Marine Geology 375 (2016) 44–63

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Off-shelf fluxes across the southern Adriatic margin: Factors controlling dense-water-driven transport phenomena

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ARTICLE INFO

Article history:
Received 1 October 2014
Received in revised form 21 August 2015
Accepted 25 August 2015
Available online 29 August 2015

ABSTRACT

The northern Adriatic Sea is a basin where dense shelf waters form during winters if the following favorable conditions are attained: high salinities, mainly related to low river water discharge (Po river in primis) during fall season, and strong heat fluxes induced by cold and dry Bora wind events blowing from north-east. Extremely favorable conditions to Northern Adriatic Dense Waters (NAdDW) formation characterized winter 2012 when, following several months of low Po river runoff, a strong event of Cold Air Outbreak (CAO) occurred from the end of January until mid-February. Consequently, the mean temperature of northern Adriatic waters dropped to about 6°C and exceptional densities (potential density anomaly locally exceeding 30.0 kg m^{-3}) were reached. The production and spreading mechanisms of dense water in the Adriatic Sea have been modeled by means of the COAWST (Coupled-Ocean–Atmosphere-Wave-Sediment-Transport) modeling system. The model builds upon a high-resolution (1 km spaced horizontal grid), fully 3-D primitive equations hydrodynamic model coupled with a phase-averaged wave model and sediment routines, and is driven by simulated atmospheric forcings.

The dataset used to assess model outputs relies on the measurements acquired during the dedicated field campaigns “Operation Dense Water”, a set of two rapid response cruises carried out in southern Adriatic during winter 2012, and by five mooring arrays deployed in the Southern Adriatic Margin (SAM) that allowed the continuous acquisition of temperature, salinity, currents and suspended matter samples.

Results from the integrated data-model approach suggest that the NAdDW propagates along the shelf to the southern basin following both a shallower vein and a deeper stream, with a process characterized by a strong variability (mean value of 0.31 Sv with peaks rapidly growing in the first weeks after the CAO up to 2.19 Sv). Additionally, COAWST capability to couple different numerical models allowed to disentangle the relative importance of aspects on dense water generation, mixing and spreading, demonstrating how coupled runs can lead to volumes up to 50% larger with respect to uncoupled simulations. Additional light is shed on the transport pathways off the shelf and on possible sediment transport phenomena in the area, in this benefiting from an unprecedented spatial resolution and a new bathymetry reflecting very high resolution data acquired via multi-beam techniques. Although dense water propagation appears as a relatively large-scale process involving the whole western side of the SAM, topographic local discontinuities and seabed slopes appear crucial in triggering descent and governing flow patterns. The presence of suspended sediment along the water column, despite not significantly influencing the overall fluxes across sections, is responsible of pulling part of the veins towards deeper zones.

1. Introduction

The Adriatic Sea (Fig. 1) is well known as a natural laboratory to investigate many oceanographic processes (Signell et al., 2005), among which the production of dense shelf waters and its spreading dynamics (Bergamasco et al., 1999). The northernmost area of this marginal semi-enclosed basin, located in the northern Mediterranean (extending south-eastward, approximately 200 km wide and 800 km long) is constituted by a shallow continental shelf (depths in the order of few tens of meters) and is occasionally exposed to intense winds blowing mainly from north-east (Bora; see Dorman et al., 2006) or from south-east (Scirocco; see Bignami et al., 2007). This area is also characterized by high freshwater inflow from the largest river of the basin (Po river, an yearly averaged value of 1500 m^3 s^{-1}, Raicich, 1994; Falcieri et al., 2014). When a series of processes made possible by favorable conditions take place, the Northern Adriatic (NA; a list of abbreviations is presented in Appendix A) becomes a formation site of the so-called North Adriatic Dense Water, NAdDW (Bergamasco et al., 1999; Vilibic and Orlic, 2001; Benetazzo et al., 2014). Key factors are

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http://dx.doi.org/10.1016/j.margeo.2015.08.016
0025-3227/

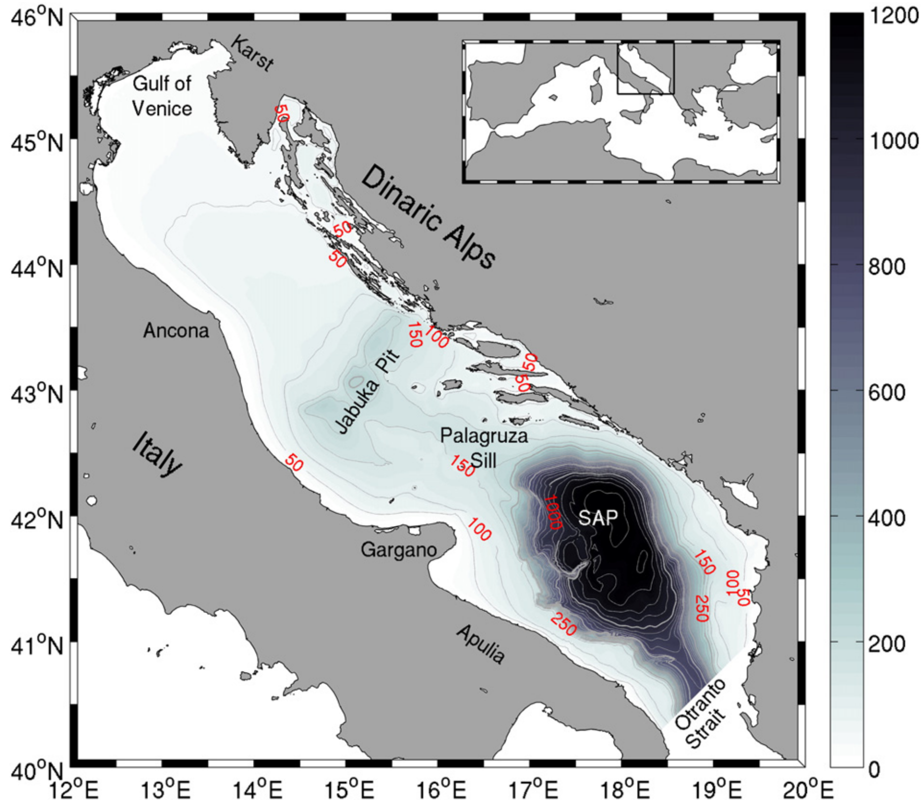

Fig. 1. Adriatic Sea bathymetry and its position in the Mediterranean basin (upper-right panel). Bathymetric contours depicting 50, 100, 150, 250 and 1000 isobaths.

low air temperatures induced by violent, cold and dry Bora wind events (Dorman et al., 2006; Boldrin et al., 2009) and associated high salinities (Raicich et al., 2013),the latter being a combined result of evaporation increase due to the winds and low river water discharge (mainly the Po river) during the previous months. To complicate the picture, small river discharges can permit the intrusion in the Gulf of Venice of saltier and warmer water masses formed in the Levantine basin (called Modified Levantine Intermediate Waters, MLIW) and entering the Adriatic Sea through the Otranto Strait, in this providing an additional preconditioning factor for the NAdDW generation in the subsequent months.

In any case, at the appearance of these intense cooling episodes (Cold Air Outbreak, CAO), ocean-to-atmosphere heat fluxes can reach values up to 1000 W m^{-2} (Supić and Orlić, 1999; Boldrin et al., 2009) and waters reach a PDA exceeding 29.6 kg m^{-3} (Bergamasco et al., 1999; Vilibić and Supić, 2005) and up to 30.0 kg m^{-3}, as reported by Supić and Orlić (1999).

After the pioneering quantitative works of early 1980s (Artegiani and Salusti, 1987), several authors (Artegiani et al., 1997; Vilibić and Supić, 2005; Querin et al., 2013; Janeković et al., 2014; Marini et al., 2016–in this issue) discussed how the NAdDW migrates towards and across the mid-Adriatic Jabuka pit (a.k.a. Pomo pit) system as an underflow vein along the isobaths (see Fig. 1) at a depth of 50–150 m. Dense waters that reach the shelf break hence progressively move along the continental margin and eventually descend towards the lower slope and the abyssal plain by successive steps, that may be happening as cascading events (Carniel et al., 2012). In doing this, dense waters generally tend to flow along topographic features as a quasi-geostrophic flow, depicting paths that are consequence of complex processes, getting diluted and mixed by entrainments of ambient waters (modifying their temperature and salinity) until they reach a neutral density level or fill topographic depressions (Canals et al., 2006; Legg et al., 2006) from which they can, eventually, overflow.

Due to its central role in controlling abyssal heat, nutrients and sediment transport as well as carbon export into the deep ocean, the complex and fascinating processes controlling the descent of dense waters off the continental shelf have been receiving growing attention in the recent past, also in a multi-disciplinary context. Excellent examples can be found in other geographic locations and under different driving conditions and morphological settings, where sometimes the pivotal role of deep submarine canyons is added to the picture (Canals et al., 2006; Puig et al., 2013; Ulses et al., 2008; Ivanov et al., 2004). Similarly, existing canyon systems within the Southern Adriatic Margin (SAM), such as the Bari Canyon System (BCS), can intercept dense waters and sediments (derived also from Po and southern Apennine rivers) and convey this material into the deep South Adriatic sub-basin (Trincardi et al., 2007a; Turchetto et al., 2007; Rubino et al., 2012).

Taking advantage of the favorable meteo-ceanic and morphological characteristics of the Adriatic and relying on recent dedicated sea campaigns, in situ data, and numerical tools of increasing complexity recalled below, physical oceanographers have been describing and interpreting the main characteristics and patterns of typical dense waters dynamics (see for instance Bergamasco et al., 1999; Vilibić and Supić, 2005; Carniel et al., 2012; Querin et al., 2013; Rice et al., 2013).

At the same time, with the help of high-resolution multibeam acquisition and in situ mooring data, marine geologists have been showing how dense water currents are associated to Southern Adriatic bedform patterns (Trincardi et al., 2007b; Verdicchio and Trincardi, 2006) and high-energy activity in the BCS and in the continental margin structures located south of it (Fig. 2 and Foglini et al., 2016–in this issue). In this region, the modeling effort of Rubino et al. (2012) explored the near-bottom circulation with a reduced-gravity model, although their considerations are admittedly limited by the use of a too coarse bathymetry (2 min resolution) and by a numerical approach not accounting for the dynamics influenced by atmospheric interaction.

Starting from this background information, the extremely favorable conditions to intense NAdDW formation that characterized the winter 2012 in the NA provided a strong motivation for a holistic effort towards a more thorough understanding of its bottom boundary layer