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Modelling the formation of dense water in the northern Adriatic: Sensitivity studies

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ABSTRACT

This study aims to document the effects of imposing different river runoff forcing and tidal forcing to the dense water formation (DWF) rates and dynamics in a semi-enclosed sea. An extreme DWF episode that occurred in the winter of 2012 in the shallow northern Adriatic Sea during a prolonged cold bora wind outbreak event has been reproduced using a one-way coupled atmosphere-ocean modelling system comprised of the atmospheric Aladin/HR mesoscale model and ocean ROMS model. Three different river runoff forcing and tides/no tides scenarios were imposed on the model. The introduction of tides and river climatology instead of real rivers did not substantially change the modelled DWF transports and volumes, whereas the simulation using the old Raicich climatology resulted in a substantial freshening of the entire Adriatic that reduced or prevented the DWF at sites in the northern and northeastern Adriatic. The necessity of using an up-to-date river runoff climatology to properly reproduce the DWF in semi-enclosed seas is emphasised.

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1. Introduction

The generation of dense waters over a shelf area during winter cold outbreaks is an important source for the ventilation of deep waters, especially in marginal and shelf seas (Ivanov et al., 2004). The Mediterranean Sea is a classic example; shelf-type dense water formation (DWF) occurs over the Gulf of Lions (Millot, 1990; Herrmann et al., 2008) during severe Mistral outbreaks and over the shallow northern Adriatic shelf (Bergamasco et al., 1999; Beg Paklar et al., 2001) during cold northeasterly (bora) wind episodes. The Gulf of Lions dense water flows as a density current along the shelf break and flushes submarine canyons (Ulses et al., 2008) and contributes to the dense water dynamics in the deep Western Mediterranean (Puig et al., 2013). The North Adriatic Dense Water (NAdDW) spreads towards the deep layers and depressions of the middle (Jabuka Pit, 270 m) and south Adriatic (South Adriatic Pit, 1230 m) (Vilibić and Supić, 2005), where it mixes with the Adriatic dense waters generated through deep convection (Gačić et al., 2002) and then flows towards the deep layers of the Eastern Mediterranean (Robinson et al., 2003).

Heat losses that cause the Adriatic DWF were found and modelled to be spatially and temporally very inhomogeneous (Dorman et al., 2006; Janeković et al., 2014) due to the large temporal and spatial variabilities in the bora wind (Grubišić, 2004; Grisogono and Belušić, 2009). The use of European Centre for Middle-range Forecast (ECMWF) products (e.g. ERA-40) for modelling surface forcing (heat losses) substantially influences the DWF rates (Vested et al., 1998) due to large underestimations of the wind strength and related heat losses and the improper representation of the spatial and temporal properties of the bora wind (Signell et al., 2005; Kuzmić et al., 2006; Klaić et al., 2011). To calibrate the model results to the observations, winds have previously been scaled by a factor to increase the heat losses in an area (by a factor of 1.5, Cavaleri and Bertotti, 1997; Zavatarelli et al., 2002; or 20%, Mantziafou and Lascaratos, 2008). However, to properly represent the bora wind and corresponding heat flux, mesoscale local area meteorological models with 1–2 km resolutions are required (Ivatek-Šahdan and Tudor, 2004). These models are operationally available for the Adriatic area (Tudor et al., 2013) and are essential for the proper reproduction of DWF processes and events in the area (Beg Paklar et al., 2001; Janeković et al., 2014).

The Gulf of Lions and the northern Adriatic shelf are also impacted by a substantial freshwater load. The proper introduction of these loads into ocean models is a prerequisite for the proper reproduction of the DWF (Estournel et al., 2009; Schaeffer et al., 2011). This particularly applies to the Adriatic Sea, which is a dilution basin with freshwater inputs that are larger than the freshwater losses (Artegiani et al., 1997). The river runoff climatology

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used in almost all the Adriatic modelling studies in the last two decades is based on a review technical note by Raicich (1994), in which all the available information for both the eastern and western Adriatic rivers were collected and catalogued. However, the use of the Raicich climatology substantially over-freshens the Adriatic (Zavatarelli and Pinardi, 2002; Oddo et al., 2005; Martin et al., 2006; Chiggiato and Oddo, 2008). Different approaches have been tested to reduce the problem, such as scaling the eastern Adriatic rivers (Oddo and Guarnieri, 2011) or adding a constant value to the basin-wide salinity (Benetazzo et al., 2014). Recently, a new climatology for the eastern Adriatic rivers based on hydrological measurements has been compiled (Janeković et al., 2014). When used, this climatology properly reproduces the measurements in the eastern Adriatic coastal area, yet a basin-wide salinity offset is still present in the simulations, which is suspected to arise from the open boundary conditions from the wider ocean model based on the Raicich climatology (Adriatic REGional model – AREG, Oddo et al., 2006).

This paper investigates the effects of posing different river forcings on the DWF production rates and evaluating their effects on the dense water dynamics in a semi-enclosed basin. The proper quantification of the DWF rates is of the utmost importance for a number of basin-wide processes such as the Adriatic-Ionian thermohaline circulation (Orlić et al., 2006; Vilibić et al., 2013), the Bimodal Adriatic-Ionian Oscillation (BiOS) intensity and periodicity (Gačić et al., 2010), ventilation of the deep Eastern Mediterranean layers (Schneider et al., 2014), and dynamics of nutrients and biogeochemical properties (Civitarese et al., 2010; Batistić et al., 2014). The simulations focused on reproducing the extreme winter 2012 DWF event, when the DWF occurred in both the coastal and open northern Adriatic areas (Mihanović et al., 2013). Section 2 describes the modelling systems, sensitivity study setup, and data used for verification and gives a brief description of the DWF event. Section 3 presents a comparison of the model simulations to the observations, their temporal and spatial differences, and changes in the dense water volumes due to different lateral freshwater boundary conditions. Section 4 discusses the results, underlines their importance for future Adriatic modelling studies and lists the major conclusions.

2. Data and methods

2.1. ROMS+Aladin/HR modelling system

The atmosphere-ocean modelling system is comprised of the Aladin/HR mesoscale atmospheric model coupled to the Regional Ocean Modelling System (ROMS). ROMS is a 3-D hydrostatic, nonlinear, free surface, s-coordinate, time splitting finite difference primitive equation model (Shchepetkin and McWilliams, 2005, 2009) that is widely used for ocean modelling and is described at http://www.myroms.org. The model horizontal resolution was set to 2 km. There were 20 vertical sigma levels with increased resolution in the surface layers. The open boundary conditions (free surface, temperature, salinity, and velocity) were taken from the Adriatic REGional model (AREG), which is part of the Adriatic Forecasting System (Oddo et al., 2006) (http://oceanlab.cmcc.it/afs), and imposed at the Otranto Strait (Fig. 1). The Flather scheme and a combination of Orlanski-type radiation boundary conditions with nudging (Marchesiello et al., 2001) were used for barotropic and baroclinic velocities with tracers (temperature and salinity), respectively. A sponge layer of six grid cells was imposed at the south boundary, with a linearly increasing horizontal viscosity and diffusivity. The bathymetry was smoothed using a linear programming technique (Dutour Sikirić et al., 2009) to maintain the stability of the long model run and to reduce the horizontal pressure gradient errors associated with the "s" coordinate used in the vertical direction. The lateral boundary forcing included river discharges from all documented Adriatic rivers and other freshwater sources (Fig. 1, Table 1), all of which were introduced into the model as freshwater point sources, without modifying the temperature field.

Aladin/HR (Tudor et al., 2013) is an operational numerical weather prediction (NWP) model operated by the Meteorological and Hydrological Service of Croatia. Its hydrostatic version was used in this study. For the period of investigation, it was executed twice a day, initialised with a 3DVar run with an 8 km resolution and with 37 vertical sigma layers and boundary conditions from the global ARPEGE model. The wind field forecasts were dynamically downscaled to a 2 km resolution (Ivatek-Šahdan and Tudor, 2004), whereas the other variables were available at a resolution of 8 km and a time step of 3 h. The Aladin/HR surface variables were transferred to the ROMS via bulk parameterisation (Fairall et al., 1996), whereas Aladin/HR itself uses sea surface temperatures from the operational ARPEGE model, which implies that the modelling systems has a one-way coupling architecture.

Additional details of the modelling system and the ROMS and Aladin/HR models can be found in Janeković et al. (2014).

2.2. The modelling exercises

The model was integrated for all the modelling exercises (runs) for a period from 1 January 2008 to 31 December 2012 using initial conditions from the wider AREG model (Oddo et al., 2005), allowing for several years of spin-up before the dense water formation event in the winter of 2012. The sensitivity studies were used to document the differences generated by various parameterisations of the lateral freshwater discharges. Four model runs were executed:

(i) REAL: without tides and with real (measured) river and other freshwater discharges (hydropower plants) where available;
(ii) TIDE: with tides and with real river and other freshwater discharges (hydropower plants) where available;
(iii) CLIM: without tides, using new climatological river and other freshwater discharges, and
(iv) RAICICH: without tides and with the old river climatology based on Raicich (1994).

The REAL model run river setup included:

(a) all available freshwater discharge measurements in the Adriatic basin obtained between 2008 and 2012, including the daily Po and Croatian river discharges (the green circles in Fig. 1; the Po River discharge was distributed according to Syvitski et al., 2005),
(b) real data on freshwater fluxes from the hydropower plants at Dubrovnik/Kupari and Senj (the red circles in Fig. 1),
(c) new climatology of Slovenian rivers (Malačič and Petelin, 2009) (the yellow circles in Fig. 1), and
(d) climatology of Italian and Albanian rivers based on Raicich (1994), Marini et al. (2010) (the blue circles in Fig. 1).

The river flux data along the Croatian coastline used in the REAL model run were made available by the Meteorological and Hydrological Service of Croatia (http://meteo.hr). For (c) and (d), the mean perpetual year daily fluxes were computed and introduced into the model using a spline interpolation between months.

The TIDE model run used the lateral freshwater setup of the REAL model run. Tidal forcing with Chapman and Flather boundary conditions (Chapman, 1985; Flather, 1976) for the free surface and barotropic velocities was imposed on the open boundary on the top of the AREG daily fields, with tidal variability in the free

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