MODELLING STUDIES OF DENSE WATER FORMATION IN THE ADRIATIC SEA DURING THE WINTER OF 2012

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Abstract
The paper overviews modelling efforts used for reproduction of extreme cold outbreak in 2012 in the Adriatic Sea. Focus was directed toward quantification of atmosphere-ocean interaction, dense water formation, effects of preconditioning, introduction of proper river forcing, wave-ocean coupling effects and dense water spreading towards the deep Adriatic. Major achievements of these studies are documented, particularly emphasizing the importance of introducing proper river runoffs along the eastern Adriatic to reproduce dense water formation.

Keywords: Air-sea interactions, Continental shelf, North Adriatic Sea

Dense water formation (DWF) has been known to occur in the northern Adriatic for a long time [1]. However, it occurs only in years with substantial cooling of the whole water column, during wintertime bora outbreaks and preconditioned by a lower-than-usual river discharges. These studies have been reinforced after the winter of 2012, which was characterized by a prolonged and extreme bora wind episode, preconditioned by a dry multi-month conditions, altogether resulting in an extensive DWF event encompassing both open and coastal parts of the northern Adriatic and ending in record-breaking densities (up to 1030.6 kg/m^3). Figure 1 shows bottom potential density anomaly distribution modelled at the end of the DWF episode.

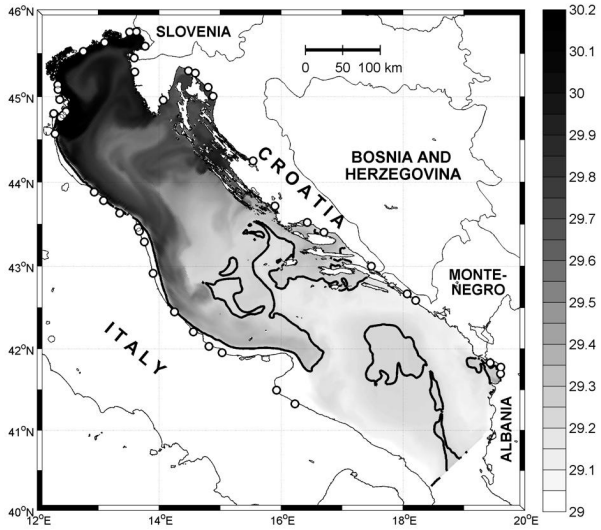

Fig. 1. Potential density anomaly (PDA, in kg/m^3) at the lowest sigma layer modelled by ROMS/ALADIN one-way high-resolution modelling system on 14 February 2012 (after [4]). Thick line stands for PDA>29.2 kg/m^3. Circles denote river sources used in the model.

Several research studies carried out immediately after the event were mostly focused on observations, including its unusual capture by an ARGO profiler [2]. The first modelling study [3] quantified the DWF volumes; however, the computations were based on old river climatology, known to substantially exaggerate the Adriatic freshwater budget. An improper introduction of rivers along the eastern Adriatic coastline was found to prevent the DWF in the eastern coastal area [4]. The DWF was modelled there for the first time when the Raicich river climatology was substituted with recently measured river discharge data. It seems that the eastern coastal area contributed by 40% to the overall dense water budget in the northern Adriatic [5]; however, this result may be a consequence of the exceptional year, both by heat losses and by preconditioning. Therefore, an "ordinary" DWF winters should be investigated to show if this area is a common DWF area or it is excited only during anomalous years.

The densest waters were formed in the shallow Gulf of Trieste [6]; however, the largest cooling and heat losses (up to 2000 W/m^2) were documented in a deep channel area off Velebit Mountain [5]. From a modelling perspective, it seems that the initialization of the atmospheric models by sea surface temperature fields strongly affects the computations of atmosphere-ocean heat exchange and in turn DWF rates [7]. Also, the wave-induced forcing was found to have a substantial role in DWF and dense water spreading phases [8]. The DWF event was strong enough to substantially impact the bottom of the deep South Adriatic Pit [9], replenishing old waters and triggering a modulation of the saw-tooth pattern, which normally has a period of 5 to 10 years.

Summarily, the extreme DWF event of 2012 is the most comprehensively researched dense water event in the Adriatic Sea so far, due to both availability of in situ data and to maturity of atmospheric and ocean models.

References
1 - Zore-Armanda M. 1963. Les masses d'eau de la mer Adriatique. *Acta Adriat.*, 10: 5-88.
2 - Vilibic I. and Mihanovic H., 2013. Observing the bottom density current over a shelf using an Argo profiling float. *Geophys. Res. Lett.*, 40: 910–915
3 - Mihanovic H., Vilibic I., Carniel S., Tudor M., Russo A., Bergamasco A., Bubic N., Ljubesic Z., Vilicic D., Boldrin A., Malacic V., Celio M., Comici C. and Raicich F., 2013. Exceptional dense water formation on the Adriatic shelf in the winter of 2012. *Ocean Sci.*, 9: 561-572.
4 - Vilibic I., Mihanovic H., Janekovic I. and Sepic J., 2016. Modelling the formation of dense water in the northern Adriatic: sensitivity studies. *Ocean Model.*, accepted
5 - Janekovic I., Mihanovic H., Vilibic I. and Tudor M., 2014. Extreme cooling and dense water formation estimates in open and coastal regions of the Adriatic Sea during the winter of 2012. *J. Geophys. Res.*, 119: 3200-3218.
6 - Raicich F., Malacic V., Celio M., Giaiotti D., Cantoni C., Colucci R.R., Cermelj B. and Pucillo A., 2013. Extreme air-sea interactions in the Gulf of Trieste (North Adriatic) during the strong Bora event in winter 2012. *J. Geophys. Res.*, 118: 5238-5250.
7 - Davolio S., Stocchi P., Benetazzo A., Bohm E., Riminucci F., Ravaioli M., Li X.M. and Carniel S., 2015. Exceptional Bora outbreak in winter 2012: Validation and analysis of high-resolution atmospheric model simulations in the northern Adriatic area. *Dyn. Atm. Oceans*, 71: 1-20.
8 - Benetazzo A., Bergamasco A., Bonaldo D., Falcier, F. M., Sclavo M., Langone L. and Carniel S., 2014. Response of the Adriatic Sea to an intense cold air outbreak: Dense water dynamics and wave-induced transport. *Prog. Oceanogr.*, 128: 115-138.
9 - Bensi M., Cardin V., Rubino A., Notarstefano G. and Poulain P.-M., 2013. Effects of winter convection on the deep layer of the Southern Adriatic Sea in 2012. *J. Geophys. Res.*, 118: 6064-6075.