summer and minimum values in December 2014 when ROMS-full shows a sharp minimum up to 37 while the other models have higher values. ROMS-hind and ROMS-full mostly differ from March to August with a positive bias around 0.2 for ROMS-hind whereas ROMS-full shows a sharp minimum in December up to 37. MEDSEA salinity is generally lower than all the other models with a few exceptions.

Second, in the Kvarner Bay subdomain (Fig. S3b), the autumn temperatures are more than 1 °C higher for AdriSC-ROMS and MEDSEA than for ROMS-hind and ROMS-full. ROMS-hind temperatures are generally little higher than ROMS-full over the whole 2015. During winter all simulations give relatively similar results while the differences become larger in spring and summer. AdriSC-ROMS and MEDSEA showed similar temperatures to ROMS-full until April when the biases increased by up to 1-2 °C. Regarding the mean salinity (Fig. S4b), as in the previous subdomain, AdriSC-ROMS showed a large positive bias up to 0.6 as well as a similar timing of the minimums and maximums for all simulations. In the whole 2015, ROMS-full salinities are higher than ROMS-hind, particularly during February and March whereas the MEDSEA salinities are mostly very low compared to other models. The obtained salinities in Kvarner Bay are generally higher than in the northern Adriatic, particularly in late autumn and winter.

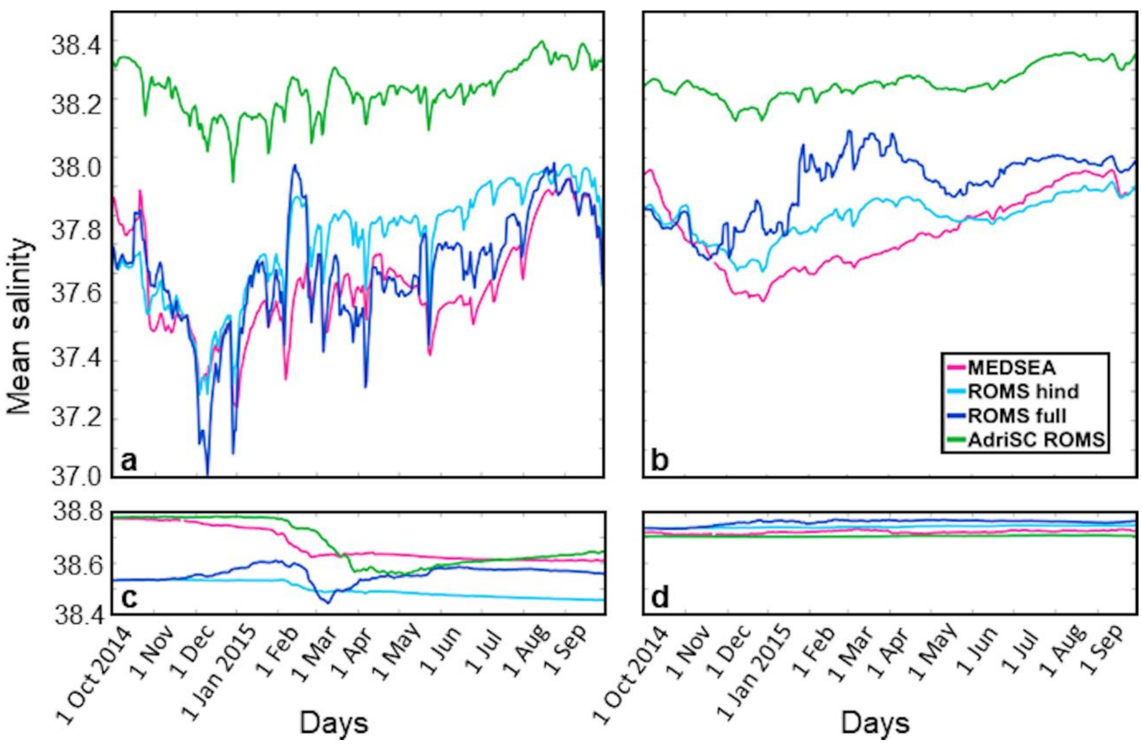

Figure S4. Time series of daily bottom salinity averaged over four subdomains: (a) northern Adriatic, (b) Kvarner Bay, (c) Jabuka Pit and (d) deep Adriatic for the 2014-2015 period and four simulations.

Third, in the Jabuka Pit subdomain (Fig. S3c), the models show the mean temperature quite differently. AdriSC-ROMS gave higher temperatures until March (up to 14.5 °C) after which they decreased to around 12.5 °C in April and then slowly increased. ROMS-full and ROMS-hind show the same temperatures (around 13.8 °C) by December when ROMS-full starts to decrease, reaching a slight peak in February and then continues to decrease almost down to 12 °C. In contrast, ROMS-hind increased up to 14 °C until mid-February and then decreased and remained around 13.5 °C throughout the year. MEDSEA results are similar to ROMS-hind but lower in autumn. Regarding the mean bottom salinity, AdriSC-ROMS gives similar results to MEDSEA but with a month later timing of the minimum. The ROMS-full and ROMS-hind salinities are lower than in other models by around 2.5 in autumn (Fig. S4c). ROMS-full produced an increase in winter, a minimum in March and an increase during spring. ROMS-hind slightly decreased throughout the whole 2015 period.

Lastly, in the deep Adriatic subdomain (Fig. S3d), the mean bottom temperature is nearly monotonic for all the simulations. ROMS-full and ROMS-hind gave the highest values, AdriSC-ROMS showed the lowest temperatures with a 0.5 °C difference and MEDSEA results are slightly higher than AdriSC-ROMS. Mean salinity is similarly produced in the deep Adriatic for all models (Fig. S3d). Larger values are obtained with ROMS-full and smallest values with the AdriSC-ROMS simulation.

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