Hydrographic and Oceanographic Characteristics of the Southern Part of the Adriatic Sea

Branislav Gloginja and Luka Mitrović

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Abstract This chapter presents a short summary and a general overview of the Adriatic Sea, particularly the southern part. The Adriatic Sea encompasses the area between Balkan Peninsula and Apennine Peninsula, at geographic latitude 39°45´ N and 45°45´ N, and geographic longitude 12°15′ E and 19°45′ E. The south border in the whole region represents the Strait of Otranto and goes through the line joining Cape St. Maria di Leuca (Italy) – north coast of Corfu island (Greek) – mouth of Butrintit River (Albania). The longitudinal axis measured from the mouth of the River Butrint (Albania) to the Porto di Lido (Italy) is 475 nautical miles and width-axis, perpendicular to the longitudinal, from the Port Omiš (Croatia) to the port Vasto (Italy) is 117 nautical miles. Three principal water masses are presented in the Adriatic Sea the Adriatic Surface Water (AdSW), the Levantine Intermediate Water

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(LIW), and the Adriatic Deep Water (AdDW). The circulation is mostly counter-clockwise or cyclonic, with a flow towards the northwest along the eastern side and a return flow towards the southeast along the western side. The cyclonic gyres vary in intensity according to the season and the sub-gyre of the southern Adriatic tends to persist throughout the year. In the Adriatic Sea prevailing mixed type of tides with a relatively high percentage of salinity.

Keywords Adriatic Sea, Bathymetry, Circulation, Gyres, Hydrography, Montenegro, Oceanography, Tides

1 Introduction

The Adriatic (Fig. 1) is the most continental basin in the Mediterranean Sea (excluding the Black Sea), is enclosed between two mountain chains (Appennini and Balkans), and elongated latitudinally. It has a major axis (oriented from SE to

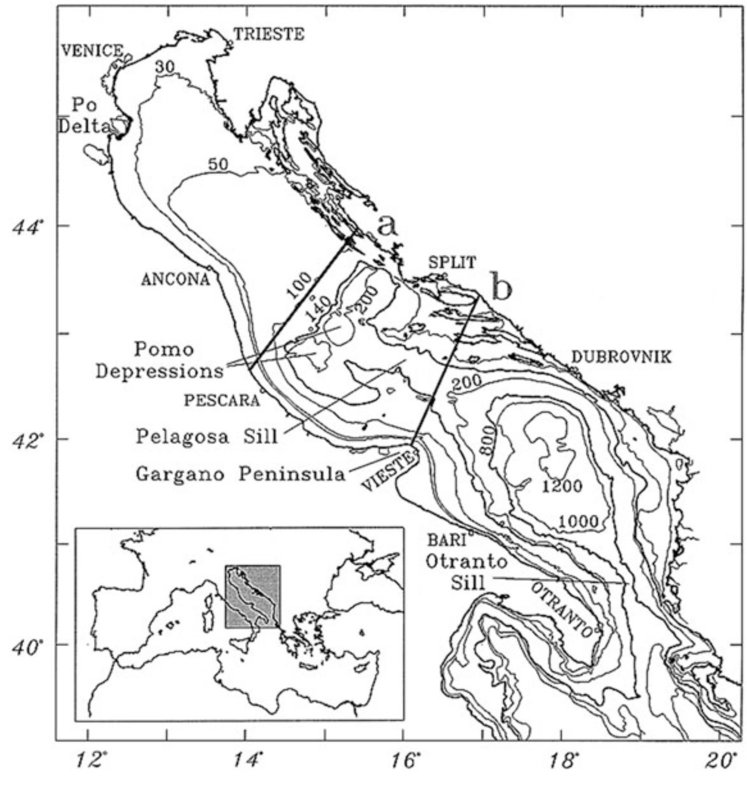

Fig. 1 The Adriatic Sea coastline and topography. Lines a and b define the northern, middle, and southern subbasins

NW) with a length of 800 km and a mean width of 180 km, and is connected to the Ionian Sea by a strait (Otranto) only 74 km wide [1]. The basin shows clear morphological differences, along its longitudinal axis and the transversal one as well, and it is divided into three subbasins [2].

The northern subbasin spans from the northernmost part to the 100 m bathymetric line (part a Fig. 1). The shallowest part of the Adriatic Sea is in the Gulf of Trieste where depths do not exceed 25 m, and up to the line joining Pula-Ancona the greatest depths are up to 50 m. From this joining line, the sea bottom descends in a long and narrow pit, which extends from the island Žirje towards Ortona, named Jabuka Pit with greatest depth of about 240 m. From the Jabuka Pit, the seabed rises to the wide and flat submarine sill (Palagruza Sill), with greatest depth of about 130 m.

The Middle Adriatic is a transition zone between the northern part and the southern subbasin (part b Fig. 1). It is an enclosed area from the 100 m bathymetric line (contour) to the Pelagosa (Palagruza) Sill.

The southern subbasin extends from the coast, between Islands Lastovo and Vis, up to north part of the Peninsula Gargano and on it are Islands Palagruža, Pianosa, and Tremiti. South of the Pelagosa Palagruža Sill, the seabed descends steep into the Southern Adriatic Pit (SAP) with greatest depths in the Adriatic Sea. However, there exists different data about the greatest depth. The Southern Adriatic is 80% of the total volume, with an area of 57,000 km^2, an average depth of 450 m, and a maximum depth of 1,233 m (Fig. 2) and contains a comparatively large bathyal basin with shelf surfaces of varying width; the continental shelf is limited in the Strait of Otranto, 750 m deep and 72 km wide, where important water exchanges with the Ionian Sea take place [3]. In the Strait of Otranto, the seabed again rises on undersea sill on the joining line Otranto – Vlore, the greatest depth is about 740 m. The depths in the channels between islands are about 60–80 m, and depths over 100 m are measured only in Kvarneric and Velebit channels.

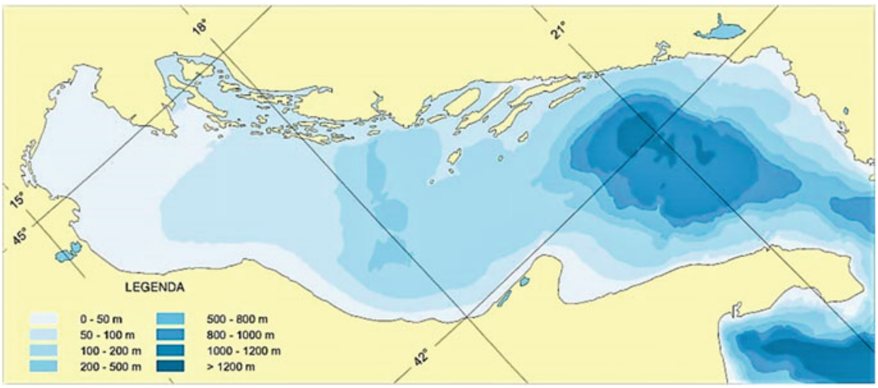

Fig. 2 Bathymetry chart Adriatic Sea (Source: According to [4])

2 Hydrographic Characteristics

2.1 Coast

Two big mountain ranges extend side-by-side along with the direction of the Adriatic Basin, one of them on the Balkan Peninsula and the other on the Apennine Peninsula. These two ranges in the northwest of the Alps continue, creating a bow like an amphitheater around the Adriatic Depression. On the east coast mountain Dinaric chain extends in the direction of NW–SE, parallel to the coastline and the island of the archipelago, and in some places just near the coast. In the central part of the Dinaric Alps, the mountain chain changes direction in the W–E, moving from the shore, so that the direction of the island archipelago, in this section, is the same as the direction of mountains on the mainland.

2.2 Islands

Except for several islands and islets south of Vis Island, between 42 and 43 parallel, all Adriatic islands extend close by its eastern coast. Cape Ploča divides them into two large groups: the north one extending in an almost parallel direction with the coastline and the south one in which bigger islands are extending in the west–east direction. Orographic forms on all islands are very characteristic points for quick and good orientation.

2.3 Seabed

Topographic and morphological forms of the undersea relief are the results of tectonic movements, abrasion, or erosion when this part of the bottom was land or coastal area. The roughness of the seabed is constantly softened by the deposition of recent sediments. It is a slow and continuous deposition. Numerous rivers bring to the Adriatic huge amounts of sediment. Sediments of certain rivers are constantly moving the coast at the expense of the Sea. The Lombardy rivers mostly embark the shallow seabed of the Southern Adriatic and move the coast further into the sea, so the Adria Port by which the Adriatic gain the name is now located 38 km from the coast, and the Roman ports Aquileia and Ravenna are deep in the inside. Due to unequal distances from the coast of the same depths and different increases of the depths, it can be distinguished into two main areas of sedimentation: the coastal area and the area of shallow sea. Coastal area is narrow, somewhere a few meters wide and elsewhere a hundred meters. In this area is stronger erosion than sedimentation factors, such as waves, tides, and currents. Area of the shallow sea covers the coastal area section, up to 1,000 m isobaths, and that means the whole Adriatic, except a small part south of Bay of Kotor. In both areas, sedimentation is influenced by surrounding land. Freshwater which from the land comes into the sea is rich in sediment which is deposited at great distances from the coast. Lombardy rivers, especially River Po, deposit a great sediment amount far from the mouth, along the Western Adriatic coast. As well, rivers on the eastern coast influence the sedimentation in the Adriatic, but it is slightly in relation to the deposition of rivers from the Lombardy area.

2.4 Tides

In the Adriatic Sea tides are of mixed type, with a pronounced inequality in height. In syzygy (new and full moon) tides are semidiurnal (12 h period) and in quadrature (first and last quarter) they are diurnal (24 h period). In transitional moon phases occurs mixed tides. Development of tides, i.e., the progress of tidal waves is shown by cotidal lines – lines of the equal arc delay (arc delay is the time interval which passes between Moon culmination and performance of high water; Figs. 3 and 4). In syzygy when tides are semidiurnal, in the Southern Adriatic phases are equal on its east and west coasts, and in the middle and Northern Adriatic they increase counterclockwise around the point between Ancona and Pag. This rotation of tidal wave is called amphidromy, having its center as the amphidromic point. Rotation of tidal wave lasts for 12 h and is equal to the period of a complete semidiurnal tide oscillation. The consequence of amphidromy is that the tides in middle and Northern Adriatic at all places through which passes cotidal lines different by 6 h so that while high tides occur on one coast, low tides occur on the other. Tidal amplitudes rise suddenly from the amphidromic point to the north, while to the south rises slower. In quadrature when tides are diurnal amphidromy is slower. High and low waters occur at the same time all along the basin, i.e., tides are in the phase. Tidal amplitudes are smaller than in syzygy, rising from the south to the north. In general, tidal amplitudes rises from the south to the north. From the Otranto Strait to Bakar this rise is small,

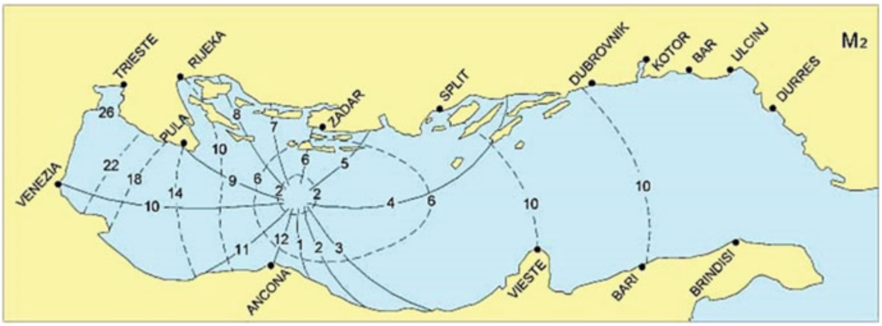

Fig. 3 Cotidal lines (–) in hours and lines of equal amplitudes (– – –) in centimeters for major semidiurnal component M2 (Source: According to [4])

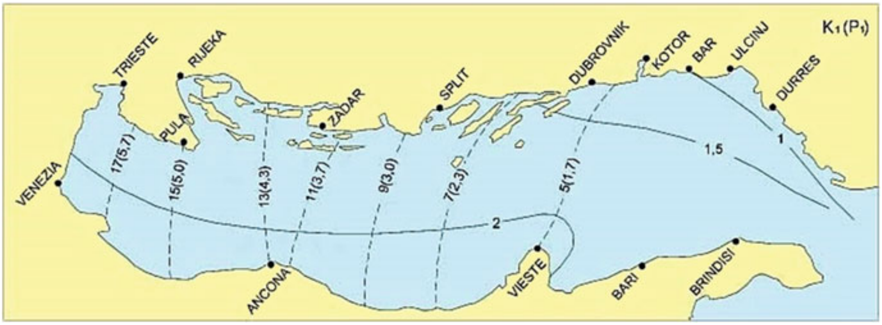

Fig. 4 Cotidal lines (–) in hours and lines of equal amplitudes (– – –) in centimeters for diurnal components K1 i P1 (Source: According to [4])

whereas from Bakar to the north it is great due to a rapid decrease in depth and the Adriatic Basin cross section [4].

Almost a regular tidal course is distributed by oscillations of the sea level influenced by atmospheric factors: air pressure and wind. With an increase of air pressure the sea level decrease and vice versa, with a decrease of air pressure the sea level rises. A change in air pressure of 1 hPa causes a change in the sea level of 1 cm. Strong winds, depending on wind direction, bring water to the coast or carry it off the coast, also causing oscillations of the sea level. Increase in air pressure and strong, persistent north winds (Bora and Tramontana) may cause a decrease in the sea level of up to 50 cm in the South and Middle Adriatic, or up to 60 cm in the Northern Adriatic. Decrease of air pressure and strong, persistent south winds (Sirocco, Libeccio) may cause a rise in the sea level of up to 80 cm in the Middle and Southern Adriatic, or up to 150 cm in the Northern Adriatic, which may cause floods in some ports [4].

3 Oceanographic Characteristics

The Adriatic Sea, with its surface of about 138,600 km^2 and its overall depth of 240 m, comprises a volume of roughly 35,000 km^3, occupied for 5% by the northern region, for 15% by the middle one, while the southern region occupies 80% of the total volume, with an area of 57,000 km^2 and an average depth of 450 m [5, 6]. The Adriatic supplies up to one-third of the freshwater flow received by the entire Mediterranean. It is estimated that the Adriatic's entire volume is exchanged into the Mediterranean Sea through the Strait of Otranto every 3–4 years, a very short period and likely due to the combined contribution of rivers and submarine groundwater discharge [7]. Duration of 150–168 days is estimated as the residence time in the Adriatic Sea for a drifting particle [8].

3.1 Currents

The general circulation is cyclonic with a northwest flow along the eastern coast and a return southeast flow along the western coast. There are three principal water masses in the Adriatic Sea: the Adriatic Surface Water (AdSW), the Levantine Intermediate Water (LIW), and the Adriatic Deep Water (AdDW), Fig. 5 [9].

The basin is characterized by the sinking of colder and heavier waters during the winter, by a relevant surface warming during the summer season and heavy rainfalls and river runoff (in particular by the Po River) during spring and autumn [2, 10]. The circulation is mostly counterclockwise or cyclonic, with up to three closed cells (in the southern, middle, and northern basin, respectively; Fig. 5). Both intensity and location of the coastal currents (Western Adriatic and Eastern Adriatic Current) and of the gyres above the Middle and Southern Adriatic Pits have significant seasonal variations [10]. The typical winds Bora and Scirocco blow along the eastern coast of the Adriatic Sea, prevailing during the colder part of the year and their role is fundamental to trigger and regulate water masses circulation. In summer is prevailing nice and dry weather with characteristic NW wind (maestral). Annual wind shows a NNW-SSE directionality in the Southern Adriatic Basin while an omnidirectional behavior may be observed at higher latitudes. Near the coastal line, winds show more irregular occurrences due to interactions with the local geomorphology. During the warmer seasons, sea and land breezes are rather frequent

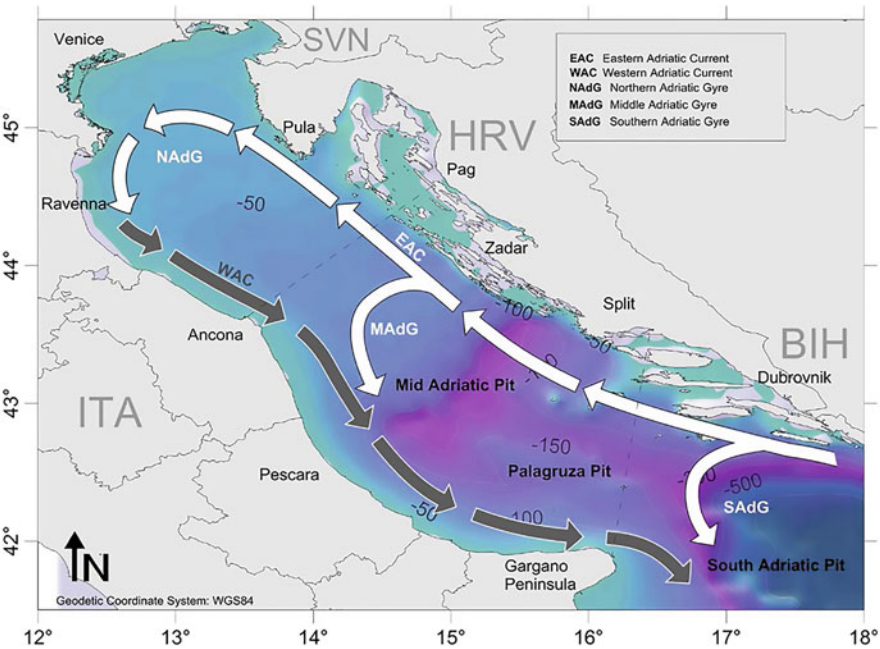

Fig. 5 Three paths followed by the main seasonal Adriatic currents

[11]. The overall Adriatic thermohaline circulation arises from the opposite effects of the thermal and haline forcing. The reciprocal variability of heat and water fluxes may be responsible for the variability of local circulation features. The Western Adriatic Current is due to the lower density of coastal waters than offshore waters (controlled to a large extend by the runoff of the Po and other Italian rivers). These waters are exchanged through the Strait of Otranto and replaced by other warmer water masses producing the Eastern Adriatic Current. The deep waters of the Adriatic can be separated into two categories: the first, clearly formed in the Northern Adriatic Region, cool and relatively less saline, found in the North and Middle Adriatic, and the second of much higher temperature and salinity, in the Southern Adriatic [2]. Deep waters production in the Adriatic Sea is an important process affecting water-mass characteristics [10] of a large portion of the Eastern Mediterranean and plays a crucial role in the complex and climate-sensitive thermohaline system of the Eastern Mediterranean [12]. The necessary conditions for the production of the deep waters are generally met in the Adriatic Sea, even if the Adriatic Sea is extremely sensitive to interannual variations with some winters rich in their production and others hardly forming any [10].

The climate characteristics are manifested in pronounced extremes of sea temperature, salinity, and other characteristics. Differences in the surface sea temperatures between summer and winter periods are high, as well as differences in salinity during the seasons. Winds which blow in the Adriatic are not of permanent character; therefore, they cannot establish certain circulation system, and even they influence the currents, especially in the coastal area.

3.2 Sea Surface Temperature

The Adriatic Sea is a warm sea with pronounced annual fluctuation of sea surface temperature. During the winter when under the influence of meteorological factors cooling is the most intensive, sea temperatures fall to a minimum. At this time of the year, there are also greatest spatial differences in the sea surface temperature, and thus in the extreme northwest the sea temperature is about 7°C, while in the Strait of Otranto about 14°C. Temperature rises rapidly in spring reaching values about 17°C to 18°C all over the Adriatic. In summer, the sea surface temperatures reach values of 22–25°C, the open sea being warmer than the decrease, this cooling being more intensive in the coastal water due to the influence of continent, so that the open sea is warmer than the coastal waters. Sea surface temperature reaches values of 14–18°C. In the coastal area, sea surface temperature reaches its maximum in July and August and its minimum in February. In the open sea area, the extremes are about 1 month late [4]. The lowest temperature has been recorded in the vicinity of large river mouths and in the areas with submarine springs, as the seawater is very much diluted by freshwater: in exceptional meteorological conditions the sea surface in these areas freezes over. In certain years, the influence of the Mediterranean on the Adriatic is greater than usual, making surface temperatures in the Adriatic higher than average.

3.3 Sea Surface Salinity

Salinity of the Adriatic Sea is in average about 38.3 psu, which is lower than salinity in the East Mediterranean and higher than the one in the West Mediterranean. The Northern Adriatic has a lower salinity than the Middle and Southern Adriatic due to the influence of Alpine rivers (especially the River Po). In the salinity variation, the Adriatic has two annual minimums: in May and December, and two maximums: in September and February. In the years when Mediterranean influences more intensively on the Adriatic, saltier water from the Mediterranean enters the Adriatic and increases its salinity, so then the salinity is over the average values and sometimes reaches the values above 39 psu.

Both surface salinity and temperature fields show large-scale patchiness during the spring–summer seasons. The salt balance of the surface layer is clearly affected by freshwater river runoff and the maximum values of salinity are found in winter (37.40 psu), while minimum values occur in summer (36.79 psu). The surface temperature has a clear seasonal cycle with maximum values of temperature during summer and maximum mixed layer depths during winter [2].

In 2015 and 2016, in the Southern subbasin was performed 2 ESAW cruises (Evolution and spreading of the Southern Adriatic Waters). The transect was between Bari (Ba; Italy) and Dubrovnik (Du; Croatia, Fig. 6).

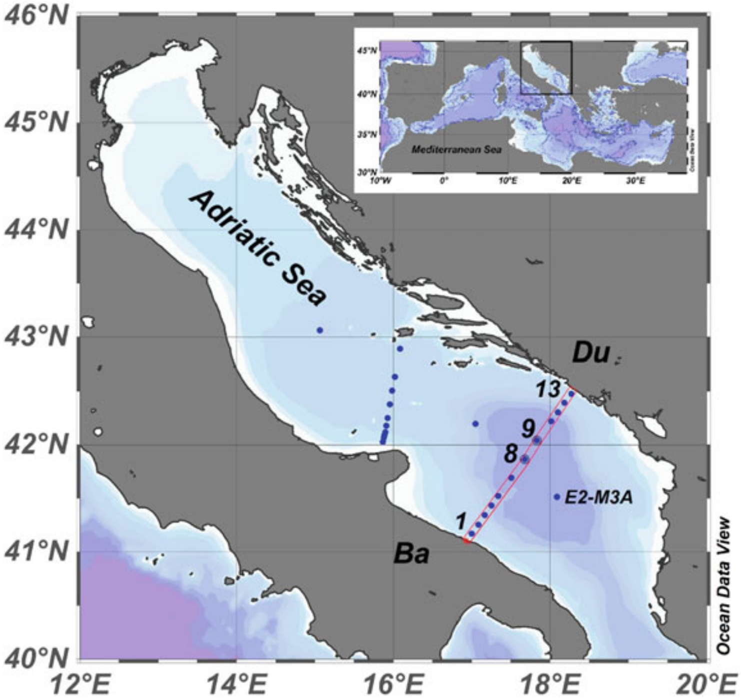

Fig. 6 The Adriatic Sea – Red line indicates the Southern Adriatic Pit transect

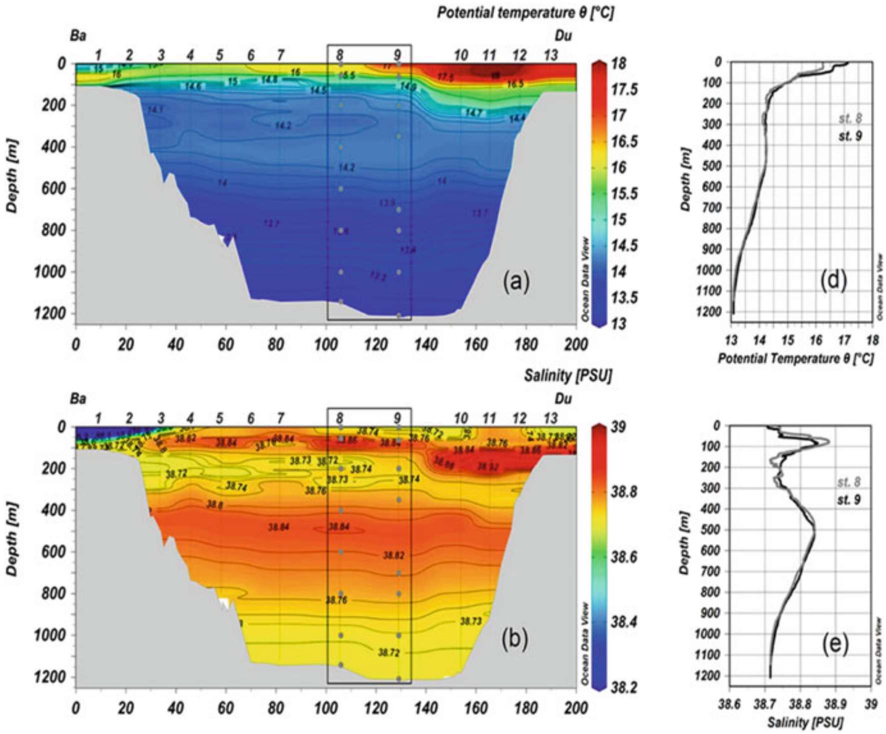

Fig. 7 Vertical distribution of (**a**) potential temperature, (**b**) salinity, and vertical profiles data collected in December 2015

The parts of data (temperature and salinity) collected during winter cruise on the station 8 and 9 (data collected in the Southern Adriatic Pit) are presented in Fig. 7.

In December 2015, the upper layer (the water column between the surface and 100 m depth) along the Ba-Du section was quite heterogeneous, which might be due to the contrasting water masses transported into the SAP by the Eastern Adriatic Current along its eastern side [2] and by the Western Adriatic Current along its western side (Fig. 7). In particular, relatively warm and saline waters moving along the eastern margin of the SAP protruded offshore, reaching the central zone of the pit (Fig. 7a, b) due to local cyclonic circulation. There complex features, such as mesoscale eddies, determine large thermohaline differences among close stations, especially between stations 8 and 9 [13]. The upper intermediate layer, between 100 and 400 m, although more homogeneous, was characterized by the presence of water with properties ($\theta > 14.30$°C and S up to 38.95 psu) typical of the Ionian surface water and the LIWs/CIWs (Levantine/Cretan Intermediate Waters). In the central zone of the SAP, θ gradually decreased with increasing depth, while S had a structure with alternating fresher and saltier layers. Moreover, between 200 and 300 m depth, a branch of fresher water with local S minimum ~38.70 psu extended from the western flank towards the center of the pit (Fig. 7b).

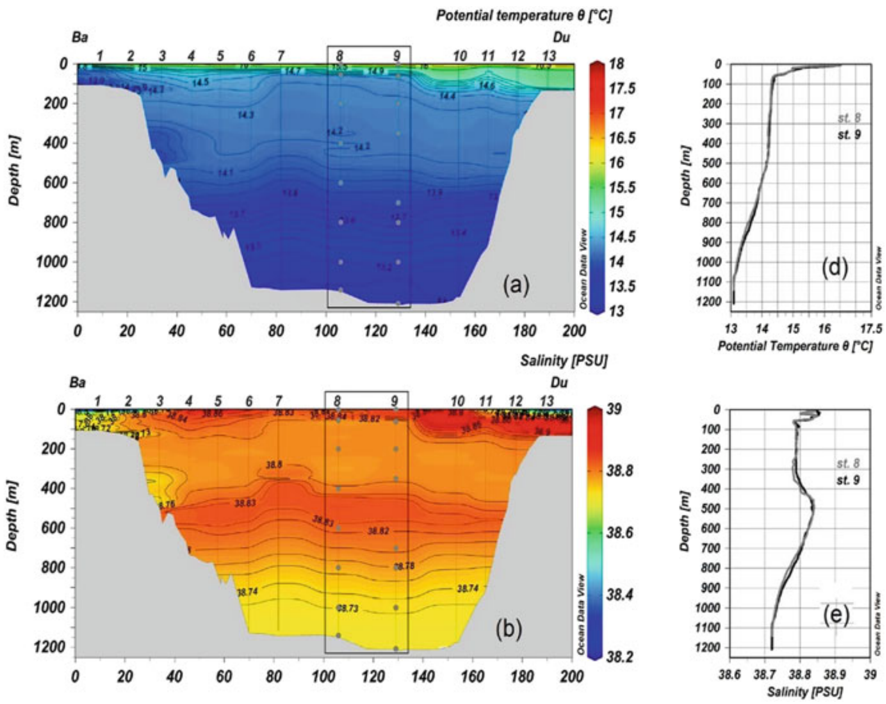

Fig. 8 Vertical distribution of (**a**) potential temperature, (**b**) salinity, and vertical profiles data collected in April 2016

In the lower intermediate layer, between 400 and 800 m, instead, S increased up to 38.84 psu, while θ slightly decreased down to 13.60°C. The deep layer (>800 m) of the SAP was occupied by relatively cold, less saline, and dense waters likely formed during previous winters in the northern Adriatic. At the time of the cruise (December 2015), θ and S in the deep layer had values of 13.10°C and 38.71 psu, respectively [13].

The data collected from the second cruise in April 2016 (Fig. 8) shows the largest differences with respect to the previous cruise in December 2015 particularly in the upper layer temperature, due to the season signal. The temperature differences between the western and eastern flanks, as well as between the surface and bottom layers over the western shelf, diminished with respect to December 2015 (Fig. 8). At the two nearby stations, 8 and 9, the thermohaline properties were almost uniform. The highest S values (~38.94) measured in April 2016, associated with the LIW influence, and were slightly lower than those observed in December 2015 (~38.95). From the physical parameters, we inferred that the doming structure, typical of the cyclonic circulation in the SAP, was much more enhanced in April than in December. This means that the subbasin-scale cyclonic gyre was probably stronger in April than in December, favoring lateral exchanges along the perimeter of the SAP. The lateral exchange between both coastal flanks and the middle of the transect seemed less active with respect to December 2015 [13].

4 Conclusion

The Adriatic Sea was explored in detail during the previous period. Hydrographic and oceanographic data are available and well explained. However, climate change has a great impact on the hydrographic and oceanographic characteristics of the Adriatic Sea; therefore, it is necessary to continue research in the future to obtain new information.

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