Interdisciplinary investigation of off-shelf transport in the southern Adriatic Sea: the role of Bari Canyon

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1. Introduction

Submarine canyons (SC) are submarine valleys with walls of variable steepness, often characterized by tributaries, deeply incising the sea floor of the continental shelf/slope, and mostly continuing seaward (Shepard and Dill, 1966; Hickey, 1995). The submarine canyons of the Mediterranean Sea are more ubiquitous than perceived, where the availability of recent investigation techniques yields more than 500 structures (Harris and Whiteway, 2011; Harris and Macmillan-Lawler, this volume).

Historically, the first motivating reasons of interests for SC exploration trace back to economic reasons, such as exploitation of fossil energy reservoirs or sand deposits, and engineering pipelines deployments; more recently, the scientific community realized that these deep regions play a key-role in ecosystem functioning (Würtz *et al.*, 2012) both for a series of physical, biological, chemical aspects (reflecting on biodiversity, climate change issues and fisheries), and for their role in connecting continental shelves to deep ocean regions as well (and possibly vice-versa).

Indeed these deep incisions within the sea bottom act as tipping-points and natural accelerators, conveying relatively large water masses from “shallow” regions to “deeper” ones in cascading areas, whereas in other areas they are often the trigger of upwellings. In both cases, they reduce the residence time, increase the mixing rates, allow organic and inorganic particles to be flushed and/or resuspended, so enhancing local productivity and boosting food webs.

Although recent efforts have clearly demonstrated the pivotal ecological role of Mediterranean SC, resulting in an increased number of studies (e.g. Della Tommasa *et al.*, 2000; Boero, 2015), much remains to be understood about their functioning mechanisms. Reasons are multiple, among which technical difficulties in operating and obtaining measurements in deep marine regions, different jurisdictions on waters and military use of bottom areas. In addition to this, the intrinsically interdisciplinary approach required to fully understand the complexity and ecological role of submarine canyons has been hampered by a long-lasting reductionist approach, based on the processes division into “scales” (both spatial and temporal).

In the Mediterranean, several large canyon systems are hypothesized to have been formed at the time of a drastic sea-level lowering in the late-Miocene (Messinian), and ensuing refill, while many others, typically smaller in extent, reflect the evolution of continental margin during the Quaternary. In the latter case, global sea level oscillations played a key role in connecting the head region of several canyons to river valleys down-cutting the entire continental shelf at low stands. In such cases, canyons that have been connected to a fluvial feeding systems may have undergone significant processes of down-cutting by turbidity current likely generated through hyperpycnal flows. Many questions about SC remain open (Würtz *et al.*, 2012), related also to their origin (retrogressive failure indenting the shelf edge, erosion by turbidity currents, subaerial erosion of the upper canyon, sidewall erosion related to sediment movement down the canyon). In certain Mediterranean settings, the role of erosive cascades of density bottom-hugged currents originated on the shelf and capable to flush a canyon mimicking a low density turbidity current flow is becoming evident (Malanotte-Rizzoli *et al.*, 2014). This is the case of most canyon systems located on North Mediterranean slopes (Gulf of Lion, Ligurian Sea, Aegean Sea; e.g. Canals *et al.*, 2006). While these canyon settings are impacted by the flow of cold water during major Cold Air Outbreak events from northerly winds, the south Adriatic slope is impacted by a similar atmospheric process but more indirectly and with a significant buffering effect induced by the orientation and extent of its broad shelf region.

We use the Southern Adriatic Sea as an ideal study area for investigating some of these open questions, suggesting a possible multi-disciplinary approach in order to shed some light on processes such as: the interaction between open-slope and canyon dense water downflows, the canyons' role in triggering upwelling currents in a circulation cell (that may lead not only to off-shore, but also to on-shore fluxes, with paramount ecological implications, Hickey, 1995; Canepa *et al.*, 2014; Boero, 2015); the interaction with the bottom boundary layer and the canyons' role as bottom shapers; their relationship with meteoceanic events taking place on the continental shelf.

2. Measurements and modelling approaches in the Southern Adriatic

The Adriatic Sea is a semi-enclosed, basin in the Northern Mediterranean Sea (see Figure 1, left panel), elongated in the NW-SE direction. Its northern sub-basin, gently-sloping and nearly 50 m deep on average, spans from the gulf of Venice to south of Ancona, providing a broad basin for North Adriatic Dense Water (NAdDW) formation by surface cooling under the effect of dominant cold northeasterly winds. South of Ancona, the bottom depth drops from 150 to 280 m below the mean sea level in the Jabuka pit.

The shelf eventually breaks off the Apulian and Albanian coast, dipping into the Southern Adriatic Pit, 1200 m below the mean sea level. The SAP is connected to the Jabuka Pit by the Palagruza Sill in the North, and to the deeper Ionian Sea by the Otranto Sill in the South. As an interface between the Mediterranean and an epicontinental basin acting as a cold engine for regional circulation, the Southern Adriatic Margin is thus a crossroads for a variety of hydrodynamic, geological and biological processes.

During the last decade, observational investigations of dense water dynamics in the Southern Adriatic Margin underwent a change in strategy in the wake of two major elements.

On the one hand the appearance of the first large-scale seabed mapping at an unprecedented degree of detail, obtained by the joint use of traditional sampling techniques and new technologies such as multi-beam echo-sounding (Ridente *et al.*, 2007; Trincardi *et al.*, 2007), allowed to identify patterns of geomorphological features indicating the occurrence of partially recognizable hydrodynamic regimes (Verdicchio and Trincardi, 2006). On the other hand, the advent of relatively high-resolution modelling at basin scale (Carniel *et al.*, 2009), made possible by increasing computational capabilities, allowed a more detailed description of Dense Water (DW) preferential migration and cascading paths and their spatial scales. These factors, together with the increasing awareness of the strong space and time variability of DW dynamics, progressively drove the measurement approach towards a long-term, high-frequency strategy relying on the deployment of fixed moored instrumental chains on some key zones of the continental margin.

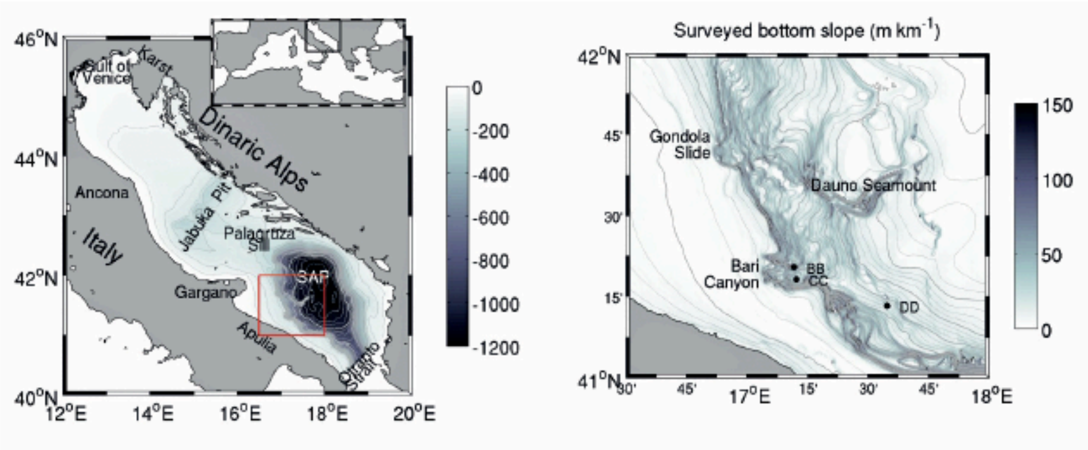

Figure 1. Adriatic Sea (left panel) and detail of the Southern Adriatic Margin (right panel) showing the bottom slope. Moorings name and main locations discussed in the text are also indicated.

These were identified based on geological and modelling clues of DW activity, and such point observations were flanked by a set of traditional (e.g. CTD, XBT, L-ADCP) and non-traditional (Seismic Oceanography, Micro-structure turbulence profiling) measurements carried out during oceanographic cruises for providing a spatial picture of nearly-instantaneous information.

After earlier works (e.g., Bignami *et al.*, 1990; Vilibić and Orlic, 2002), an extensive, interdisciplinary data set was collected on the Southern Adriatic Margin and on the Bari canyon in particular during the last decade, in the framework of a number of national and international efforts, such as EuroSTRATAFORM Project (Ridente *et al.*, 2007; Trincardi *et al.*, 2007; Turchetto *et al.*, 2007) or ADRIASEISMIC Oceanographic cruise (Carniel *et al.*, 2012).

Together with temperature, salinity and current velocity, suspended sediment samples were collected at three mooring sites on the main branches of the Bari canyon and the neighbouring open slope north of the conduits from March 2004 to April 2005 (Turchetto *et al.*, 2007). A longer campaign was set up from March 2009, again on the two channels of the Bari canyon but with a third mooring deployed down-slope and south of the canyon.

An exceptional cooling episode occurred in winter 2012, providing a paramount opportunity for investigating DW dynamics: to this end, two dedicated rapid environmental assessment campaigns named Operation Dense Water (ODW 2012) were carried out from late March to late April 2012, and characterized by a model-driven sampling strategy.

The large amount of data collected during the ODW 2012 campaign and the mooring activity, together with those recorded in the Northern Adriatic especially during the 2012 Cold Air Outbreak event (Mihanovic *et al.*, 2013), provided a sound validation set for a variety of numerical model experiments aiming at a broad characterization of NAdDW dynamics and their drivers.

NAdDW formation, spreading and cascading have been modelled by means of the COAWST (Coupled Ocean, Atmosphere, Wave, Sediment Transport) System (Warner *et al.*, 2010), coupling a fully 3-D, primitive equations, hydrodynamic model (Regional Ocean Modeling System, see Shchepetkin and Mcwilliams, 2005), a phase-averaged spectral wave model (Simulating Waves Nearshore, see Booij *et al.*, 1999) and a sediment transport module (Community Sediment Transport Modeling System, see Warner *et al.*, 2008). The system was implemented with reference to the period November 01, 2011 to June 30, 2012, over an eddy-permitting regular grid with 1 km horizontal resolution, and vertically subdivided into 30 terrain-following levels, stretched in order to achieve improved resolution close to the surface (for better describing cooling and densification processes) and close to the bottom (aiming to capture vertical variability within the bottom-hugging DW vein). While a complete description of the model settings can be found in the works by Benetazzo *et al.* (2014) and Carniel *et al.* (2015a), it is worthwhile recalling here that the set of implementations was characterized by different combination of forcing factors such as tides, riverine input, sediments and waves, selectively activated or deactivated in order to investigate their effects on DW dynamics and their interrelations.

3. Observations in the Adriatic – Bari canyon and South Adriatic Margin

3.1 Geomorphological setting

The Southern Adriatic Margin (see Figure 1) was shaped during the last half million years over a tectonic structure of Mesozoic carbonate platforms controlling lateral variability in shelf width and dip gradients (De' Dominicis and Mazzoldi, 1987). Local margin tilts and deformations are nevertheless controlled by patterns of Pleistocene regressive frequencies, where mass wasting and slope failure gave rise to deep incisions on the shelf edge. The progressive evolution of these scars towards a canyon configuration (such as in the case of Bari canyon, Figure 2) or a slide-deposit form (Gondola slide, see again Figure 1, right panel) depended on the frequency of failure and the location of the head with respect to the shore, controlling the capability of capturing dense bottom currents during both highstand (dense shelf water cascading) or lowstand (sediment-driven turbidity currents, see Ridente *et al.*, 2007).

Thus the present structure of the Bari canyon system (Figure 2), approximately 10 km wide and extending offshore for 30 km, consists of three sub-parallel conduits carving the continental slope in the W-E direction. The northernmost conduit, referred as Moat A (Trincardi *et al.*, 2007) is sinuous, slope-confined, downslope-broadening, and displays erosional features on its northern flank and likely muddy deposits on the southern one. South of Moat A, two shelf-indenting channels develop with a significant cross-slope variability in morphology and gradient. Adjacent to Moat A, Channel B appears straight, confined and erosional in the upper slope (down to 620 m), narrower and sinuous down to 750 m and eventually more defined until disappearing in water depths greater than 1100 m (Trincardi *et al.*, 2007). The southernmost conduit, identified as Channel C, is broader, straight and asymmetric, being separated from Channel B by a gently-sloping (0.6°) mounded relief in the north and flanked by a steep southern wall in the south (Ridente *et al.*, 2007).

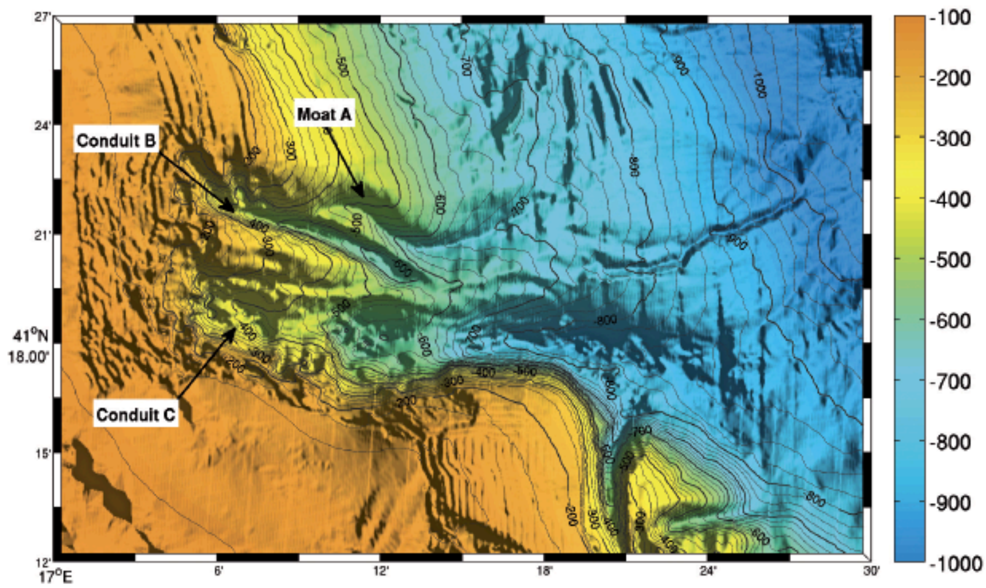

Figure 2. Detailed bathymetry of the Bari canyon system (m).

At a smaller scale, the Bari canyon system exhibits (see again Figure 2) the marks of a complex morphodynamic activity, involving the conduits and the neighbouring slope. Seismic profiles show a lateral spreading of the southern levee of channel B towards conduit C, consistently with flows predominantly overbanking to the right of the conduit (Trincardi *et al.*, 2007). Furthermore, erosional features in the median relief between B and C suggest the presence of energetic mass exchanges from the northern to the southern channel (Ridente *et al.*, 2007). Along the southern wall of canyon C, approximately 700-850 m deep, furrows have been observed, prevailingly oriented along-axis and progressively right-veering downslope (Verdicchio *et al.*, 2007). About 10 km seaward, at a depth ranging between 800 and 950 m, sediment undulations oriented in the NNE-SSW direction and with wavelength of 700-1300 m have been described by Trincardi *et al.* (2007) and Foglini *et al.* (2015), where mooring DD was positioned.

Interestingly, even south of the Bari canyon the continental margin towards the Otranto strait appears marked by highly-energetic, nearly contour-parallel currents (Foglini *et al.*, 2015), with extensive erosional fields along the slope change and a transverse scouring involving a canyon system, formerly delivering coastal sediment to the deep basin during the Last Glacial Maximum and now relict and partially disconnected from the shelf.

In fact, a manifold pattern of erosional and depositional bedforms indicative of a strongly space- and time-variable hydrodynamic regime (Verdicchio and Trincardi, 2006) studs the whole South Adriatic Margin. Their metrics and disposition, made readable by new techniques of multi-beam echosounding combined with stratigraphic chirp data (Foglini *et al.*, 2015), mark on a broader scale the activity of interacting bottom currents at the edge of this reach of the continental shelf.

3.2 Hydrology

Thermohaline properties on the continental margin exhibits seasonal modulation, with (potential) temperature at near bottom ranging overall between 12.20 (Langone *et al.*, 2015) and 14.42 °C (Turchetto *et al.*, 2007), with a maximum typically occurring in December and a minimum in March-April. Salinity in turn spans a narrower range (38.62-38.74 during Spring 2012 event, see Langone *et al.*, 2015). Hydrodynamic regime displays a strongly variable bottom current intensity throughout both the open slope and the canyon conduits, with pulses up to 0.60 m/s and 0.75 m/s respectively, corresponding to cold, dense shelf waters transit. 2004-2005 EuroSTRATAFORM dataset reports a nearly constant current direction in the open slope north of Bari canyon, oriented on average along the regional isobaths and with a few degrees downslope veering in presence of stronger speed (>0.30 m/s) episodes (Turchetto *et al.*, 2007). Positions of active moorings are presented in Figure 1 (right panel). Observed potential density at moorings BB, CC, DD, registered during ODW 2012 campaigns are shown in Figure 3.

Current directionality in the canyon proper exhibits instead a more variegate behaviour. Both the available datasets (2004-2005, see Turchetto *et al.*, 2007 and Rubino *et al.*, 2007; and 2009-2012, see Langone *et al.*, 2015) highlight in BB a clustering along two directions (see Figure 3), one oriented southward along the regional contours, and one oriented downslope along the conduit axis Whilst the former is dominant during most of the year, the latter is especially active in spring, corresponding with dense water arrival. Dense water downflow takes place along both directions (Turchetto *et al.*, 2007), but with a fundamental difference in water properties; indeed, as along the conduit the NAdDW cascading signature is most clear in terms of both velocity and thermohaline properties, in the slope-parallel direction only the kinetic signal is strong, while the density signature is only partially retained. Lower velocity (less than 0.20 m/s) concomitant with smaller density anomaly (below 29.2 kg/m3) can be interpreted as a signature of the background circulation, exhibiting thermohaline properties that can be ascribed to the Modified Intermediate Levantine Water (Carniel *et al.*, 2015).

In turn, the steep southern wall of conduit C acts as a major constraint for the flow along the canyon axis towards the off-shelf direction, practically independent of the physical properties of the water mass.

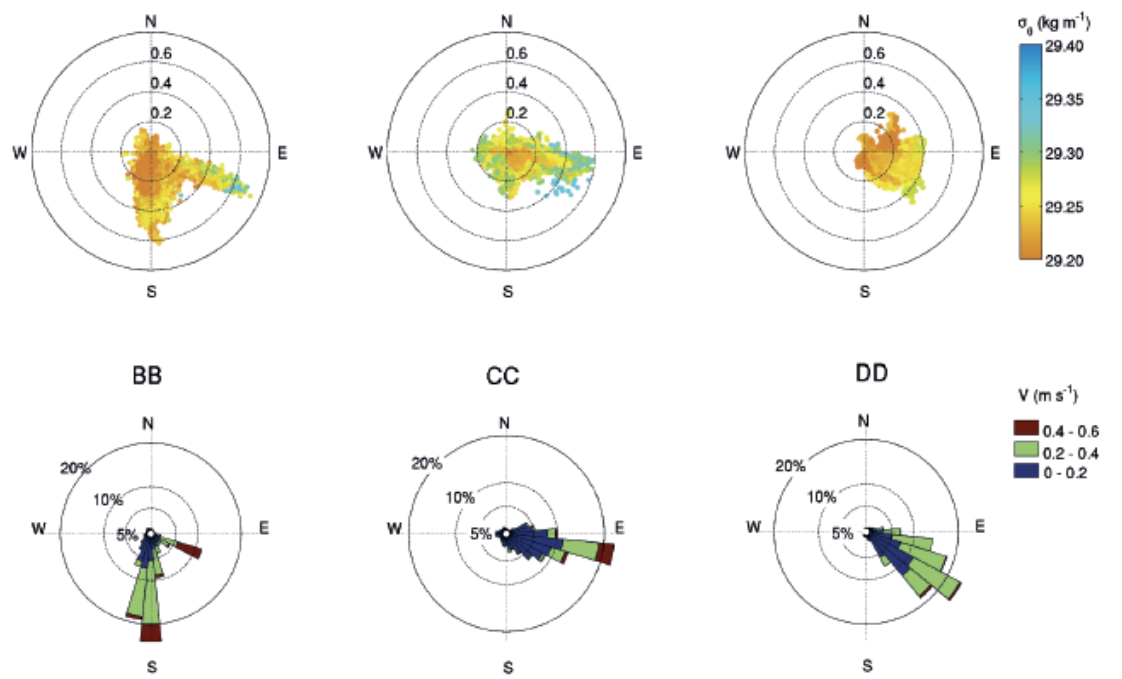

Figure 3. Upper panels: observed directional current velocity (m s^{-1}) and potential density (kg m^{-3}) at moorings BB, CC, DD (see Figure 1, right panel). Lower panels: occurrence probability of observed current velocity (m s^{-1}) clustered every 0.2 m s^{-1}. Data were obtained during ODW 2012 campaigns.

Together with a physical characterization of water masses transiting through this sector of the continental margin, the availability of yearly or longer observational records allows the identification of timing and modulation of dense water descent on the conduits of the Bari canyon. Several studies (e.g. Vilibic and Orlic, 2002; Rubino *et al.*, 2012) identify in 2-4 months the period needed for NAdDW to propagate from the generation basin to the Southern Adriatic region. On the other hand, during winter-spring 2012 episode, high-frequency cold and low-salinity water pulses have been observed on the continental margin since mid February, only two weeks after the Cold Air Outbreak inception, with negative shift in temperature on the order of 0.35 – 0.60 °C. Subsequent intrusions of cold water were recorded until June, with variable characteristics along the continental margin (Langone *et al.*, 2015).

Besides traditional measuring strategies, new advances toward nearly-synoptic observation of large-scale patterns of dense water spreading along the continental margin are made possible by seismic oceanographic techniques (Holbrook *et al.*, 2003). By using the techniques primarily designed to image sub-seafloor geologic structures, it was recently shown that it is possible to provide images of water layers in the ocean, since the lower frequency sound waves used (from about 10 to 200 Hz) are coherently reflected directly by the thermohaline boundaries between water masses on the scale of meters to tens of meters (Ruddick *et al.,* 2008). Such acoustic measurements were integrated with eXpendable Bathy-Thermographs (XBTs) or Conductivity-Temperature-Depth (CTD) casts during the international ADRIASEISMIC cruise (March 3-16, 2009), carried out on board the CNR R/V *Urania* in the southern Adriatic Sea. It was the first experiment in seismic oceanography that specifically targeted structures in shallow waters (along the western margin of the Adriatic Sea between the Gargano promontory and the Bari canyon, see Figure 1).

3.3 Sediment transport and biological/biogeochemical aspects

The export rate of organic carbon provides a proxy for the efficiency of the biological pump in delivering mass, produced by phytoplankton in the photic layer, into the deep ocean (Boldrin *et al.*, 2011) and Bari canyon is considered to play an important role in the sediment transport dynamics in the southern Adriatic basin, representing an efficient conduit in delivering suspended sediment from the continental shelf to the deep basin (Turchetto *et al.*, 2007). In this, long-term sampling via time-series sediment traps allows a characterization of timing and biogeochemical composition of sediment transiting in the measurement zone.

A set of sediment traps moored along the continental margin, together with current meters and other instruments, provided background for a number of inferences and, particularly, important information about cross-shelf sediment transport. Turchetto *et al.* (2007) showed that, although dense water downflow processes involve also the open slope, the Bari canyon acts as a main pathway for off-shelf sediment fluxes, and highlighting that the DSW cascading is responsible for the higher particle delivery both in the open slope and canyon stations. Monitoring efforts in the Bari canyon highlighted that the main organic carbon source is constituted by vertical sinking of marine phyto-detritus, ranging from ~60% during dense water cascading, up to 90% during low energy conditions (Tesi *et al.*, 2008), the remaining part constituted by horizontally-advected kerogen and soil-derived organic carbon in almost similar proportions.

Superficial sediment sampling on the continental shelf and on the slope allows the identification of the origin of laterally-advected particles. Tesi *et al.* (2008) assessed the origin of exported sediment, highlighting that the direct transport of material from river mouths and inshore region is practically excluded in present highstand conditions and therefore that the downflowing matter is mostly resuspended on the slope and outer shelf. In contrast, Langone *et al.* (2015) concluded that during the 2012 DSW cascading events particles in transit in the water column had a larger contribution of fresh organic matter resulted from enhanced productivity, which was quickly transferred from surface waters of Northern Adriatic shelf to the bottom of Southern Adriatic. Overall, DSW cascading acts as a primary control on the particulate fluxes through the western margin of the Southern Adriatic, whereas storm-induced sediment transport can play a secondary role (Langone *et al.*, 2015).

Due to the prolonged flushing of sea bottom during DSW cascading and the low but relatively constant organic carbon supply during the rest of the year, the Bari canyon appears to be a suitable area to be colonized by sessile deep-sea benthic communities (e.g., cold-water corals).

Conspicuous megafaunal sessile communities, including cold-water and sponge habitats, show an asymmetric distribution in the southern Adriatic with most diverse and abundant live corals settling on the western side, especially the Bari canyon (Taviani *et al.*, 2015). This observation has been hypothesized to be at least partly a response to the seasonal action of dense shelf water cascading flushing the canyon and adjacent areas by limiting excess silting and favouring the food web (Taviani *et al.*, 2015).

This brief summary provides an account of the wealthy set of traditional and new-generation observational data currently available on the Southern Adriatic Margin, and in particular on the Bari canyon system. In this picture, a number of questions should be framed into a multi-disciplinary context arise. What are the interactions between dense shelf water cascading and large-scale circulation in the Bari canyon and what is, in integral terms, the relative weight of open-slope and canyon cascading in NAdDW descent? How does this relate to the hydrological and geological patterns observed (or conjectured) in this zone? What is its relationship with the forcing factors driving water cooling in the Northern basin? Vice versa to what extent does canyon-induced upwelling recirculate deep sea matter towards the continental shelf, and in general what are the mechanisms and connections by which Mediterranean circulation and large-scale atmospheric patterns control cross-shelf mass transport?

4. Model results

Although near-bottom currents in the Bari canyon region were recently explored by Rubino *et al.* (2012) by means of a reduced-gravity numerical model, the extent of some conclusions was admittedly limited by the coarse bathymetry resolution and the impossibility of accounting for the effect of air-sea interactions and ocean dynamics at regional scale.

Benetazzo *et al.* (2014) addressed these questions by investigating the process dynamics using a coupled numerical model approach and adopting a high-resolution description of the bathymetric forcing, modeling the whole Adriatic basin under the effect of a number of variable drivers. In this direction, a comprehensive description of dense shelf water formation and spreading processes was stimulated by the exceptional Cold Air Outbreak event of 2012 and the ODW dataset, that also provided a striking examples of how deep basin dynamics (including those characterizing the Bari canyon system) can be intrinsically linked with shelf processes

From 29 January to 13 February 2012 the Northern Adriatic basin was hit by a Cold Air Outbreak with strong, cold and persistent winds blowing from SE across the Karst and the Dinaric Alps, with a prolonged establishment of large significant wave height (more than 2 metres), current velocity (up to 1 m s^{-1}) and turbulent heat fluxes at the air-sea interface (up to 800 Wm^{-2}, see Mihanovic *et al.*, 2013). As a response, a steady circulation pattern appeared, with a cyclonic gyre in the gulf of Venice and an intense meridional stream from the Kvarner gulf towards the Italian coast and then southwards along the shelf contours, partially recirculating north of Ancona.

The southernmost front of the very dense water originated in the northern basin (up to record-breaking value of 30.30 kg m^{-3}) left the generation basin, reaching the southern basin before the end of the Cold Air Outbreak. In subsequent weeks, dense water vein migrated southwards parting into two branches south of Ancona: hence, the fraction flowing along the deepest reaches of the shelf was partially deviated towards the Jabuka Pit before proceeding towards the Southern Adriatic Pit across the Palagruza Sill, whilst the shallower fraction maintained its nearly-coastal route, exhibiting a meandering behaviour especially south of the Gargano promontory, compatible with the pulses observed at the mooring stations by Langone *et al.* (2015), with a PDA greater than 29.2 kg m^{-3}, and with the propagation of topographic waves along and off the continental shelf (Carniel *et al.*, 2015a).

Dense water cascading, initially occurring as intermittent pulses, becomes progressively more regular as the process becomes dominated by the buoyancy difference and as the memory of the kinetic energy injection during the Cold Air Outbreak is lost. At the end of April the South Adriatic Pit appears completely renewed, with the 29.2 kg m^{-3} isopycnal set about 900 m deep and a cyclonic circulation established along the lower slope. With the depletion of the generation basin in May, the cascading intensity progressively decreases up to eventually ceasing in June.

Figure 4 shows some modeling results (for a complete model validation see Carniel *et al.*, 2015a; Bonaldo *et al.*, 2015), such as the vertically integrated water and sediment fluxes along the western margin within the period 01 February – 31 May, 2012. Although most of the western slope is hit by dense water cascading, in the Bari canyon water and sediment transport occur with special intensity and with a strong spatial variability. Vertically averaged velocity on the NAdDW vein (Figure 4, left bottom panels) and mean acceleration patterns of bottom currents (right) are also shown.

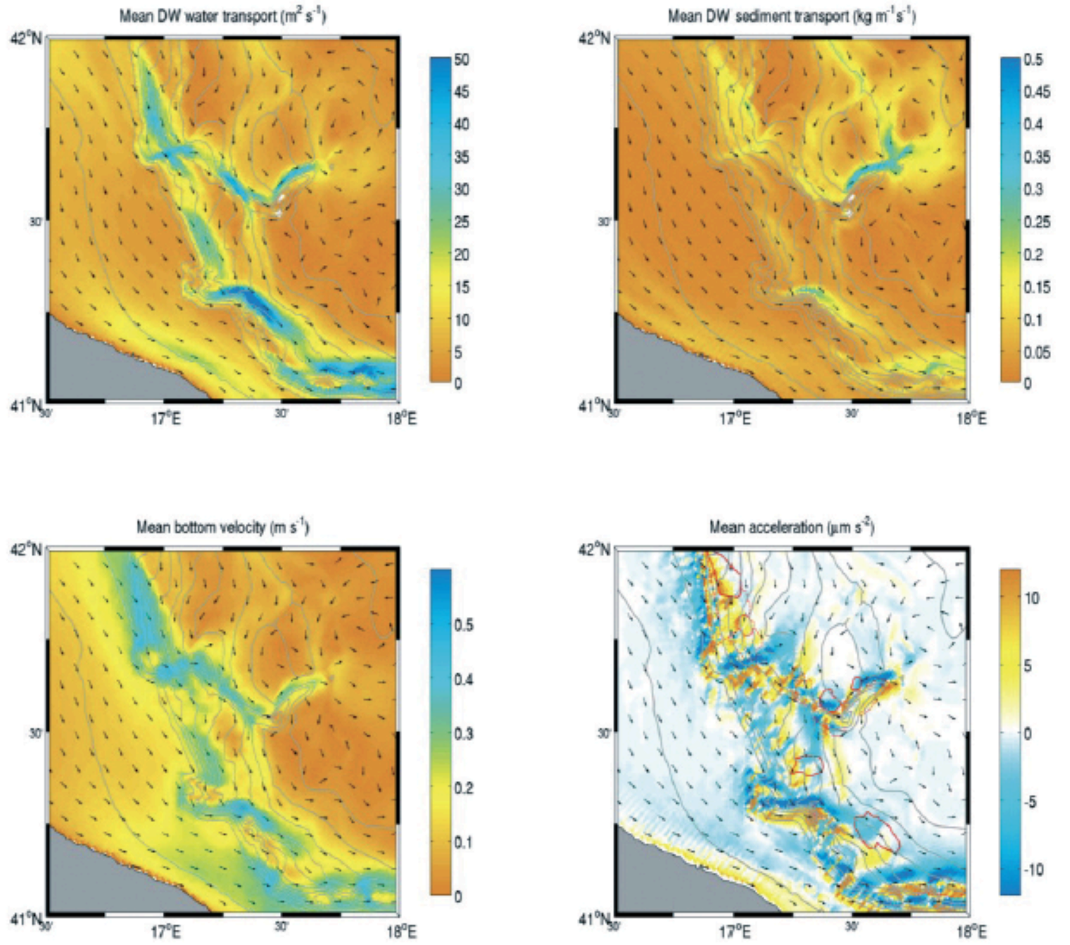

Figure 4. Modelled features of the NAdDW vein in the Southern Adriatic, averaged within the period February 01 to May 31, 2012.
Upper panels: vertically-integrated water (left) and sediment (right) fluxes within the dense water vein.
Lower panels: bottom velocity (left) and acceleration patterns of bottom currents (right). Red polygons represent erosional (dashed) and depositional (solid) fields (see Foglini *et al.*, 2015).

Bonaldo *et al.* (2015) showed that modelled flow field provides a good instrument for understanding the mechanisms responsible for bottom reshaping along the continental margin. In particular, acceleration and deceleration pattern proved to match rather well with observed erosional and depositional features (see again Figure 4, right bottom panel), while the analysis of modelled time series allowed to identify the suitable conditions for the appearance of the considered bedforms. Focusing on the Bari canyon system, it was found that the Flood criterion (Flood, 1988) for mudwave maintenance is fulfilled on the depositional zone north of channel A throughout most of the considered period, but the sediment supply necessary for their accretion is provided by dense water downflow from the northern reaches of the continental slope. In turn, downslope the steep southern flank Conduit C, current velocities are compatible with sediment deposition, whereas strong, directionally stable speed occurring during the Feb-May period are capable of inducing furrows formation (Stow *et al.*, 2009). It is worth pointing out that strong current speed (up to 0.50 m s^{-1}) occurs during February 2012 but before the arrival of the NAdDW vein, suggesting that this zone is ordinarily active under the effect of strong coastal storms characterized by local cooling. Current speed frequently exceeding 0.30 m s^{-1} in the February-April period can give rise to the erosional features observed in the downslope flank of the waves by Foglini *et al.* (2015).

An intercomparison among the results of our set of numerical experiments allowed to identify the role played by various forcing factors in controlling dense shelf water formation and spreading.

Although the general pattern of DSW dynamics (formation north of Ancona, presence of a northern gyre and a zonal current, splitting into a "coastal" and a "Palagruza" stream modulated by the transit in the Jabuka pit, downflow distributed along the western margin) is a common aspect for all implementations considered, major implications from variations in model settings and forcings concern timing, dense shelf water volume and thermohaline and dynamic properties, and distribution between the coastal and deep streams.

Benetazzo *et al.* (2014) pointed out the role of wave coupling in modulating heat and momentum transfer from the atmosphere into the water column and the relevance of explicitly computing the intensity of Stokes currents. In the absence of these factors, surface currents in the northern basin are reduced by about 20% the average current speed and heat fluxes are reduced by 10%. This results in a different estimate of overall dense water volume approaching the SA (3160 km^3 vs 2075 km^3, Carniel *et al.*, 2015b). Furthermore, potential vorticity conservation implies that a dense water vein leaving the generation basin at a higher speed establishes at a shallower depth, favouring the coastal path and the eventual passage through the Otranto Strait on the continental shelf rather than across the Otranto Sill (Carniel *et al.*, 2015a). Tides as well have been found effective in modulating instantaneous dense water fluxes (Benetazzo *et al.*, 2014), urging a deeper exploration of the role of the tidal forcing in driving dense water dynamics. Although autumn 2011 was not characterised by exceptional riverine freshwater input, Carniel *et al.* (2015) estimated that this factor accounts for approximately 30% difference of dense water production.

The same authors evaluated the effect of the presence of suspended sediment along the water column, suggesting that in the absence of a substantial influence on the overall fluxes, the effect of density (and horizontal density gradients) on the spatial distribution can concentrate part of the vein towards the deeper zones, enhancing Jabuka pit renewal and the "Palagruza" stream.

To complete the picture, other works (Carniel *et al.*, 2015b) showed how interface processes can modulate ocean circulation and cooling and condition the pathways of newly dense water up to its eventual cascading into the Southern Adriatic Pit.

Further they highlighted two recurrent features of dense water downflow, namely the relevance of open-slope in the overall off-shelf fluxes and the role of shelf break morphology in selectively triggering cascading processes. Based on the same model results described by Benetazzo *et al.* (2014), Bonaldo *et al.* (2015) point out the role of the topographic constraint in driving DW cascading under the dynamic effect of shelf indentations and variations in seabed slope and curvature.

5. Discussion and conclusions

Submarine canyons are key-regions playing a relevant ecological role in connecting the shelf regions to the deeper ones, where *in situ* measurements are very difficult to be collected and long-term series are very scarce. Therefore, a good practice to employ when studying these underwater conduits is to follow an integrated use of available data and high-resolution numerical modelling. This approach is valuable for capturing dense water dynamics variability in space and time, and for interpreting available measurements in terms of interacting processes at different scales (Rubino *et al.*, 2012). Lessons learned from the activities carried out in the Southern Adriatic during the last decade represent a sound background for the analysis of canyon dynamics and their relation with open-slope processes in a broader framework. A similar approach has been also proposed by Fabri *et al.* (this volume), as support to "habitat mapping" procedures.

In the specific case of the Bari canyon system, the collection of long-term series of continuous temperature, salinity and current velocity data at near-bottom layer in the main conduits provides a comprehensive picture of current regime and thermohaline properties, their modulation in time and interannual variability (Langone *et al.*, 2015). Suspended sediment sampling by means of automatic sediment traps undergoes well-known limitations related to the low measurement frequency, unavoidable in the case of long deployments, and to the difficulties in reconstructing the transport regime actually responsible for the observed sediment deposition. Some effort towards a continuous, high-frequency suspended sediment transport monitoring strategy would probably pay back with a clearer identification of the drivers and intensity of sediment transport processes, permitting an assessment of their dynamic implications especially during intense events. Nevertheless information provided by sediment traps allowed to draw important inferences about sediment transport seasonal and interannual variability (Turchetto *et al.*, 2007; Langone *et al.*, 2015), their origin (Tesi *et al.*, 2008) and a proxy of its distribution along the continental margin (Langone *et al.*, 2015; Carniel *et al.*, 2015a).

Recent high-resolution, state-of-the-art modelling efforts shed additional light on the processes taking place on the Bari canyon from a continental margin perspective. The extensive data set highlighting the intense processes occurring on the Bari canyon was combined with state-of-the-art model results, showing that dense water downflow in the open slope (experimentally observed albeit with a locally weaker intensity) is responsible for the majority of mass transport towards the Southern Adriatic Pit. In general, while the forcings acting on the dense water mass during its formation and its spreading are crucial in determining the "capture efficiency" of the shelf break (namely, the ratio between total dense water approaching the Southern basin and the cascading fraction), the distribution of downflow along the margin appears controlled by the large-scale shelf morphology. Seabed topography, and especially variations in slope and curvature, then defines preferential pathways for the downflowing streams. In turn, NAdDW descent is a main (but not the unique) cause for the emergence of peculiar patterns of erosional and depositional bedforms with intermediate characteristics between the well-known categories of contourites and turbidites.

Successes and limitations arising from this experience indicate major axes to be addressed in dense water processes and submarine canyon hydrodynamics modelling strategies. Besides the obvious opportunity of having an appropriate horizontal (at least eddy-permitting) and vertical (both close to the surface and close to the bottom) resolution for the computational grid, Bonaldo *et al.* (2015) emphasize the importance of a detailed bathymetric description, with special attention to the trade-off between numerical stability and quality of the topographic information (Haney, 1991). Waves and tides appear as essential ingredients for a comprehensive insight on the processes related to DW formation and propagation. In particular, the paramount importance of air-sea interactions and their modulation by waves highlights the necessity of an integrated, fully coupled modeling approach. The challenge of a model fine-tuning by improved parameterizations and an extensive calibration appears as a staging post in this direction.

More generally, if recently relevant progresses have been achieved in understanding the driving mechanisms and the preferential pathways of continental margin flushing, its on-shelf counterpart is still partly unexplored. Whilst the function of canyons in off-shelf transport may in a way appear diluted by the broader extent of open-slope downflow, their role can gain centrality as funnels for upwelling circulation from the lower slope and abyssal plain to the shallow coastal zone (Hickey, 1995; Connolly and Hickey, 2014; Canepa *et al.* 2014; Boero 2015).

As suggested by some, the effect of these processes in governing the functioning of ecosystems is potentially fundamental. For instance, Canepa *et al.* (2014) point out that beach stranding of *Pelagia noctiluca* jellyfish occurs in greatest concentrations in proximity of submarine canyon heads, leading to hypothesize a seasonal migration strategy along submarine canyons for a number of other species (Boero, 2015), based on fluctuations in temperature and nutrient supply.

If the cold engines of the Mediterranean warrant the deep water renewal at sub-basin level (with the Gulf of Lion acting in the Western Mediterranean, and the Northern Adriatic and Northern Aegean acting in the Eastern Mediterranean) by cascading phenomena that flow through canyons, (the Bari canyon being the route of the Northern Adriatic cold engine), the upwelling generated by canyons might be a further engine system leading to localized vertical mixing. Cascading phenomena are not generated by canyons but use canyons (Malanotte-Rizzoli *et al.*, 2014), whereas upwelling phenomena are often generated by canyons. In this way, the vertical mixing of Mediterranean waters may be due to a combination of both cascading and upwelling phenomena. The impairment of the cold engines (as happened during the Eastern Mediterranean Transient) might be, at least partially, buffered by the synergistic action of a myriad of canyons indenting a the whole Mediterranean slope and generating localized upwellings.

Unwinding the thread of these concepts is a real challenge, as it is evident enough that a coherent view of submarine canyons functioning intersects marine trophic networks, nutrient and carbon exports, fisheries, climate dynamics, towards a global reach that is far beyond the apparently local canyon dynamics.

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