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Preface

Cascading dense shelf-water during the extremely cold winter of 2012 in the Adriatic, Mediterranean Sea: Formation, flow, and seafloor impact

1. Introduction

Three sites of dense water formation significantly impact the deep circulation of the Mediterranean Sea. These sites are the northernmost continental shelves of the basin: the Gulf of Lion, the Northern Adriatic, and the Northern Aegean (Canals et al., 2009). While the Gulf of Lion responds rapidly to the formation of dense seawater (DSW) through the flushing of its western portion and adjacent slope canyons during cyclogenesis conditions (Canals et al., 2006; Puig et al., 2013), the Adriatic is elongated southeast-ward (800 km) and acts as a buffered system where the propagation of DSW requires at least several weeks to reach the southern slope where cascading occurs. Several hypotheses and observations have been proposed (e.g., Bignami et al., 1990a, 1990b; Vilibić and Supić, 2005). However, until a few years ago, the Adriatic region lacked a comprehensive, synoptic view of an event of DSW formation, its flow and modification along the shelf, and its consequent downslope cascading.

The present special issue reports results from the impact of a major cold air outbreak on the formation of dense shelf water in the Adriatic. This occurred in February 2012, when the European region experienced a 2 weeks severe cold spell that heavily impacted the Northern Adriatic. This cold spell was accompanied by the onset of severe north-easterly Bora winds (Raicich et al., 2013), blowing almost continuously, and being intermittently reinforced by cyclogenesis in the western Mediterranean. A significant heat loss took place in the basin and a substantial decrease of Adriatic surface temperature down to temperatures as low as 3–6 °C (Fig. 1) while the shallow Lagoon of Venice partially froze (Fig. 2). The cold outbreak, the severe cold and dry Bora flow, accompanied by the very limited discharge of the Po River in the preceding autumn, caused the formation of extremely dense shelf water (Mihanović et al., 2013).

The dense shelf water mass moved southward along the Italian coast (Fig. 3), following the seafloor topography in near geostrophic equilibrium. Part of the dense water mass filled a 250 m deep depression located in the middle Adriatic serving as a place of temporary storage. Typically, the dense shelf water reaches the Southern Adriatic in several months (Vilibić and Supić, 2005) where it sinks through successive cascading events (see Supplementary data S1), though, recently, Benetazzo et al. (2014) estimated that the southeast-ward flow of the newly formed DSW in 2012 took place in pulses with a first major event as early as three weeks after the onset of the cold air outbreak through a barotropically adjusted jet propagating to the south with an average speed of as much as 30 cm/s. Once beyond the shelf edge, the dense bottom water impacts both the submarine canyon cutting the shelf break off Bari (Bignami et al., 1990a; Turchetto et al., 2007; Trincardi et al., 2007a) and on the open slope north of it (Trincardi et al., 2007b); in addition, during its descent, the DSW cascade entrains Levantine Intermediate water (LIW), becoming thus warmer and saltier. These previous papers hint to a focusing of bottom currents along paths that at least in part reflect the pre-existing seafloor morphology; on the other hand, the same papers hint to a significant role of the dense shelf waters in shaping, at least locally, the sea floor morphology.

2. Design of the rapid response experiment and scientific outcomes

Rapid response experiments are crucial for several scientific and practical reasons, e.g., capturing extreme events to improve our understanding of natural systems in a global-change scenario, evaluating their impact on marine systems and the biota to address issues related to fluctuating fish stocks (Company et al., 2008) as well as C export and sequestration in the deep sea (Canals et al., 2006). As a contribution to the Italian research program RITMARE (Italian research for the sea), we set up a rapid response experiment by exploiting expertise spanning from oceanographic modeling, physical and biogeochemical oceanographic observations to sedimentological analyses of the erosional and depositional bedforms. The results of this experiment show that choosing the sites for the rapid mooring deployment based on the detection of erosional and depositional seafloor bedforms proved functional and resulted in a cost-effective choice of a limited number of significant sites. In fact, extensive morpho-bathymetric and seismic surveys on the Southern Adriatic margin (e.g., Trincardi et al., 2007a, 2007b, and 2014) pointed out sedimentological features testifying a strong interaction between bottom currents and seabed morphology with a suite of depositional and erosive structures (Foglini et al., 2016–in this issue). The location of the mooring sites was eventually chosen based on an integration of modeling-based predictions and geology-driven inferences defining areas where the passage of dense shelf water was most prospective.

A few weeks after the cold spell, the Southern Adriatic was extensively sampled by the R/V Minerva Uno (leg1, 23 March – 2 April 2012) and R/V Urania (leg2, 14–20 April 2012) with CTD-rosettes equipped with additional sensors for fluorescence, dissolved oxygen, LADCP as well as ship-borne ADCP and XBTs (see Chiggiato et al., 2016–in this issue). Several water samples for biogeochemical measurements were collected at the same time. In addition to the 3D snapshots carried out during the two ship surveys, five moorings (see Langone et al., 2016–in this issue) continuously measured temperature, salinity, currents, and downward particle fluxes by means of SBEs, ADCPs and automatic sediment traps. Overall, the observations gathered matched real-time modeling simulations. The dense shelf-water plumes have

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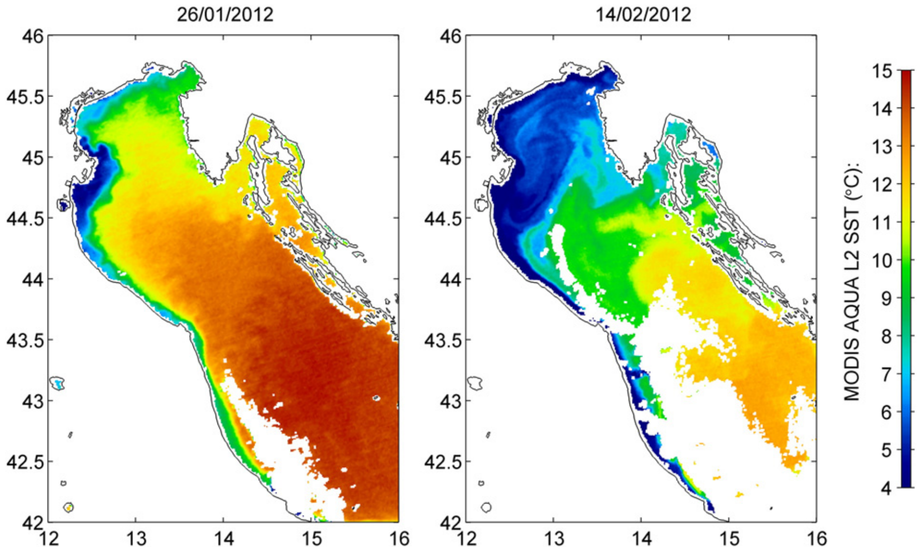

Fig. 1. MODIS L2 Sea surface temperature in the Northern Adriatic right before the onset of the cold spell (26 Jan 2012, left panel) and soon after the end (14 Feb 2012, right panel). MODIS data are courtesy of Ocean Color Web, NASA Goddard Space Flight Center. Data reprocessing is courtesy of Federica Braga (CNR-ISMAR).

been observed in the open slopes of the northern sector of the Southern Adriatic and traced southward to evaluate how they impacted a 100 km slope stretch all the way to the Bari canyon. Speed and direction of currents at the bottom were consistent with the bedform distribution (also in the deepest part of the basin), and events have been recorded to occur with multiple pulses of cascading events (variability at scale of a few days) and reaching speedabove 70 cm/s.

The present special issue gathers eight contributions covering complementary aspect of this multifaceted process of DSW cascading. The formation and along-shelf advection of DSW, quantifying its timing, defining its path, has been tackled both via observations (Chiggiato et al., 2016–in this issue) and modeling (Carniel et al., 2016–in this issue). In particular, Chiggiato et al. (2016–in this issue) pointed out the submesoscale characteristics of the dense water flow and cascading, supporting numerical modeling evidences (Rubino et al., 2012; Carniel et al., 2016–in this issue) that downslope flow occurred in several locations and with diverse dynamical characteristics. Langone et al. (2016–in this issue) shed new light on the inter-annual variability on the cross–shelf particle fluxes. In particular, it emerged that DSW cascading is a first order control on the particle flux, while storm-driven sediment transport is relevant only occasionally. In addition, the total mass flux did not show decline toward the deep ocean, but rather spatial differences mainly associated to local topographic features, i.e., preferred corridors to the deep sea. The impact on the sea floor and the interaction with the pre-existing seafloor morphology is discussed in Marini et al. (2016–in this issue) regarding the slope basin located half way between the formation zone in the north and the slope in the south. This study provides an analysis on the role of large bathymetric depressions (e.g., the Middle Adriatic Pit, a.k.a. Jabuka Pit) on the NAdDW routes combining geomorphological evidences (scours, giant drifts, contourites), seismic stratigraphy and physical–chemical data, discussing in detail the path followed by the main bottom water masses. The impact of the morphologically articulated southern slope where the presence of reliefs of different origin forces the bottom-water flows to veer and, locally, accelerate, is discussed in Foglini et al. (2016–in this issue) and the DWS in its turn concurs to a "restyling" of the submarine landscape. Alongside this effort, it became that introducing high-resolution bathymetric constraints is important in modeling the flow of the bottom-trapped DSW. Bonaldo et al. (2016–in this issue), using a high-resolution, state-of-the-art numerical ocean model, in fact discussed how the bathymetry plays a primary role in constraining small-scale down-flow dynamics. Similar processes are reported in two additional contributions (Tripsanas et al., 2016–in this issue; Bellacicco et al., 2016–in this issue). These documented the impact of dense shelf water formed in the northern Aegean Sea on the continental slope where large-scale sediment drifts and bedforms are documented by high-resolution seismic data. In particular, the stratigraphic work by Tripsanas et al. reports intervals of intensification in the bottom current activity both during the coldest intervals of the last glacial cycle (the Younger Dryas and the Heinrich event cold spells) and in the Holocene when the flooding of the continental shelf enlarges the shallow-water area where dense waters can form through winter cooling with a mechanism similar to that of the Northern Adriatic Sea (Verdicchio et al., 2007).

Fig. 2. View from a public transport boat of the Lagoon of Venice with floating "pancake" ice (courtesy of Andrea Bergamasco, CNR-ISMAR).

Finally, the volume investigates the impact of dense-water-formation process in subtracting a C-enriched water mass thereby potentially hampering, to some extent, the on-going acidification of the Mediterranean waters. To this regard, Cantoni et al. (2016–in this issue) showed that during DSW production, absorbed CO_2 was 3 times larger in 2012 compared to an average year (2008). NAdDW plumes, intercepted during the field campaign in 2012 in the southern Adriatic, were characterized by low pH, high total alkalinity and dissolved inorganic carbon, although diluted, along the advection southward, with respect to the source water mass in the Northern Adriatic. Thus, during and soon after the cold spell, the Northern Adriatic acted as a sink of CO_2, flushed away by the dense bottom