Marine Geology 375 (2016) 5–14

Contents lists available at ScienceDirect

Marine Geology

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

Role of the Mid-Adriatic deep in dense water interception and modification

Mauro Marini [a,*], Vittorio Maselli [b], Alessandra Campanelli [a], Federica Foglini [b], Federica Grilli [a]

[a] National Research Council (CNR), Institute of Marine Science (ISMAR), Ancona, Italy
[b] National Research Council (CNR), Institute of Marine Science (ISMAR), Bologna, Italy

A R T I C L E I N F O

Article history:
Received 10 December 2014
Received in revised form 19 August 2015
Accepted 24 August 2015
Available online 29 August 2015

Keywords:
Nutrate
Dissolved oxygen
bottom water
contourite drift
Adriatic sea

A B S T R A C T

This study set out to gain insights into: i) the route of dense water (DW), which leaves a morphological signature including large-scale erosion, moats, and contourite sediment drifts, and ii) the physical and chemical modifications undergone by Northern Adriatic Dense Water (NAdDW) due to its entrapment in the Mid-Adriatic Deep (MAD) for one or more years, which leads to biogeochemical transformation into Mid-Adriatic Dense Water (MAdDW), a less dense and colder water mass with reduced oxygen content as a result of prolonged biological consumption. The paper provides an accurate description of how NAdDW, on its way to the Southern Adriatic basin, mixes with MAdDW on Palagruža Sill. Analysis of water column data (CTD) collected in spring 2005 and 2012 showed that part of the NAdDW flowing down the Western Adriatic shelf swerves left, splitting into a branch that fills the western MAD pit and another flowing along the 170 m contour towards the eastern pit and then south through Palagruža Sill. Due to the density difference, the recently formed NAdDW flows as a bottom-trapped current underneath the older MAdDW, lifting and pushing it over Palagruža Sill, thereby promoting water exchange among the MAD pits. The two water masses eventually mix as they flow over Palagruža Sill, in proportions that depend on NAdDW volume and the changes undergone by MAdDW, thus generating a new mixed bottom-flowing DW with a distinctive chemical signal. The bottom water pattern disclosed by CTD transects is consistent with seafloor and sub-seafloor morphologies detected on high-resolution seismic profiles, which show both erosion and deposition features along bottom water routes. Moreover, confinement of the mixed water within structural highs as it flows southward through Palagruža Sill promotes formation of shallow water contourites and giant sediment drifts, demonstrating a significant role for topography in the flow of all Adriatic DW.

1. Introduction

The formation and flow of Northern Adriatic Dense Water (NAdDW) exerts a strong impact on Central Mediterranean oceanography, Adriatic shelf and deep basin morphology, and stratigraphic architecture. The Central Adriatic is a transition zone between the shallow Northern Adriatic shelf and the deep Southern Adriatic basin. It is characterized by three pits collectively called Mid-Adriatic Deep (MAD), whose depth ranges from 240 to 270 m. Such complex morphology, providing areas where dense water (DW) is trapped for one or more years, significantly affects the NAdDW route. In this area, Palagruža Sill (170 m deep) acts as a spill area between the three pits and the Southern Adriatic basin. DW formation and flow have been attracting considerable interest worldwide (Shapiro and Hill, 1997; Shapiro, 2003; Harris et al., 2001), and play a large role also in the Mediterranean Sea. The process exerts a strong impact on seafloor morphology and affects nutrient and organic matter export to the deep sea (Canals et al., 2006, 2009). The Adriatic Sea (Fig. 1) has long been known to enable DW generation (Gaćić et al., 2001), due especially to the strong, cold and dry winter NE winds (Bora) that blow on the northern shelf, occasionally reaching the Middle and Southern Adriatic. Bora events (Lee et al., 2005; Jeffries and Lee, 2007; Raicich et al., 2013) influence the hydrology of the shallow Northern Adriatic shelf, which is otherwise predominantly affected by riverine inputs. The River Po provides the largest outflow with average freshwater discharge about 1500 $m^3\ s^{-1}$ and maxima up to 10,000 $m^3\ s^{-1}$ (Supić and Orlić, 1999; Nittrouer et al., 2004). Very strong, cold, and dry winds combined with a low discharge rate contribute to the formation of extremely dense NAdDW (Hendershott and Rizzoli, 1976; Orlić et al., 1992; Vilibić and Supić, 2005). Strong Bora events result in surface cooling which usually precondition the North Adriatic about 2 months prior to NAdDW generation events (Vilibić, 2003), and vertical mixing due to marked wind inhomogeneity in the region where NAdDW is generated. In such environmental situation, large freshwater inputs can lower salinity in the Northern Adriatic and inhibit subsequent DW formation (Campanelli et al., 2011).

NAdDW is the densest water mass formed in the Mediterranean (Franco et al., 1982 and Malanotte-Rizzoli et al., 1997), and has been estimated to account for up to 20% of the total Adriatic deep water volume (Vilibić and Orlić, 2002). Its temperature (T), salinity (S) and density (σ_t)

* Corresponding author.
E-mail address: m.marini@ismar.cnr.it (M. Marini).

http://dx.doi.org/10.1016/j.margeo.2015.08.015
0025-3227/

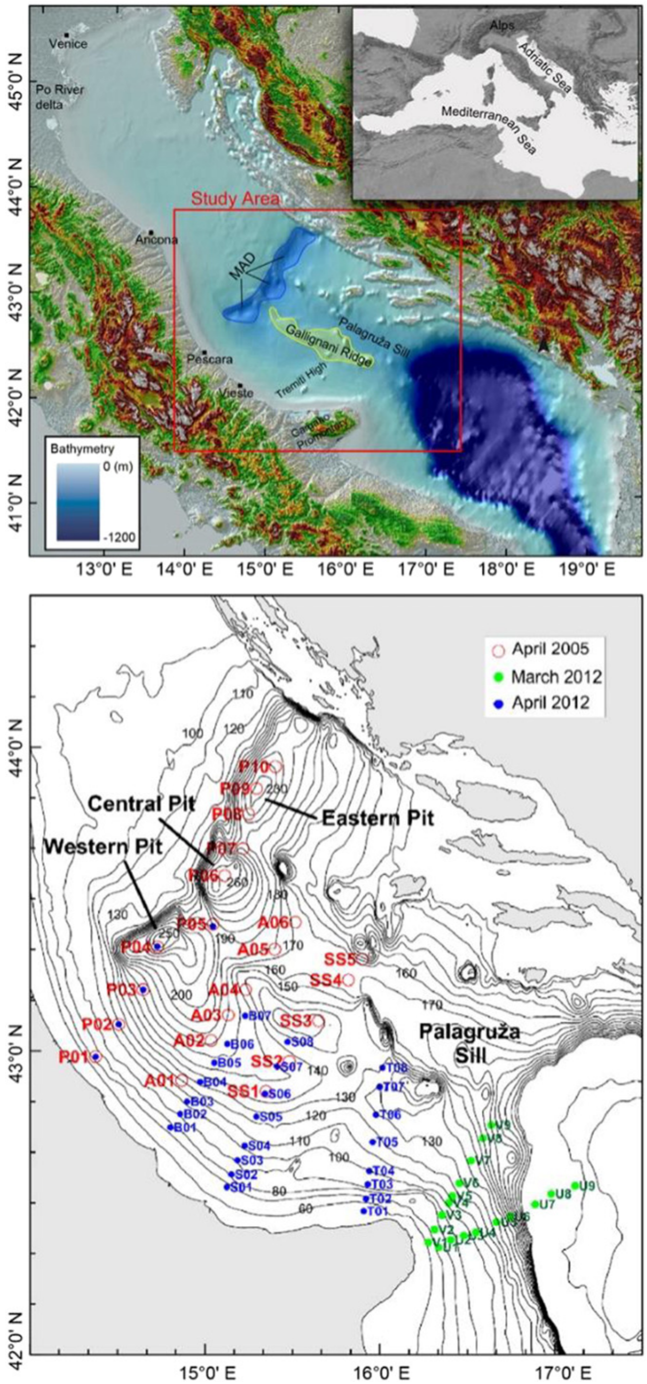

Fig. 1. Top: 3D bathymetry of the Adriatic Sea and main morphological elements. Red box: study area. The Adriatic is the only area in the Mediterranean, where DW forms, in which a set of depressions trap the shelf DW temporarily (from one to several years), transforming and releasing it when newly formed deep water replaces it. Bottom: Bathymetry of the MAD (contour interval every 10 m until 200 m and every 100 m in deeper water. Geographical position of CTD casts during the oceanographic surveys of April 2005 (red circles), March 2012 (green dots), and April 2012 (blue dots).

range from ~9.0 ≤ T ≤ 11.35 °C, ~38.30 ≤ S ≤ 38.50, and ~29.35 ≤ σ_t ≤ 29.51 kg m^{-3} (Orlić et al., 1992; Russo and Artegiani, 1996, Supić and Vilibić, 2006; Wang et al., 2006). Once formed, NAdDW flows as a bottom-trapped density current in SE direction (Franco et al., 1982; Artegiani and Salusti, 1987, Gačić et al., 2001), mixing on the way with warmer and saltier ambient water masses, which raise its temperature and salinity. Approximately a month later NAdDW fills the MAD (Artegiani et al., 1997b). It reaches the area of Bari Canyon (Southern Adriatic), about 2 months after its generation (Vilibić and Orlić, 2002), or faster in colder winters, when larger DW amounts are generated (Benetazzo et al., 2014). In this area NAdDW exerts a strong influence on topography due to turbulent mixing, and sinks to the bottom (Bignami et al., 1990; Manca and Giorgietti, 1999). However, few data are available on the role of slope and shelf basins as areas of temporary storage for shelf-formed DW and on its route to the deep sea (Harris et al., 2001).

Mid-Adriatic Dense Water (MAdDW) is characterized by a climatologically average T of 11.62 ± 0.75 °C, an S of 38.47 ± 0.15, and a σ_t > 29.2 kg m^{-3} (Artegiani et al., 1997). It forms in the Mid-Adriatic and remains trapped throughout the year or longer in the bottom layer of the MAD (Marini et al., 2006). When large MAdDW volumes are generated, part of the water mass is believed to overflow and move down in SE direction. Analysis by Vilibić et al. (2004) of Northern and Mid-Adriatic thermohaline data when a dense NAdDW (σ_t > 29.7 kg m^{-3}) formed in late January/early February 1999, has demonstrated T, S and σ_t changes in the MAD and Palagruža Sill sections a mere month after the major DW generation event in the Northern Adriatic, documenting NAdDW passage. NAdDW preconditioning, generation, and spread have been reviewed by Vilibić and Supić (2005). Despite a number of uncertainties, these two studies have for the first time allowed tracking NAdDW flow patterns using experimental and modeling approaches. In particular, on its way down to the MAD and the Southern Adriatic, NAdDW was seen to replace older water, carrying oxygen and nutrients to the deep layers.

This paper investigates the exceptional DW formation event that occurred in the Northern Adriatic in winter 2012 focusing on the Mid-Adriatic and using a dense grid of hydrological data. The work is to be viewed in conjunction with other studies of DW flow towards the MAD. In fact, Vilibić (2003) documented the NAdDW formation mechanism in the Northern Adriatic shelf and its flow to the Middle and South Adriatic using a diagram (Fig. 1 in Vilibić, 2003); Janekovic et al. (2014) applied a numerical model to investigate its preconditioning and generation phase and its spread to deep basins, including the routes of bottom density currents, in winter 2012; Rice et al. (2013) focused on how NAdDW mixed with other water and changed as it flowed south from Gargano to the Bari area in spring 2009, when DW generation in winter had been limited; Vilibić and Mihanović (2013) documented the bottom density current using an Argo profiling float over the MAD; finally, Benetazzo et al. (2014) documented how, during the major 2012 event, DW flowed southward across the continental shelf at the beginning of the cooling event, even before completion of Northern Adriatic shelf cooling.

Measurement of water and nutrient fluxes in the different water masses across the Vieste (Gargano) – Split transect has shown that the nutrient flux towards the Southern Adriatic was mostly due to NAdDW flowing along the Italian bottom slope and to MAdDW flowing through the deepest passage in the centre of Palagruža Sill (Grilli et al., 2013).

According to the modeling study by Wang et al. (2006), the NAdDW had a T < 11.35 °C, a S < 38.30 and a σ_t > 29.2 kg m^{-3}, with marked spatial variability. The time needed for this water mass to reach the Southern Adriatic basin has been estimated to be 2–3 months (Vilibić, 2003), but the exceptional DW formation event in the Northern Adriatic in winter 2012 allowed demonstrating that it was in fact shorter (Mihanović et al., 2013; Vilibić and Mihanović, 2013 and Benetazzo et al., 2014). According to Janekovic et al.'s (2014), NAdDW reached the MAD about a month from its formation, while Bensi et al. (2013) recorded its arrival in the Southern Adriatic basin about two months later. After the cooling and cascading phases, at the beginning of March 2012 the NAdDW entrapped in the deepest part of the MAD (a layer up to 100 m thick) was characterized by a markedly lower T (~1 °C) with respect to summer 2011 (Bensi et al., 2013).