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Long-term variability and trends of relative geostrophic currents in the middle Adriatic

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ABSTRACT

The paper documents dynamics of the middle Adriatic region, and is based on computation of relative geostrophic currents from temperature and salinity data taken along the Palagruža Sill transect between 1957 and 2010. The strongest westward current is found in the central part of the sill, corresponding to the offshore deflected Eastern Adriatic Current (EAC). The Western Adriatic Current (WAC) is, as expected, found in the southern part of the measured transect. The WAC is most significant during the summer season and exhibits stronger variability than the EAC due to the frequent growth of eddies within it. Long-term trends in both the central and southern parts of the sill oppose mean currents, indicating the weakening of the EAC and WAC and therefore of the entire Adriatic thermohaline cell. These opposing trends have not been reproduced by a climate model.

1. Introduction

The thermohaline circulation of the Adriatic Sea, a semi-enclosed 800 km × 200 km wide Mediterranean basin penetrating deeply into the European mainland (Fig. 1), is a result of two major drivers: (i) the northern Adriatic rivers discharges, and (ii) dense water generation at the northern Adriatic shelf (Vilibić et al., 2013) and at the deep South Adriatic Pit (SAP, Gačić et al., 2002).

Northern Adriatic river discharges, primarily from the Po River (Raicich, 1994), form the Western Adriatic Current (WAC), which may be tracked at the surface and intermediate layers along the western coastline down to the Otranto Strait. Its intensity is seasonally modulated by winds (Magaldi et al., 2010) and dense water outflow from the northern Adriatic during wintertime (Sellschopp and Alvarez, 2003). Dense water generated at the northern Adriatic shelf and at the SAP flows as a bottom density current along the western Adriatic shelf (Vilibić and Supić, 2005), exits the Adriatic, and enters deep layers of the Ionian Sea (Bensi et al., 2013). Both the WAC and the bottom dense water outflows are compensated by the Eastern Adriatic Current (EAC), which brings more saline and warmer Surface Ionian Water and Levantine Intermediate Water (LIW) into the surface and intermediate layers of the eastern Adriatic, respectively (Malanotte-Rizzoli et al., 1997).

The dual thermohaline forcing of the Adriatic circulation is, together with the basin topography (the deep SAP and the shallower Jabuka Pit separated by the Palagruža Sill; and shallow northern Adriatic shelf), responsible for major circulation patterns and the distribution of water masses in the Adriatic Sea (Zore-Armanda, 1963; Orlić et al., 1992).

Aside from general circulation, many permanent and transient mesoscale circulation features may be found in the Adriatic Sea, especially over areas of rapidly changing bathymetry such as the Palagruža Sill. Permanent mesoscale features found in the middle Adriatic are associated with rapidly changing bathymetry (Martin et al., 2009), and transient features are associated with varying river discharge and wind field. Transient baroclinic instabilities may grow along the WAC edge (Burrage et al., 2009) and allow for occasional cross-shelf transport of western surface waters toward the eastern Adriatic (Vilibić et al., 2009) over the Palagruža Sill. Topographically driven cyclonic–anticyclonic pair of quasi-permanent gyres may be generated along the Palagruža Sill and, under a favourable wind, transpose the LIW inflow and the EAC closer to the western Adriatic coastline (Vilibić et al., 2009). Palagruža Sill is also a key area for the exchange of water masses between the deep SAP and the rest of the Adriatic (Buljan and Zore-Armanda, 1976) because the sill is a barrier for the inflowing LIW waters. These LIW waters are captured within the quasi-permanent cyclonic SAP gyre (Poulain, 2001), which is one of the most stable features of the Adriatic general circulation (Artegiani et al., 1997).

Such a barrier as the Palagruža Sill may introduce strong mesoscale dynamics and along-sill deflection of major circulation

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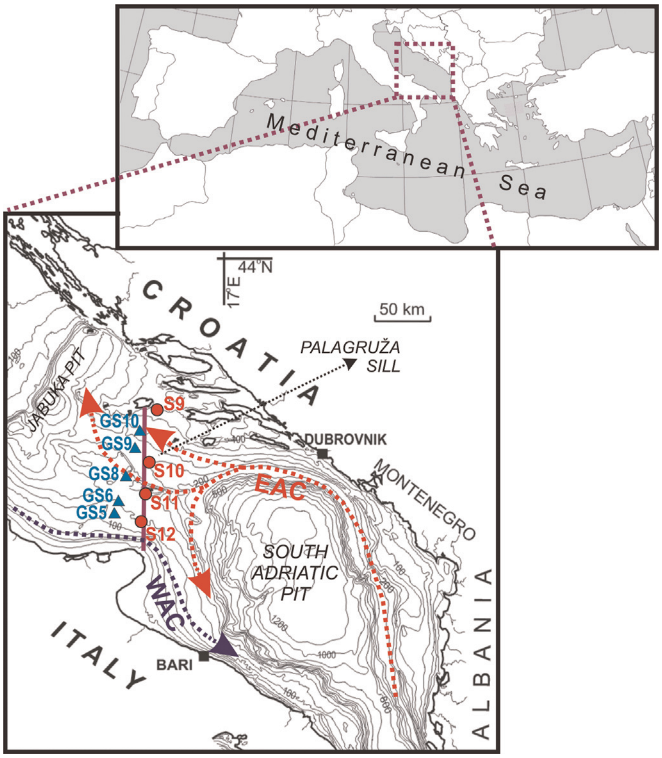

Fig. 1. The investigated area, with locations of the climatological stations (S9–S12) along the Palagruža Sill and ADCP stations (GS5, GS6, GS8, GS9, GS10) moored during the DART project between October 2005 and September 2006. Purple line denote the transect where NEMOMED8 climate simulation data were extracted. Major surface current systems are also indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

regimes (WAC and EAC, Burrage et al., 2009; Martin et al., 2009; Vilibić et al., 2009). Deflection of the EAC toward the western shore was first indicated by early computations of dynamic topographies (Zore, 1956; Buljan and Zore-Armanda, 1976). However, the deflection did not receive much attention in subsequent classical review papers on the Adriatic circulation (e.g., Orlić et al., 1992; Artegiani et al., 1997). Ten years of surface drifter data allowed for a better understanding of mesoscale variability at the sill, as a strong EAC current was found in the northern part of the sill during summer and autumn, and more to the centre of the sill during the winter (Poulain, 2001). Simulations performed by Oddo et al. (2005) reproduced the interannual variability of the EAC, placing its maximum along the eastern coastline during the winters of 2000–2002 and the summers of 2000–2001, and at the central part of the sill during the summer of 2002. Similarly, numerical modelling results by Martin et al. (2009) indicate strong variability of the EAC: during autumn and wintertime (November 2005 through January 2006) the EAC core was positioned along the northern part of the sill; in contrast, between February and August 2006, the EAC over the Palagruža Sill was modelled to have two maxima, one very close to the eastern shore and another positioned along the central part of the sill. The latter was dominant in June 2006 (Vilibić et al., 2009), when the EAC was modelled to meander within cyclonic–anticyclonic pairs of gyres.

The Adriatic thermohaline circulation has been found to weaken during the last decades (Vilibić et al., 2013). This weakening can be recognised from a strong increase in coastal water salinity, in particular at the WAC area, resulting in a decrease of cross-basin density gradients and respective buoyancy-driven currents (Orlić, 1996). Weakening of thermohaline circulation is also evident from the negative temperature and low positive salinity trends observed in the area of the LIW, indicating its decreased inflow to the middle Adriatic (Vilibić et al., 2013). Additionally, a less effective ventilation of the deepest waters during the last decades, which is detectable from data of deep dissolved oxygen concentrations (Vilibić et al., 2013), is presumably a result of the weakening of bottom density currents, which consequently influences the weakening of the inflowing branch (EAC) of the Adriatic thermohaline circulation. The observed trends are important because they can have a noteworthy impact on the deep waters and organisms living there; for example, the weakening of the Adriatic circulation results in less oxygenised deep waters and a higher frequency and duration of anoxic and hypoxic events in the middle and northern Adriatic (Degobbis et al., 2000; Giani et al., 2012). On the other hand, according to climate simulations and projections (Somot et al., 2006; L'Heveder et al., 2013), weakening and shallowing of the dense water formation and thermohaline circulation is expected in whole of the Mediterranean Sea, aside for the Adriatic Sea, where both dense water generation and thermohaline circulation are expected to maintain their intensity.

In this paper, the circulation patterns and their long-term trends will be assessed from temperature and salinity data collected between 1957 and 2010 in the middle Adriatic, across the Palagruža Sill. The data will be used for the computation of relative geostrophic currents. A majority of these data were used by Vilibić et al. (2013) to document long-term variability and trends in temperature, salinity and dissolved oxygen and associated water masses over the Palagruža Sill. The present paper is a continuation of these analyses with the aim of understanding the dynamical properties of the area. Previous computations of geostrophic currents in the northern Adriatic indicated that geostrophic approximation reproduces fairly well the real current field during the warm part of a year (Krajcar, 2003; Grilli et al., 2005). During wintertime, the approximation is found to be less correct due to wind effects and density currents that may be dominant in the area. The best matching between geostrophic and real currents was found in the area affected by the river discharges (WAC, Grilli et al., 2005). Our analysis will include spatial and temporal properties, seasonal variability and long-term trends of geostrophic currents across the Palagruža Sill transect, including the verification of currents via one-year long Acoustic Doppler Current Profiler (ADCP) measurements, and comparison with geostrophic currents obtained with state-of-the art numerical ocean model NEMOMED8 (Beuvier et al., 2010). Furthermore, the obtained geostrophic currents will be compared to the known properties and dynamics of the Palagruža Sill water masses, including their interchange, pathways and long-term trends. Section 2 presents the data used for the computation and verification of the relative geostrophic currents; Section 3 provides verification analysis, the computations of mean and seasonal current patterns, and their variability and trends; and Section 4 discusses the results and presents major conclusions.

2. Data and methods

2.1. T–S data and geostrophic currents

Temperature and salinity data measured at four open-ocean stations (stations S9–S12, Fig. 1) between 1957 and 2010 were used. The data were measured at standard oceanographic depths (0, 10, 20, 30, 50, 75, 100 m). Station S9 was surveyed largely on monthly basis, whereas the rest of the stations were surveyed mostly on seasonal basis. Temperature was measured using reversing thermometers (accuracy ±0.02 °C) until 1998, and salinity was measured from samples taken by Nansen bottles (with an