Annual of Sofia University "St. Kliment Ohridski", Faculty of Physics, Volume 109, 2016

DEEP BLACK SEA CIRCULATION DESCRIBED BY ARGO PROFILING FLOATS

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Милена Миланова, Елисавета Пенева. ДЪЛБОЧИННА ЦИРКУЛАЦИЯ НА ЧЕРНО МОРЕ, ОПИСАНА ОТ ПРОФИЛИРАЩИ СОНДИ АРГО

Програмата Арго за Черно море стартира през 2002. Оттогава са пуснати в действие 29 сонди, които са генерирали ~3600 профила на термохалинните характеристики на морето в слоя до 2000 m. Сондите плават на фиксирана дълбочина и високата времева резолюция на техните данни (повечето сонди правят пълен цикъл за 5 дни) позволява да се използва дълбочинното им преместване като индикатор на дълбочинните теченията на тяхната паркираща дълбочина (варираща между 200 и 1000 m). В това изследване е направено проучване на дълбочинната циркулация, описана от траекториите на скорошните Арго сонди на четири дълбочини (200, 350, 750 и 1000 m). Резултатите са анализирани отделно за различните времеви мащаби: сезонно и междугодишно разпределение. Главните резултати могат да бъдат обобщени по следния начин. Дълбочинната циркулация е подобна на тази на повърхността, като скоростта намалява с дълбочината. Като цяло теченията са по-силни в близост до брега и по-слаби в открито море, а най-големите скорости се наблюдават по южния бряг. Сезонните вариации на теченията са по-изразени в близост до повърхността и намаляват с дълбочината. Наблюдава се междугодишна изменчивост на всички 4 изследвани нива.

Milena Milanova, Elisaveta Peneva. DEEP BLACK SEA CIRCULATION DESCRIBED BY ARGO PROFILING FLOATS

The Black Sea Argo program has been initiated in 2002 and since then 29 Argo floats have been deployed generating ~ 3600 profiles of the termohaline properties of the sea in the 2000 m water column. The floats drift at a fixed depth, so the high temporal resolution of the data (float cycling period of ~5 days) allows to use the floats' displacement as an indicator of the deep sea currents at their parking depth (varying from 200 m to 1000 m). In this study an investigation of the deep circulation derived from the recent Argo floats trajectories is performed at 4 depths (200, 350, 750 and 1000 m) and the results are analysed separately for the different time scales: seasonally and inter-annually. The main results could be summarized as: The deep circulation is similar to the surface circulation and the speed decreases with the depth; Overall the currents are stronger closer to the shore and weaker in the open sea and the largest speeds are observed along the South coast; The seasonal variations of the currents are more significant closer to the surface and decrease with depth; There is an inter-annual variability observed at all 4 levels investigated.

Keywords: Black Sea circulation, Argo profilers
PACS numbers: 92.10 ad, 92.10ak

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1. INTRODUCTION

The Black Sea is one of the largest inland basins of the world with a surface area of ~4.2×10^5 km^2 (zonal and meridional dimensions ~1000 km and ~400 km) and a maximum depth of ~2200 m. It is almost completely isolated from the world oceans; it is connected to the Sea of Azov via the Kerch Strait in the North and to the Marmara Sea (which is connected to the Aegean Sea through Dardanelles Strait) via the Bosphorus in the southwest.

The Black Sea is characterized by a basin-wide cyclonic boundary current (Rim Current) which is formed by several factors: the curl of the wind stress field and the fresh water discharges from rivers (buoyancy forces), bathymetry and thermohaline fluxes [1]. The Rim current is quasi-geostrophic thus it engages the surface and several hundred meters water column. In addition to the Rim Current, the Black Sea circulation system contains many mesoscale eddies (see Figure 1), meanders and filaments spread over the basin. The Rim Current separates the cyclonically dominated inner basin from the anticyclonically dominated coastal zone [1].The Sinop and Kizilirmak [1], Batumi, Bosphorus, Sukhumi, Kerch, Sevastopol, Danube, Caucasus, Constanta, Crimea and Sakarya eddies reside on the coastal side of the Rim Current zone. In the inner basin, two cyclonic cells (Western Gyre and Eastern Gyre) are formed [2].

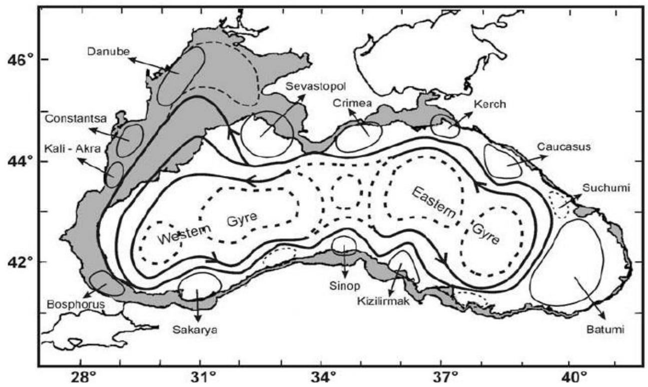


Fig. 1 Main features of the Black Sea circulation system [2]

The deep-layer circulation and thermohaline structure in the Black Sea have been traditionally accepted to be sluggish and rather invariant at seasonal-to-inter-annual scales.

The early studies [3] claim that the underwater circulation in the 150–500 m layer is similar to the surface one with higher speed currents around Bosporus, Sukhumi and Cape Sarich, as well as the section Bafra–Sochi.

Various cruises of research vessels later have been conducted in the Black Sea during the ends of the 80's and the early 90's making large data sets available for studying the oceanography of the Black Sea. The thermohaline structure, hydrographic properties and the circulation of the Black Sea has been studied [1, 4, 5]). The R/V Knorr 1988 expedition and the multi-ship hydrographic surveys carried out within the framework of the HydroBlack and ComsBlack Programs during the early 1990s constituted the first reliable data sets for exploring deep-water physical characteristics of the Black Sea [4–7]. One of the most important findings of these studies was an indication of horizontally as well as vertically highly structured flow systems formed by a series of large mesoscale eddies (with typical size of about 100 km) and sub-basin-scale gyres (with typical size of several hundreds of km's) within the intermediate layer between 300 and 1000 m. These observations provided only the baroclinic component of the circulation, however, they underestimated the intensity and additional contribution of the barotropic structure of the flow field, particularly along the strong topographic slope zone around the periphery of the basin. While valuable for describing in a qualitative sense large-scale basinwide circulation of the intermediate and deep layers, the geostrophic method applied to hydrographic observations was often unsatisfactory because of the questionable ‘‘level of no motion’’ assumption. The strength of the intermediate layer flow was partly elucidated by the ADCP absolute current velocity measurements carried out during April 1993 in the western Black Sea. These measurements reported for the first time relatively strong sub-pycnocline currents up to 10–20 cm s^{-1} within the 200–350 m layer [8], the latter depth being the approximate limit of the ADCP measurements [9].

However when cruises are conducted the data collected represents only a snapshot of the conditions in space and time. In addition, cruises are expensive and time intense and the countries surrounding the Black Sea cannot conduct cruises on a regular basis.

In this paper another method to describe the deep circulation is used based on the Argo autonomous profiling floats displacement.

2. CURRENTS MEASUREMENT

In oceanography and in fluid dynamics in general, our observations can be made in two ways: Lagrangian measurements and Eulerian measurements.

One way to measure ocean currents is to determine the water's velocity at one fixed place in the ocean. This type of measurement is called Eulerian**.** This is typically accomplished using an electro-mechanical current meter (which measures the velocity at a single depth) or Acoustic Doppler Current Profiler (ADCP) (which can provide a profile of velocity with depth).

Another direct way to measure ocean currents is by tagging a water material with either floats or dyes. This viewpoint of following a tagged water parcel is called Lagrangian. Near-surface ocean currents are measured by so-called drifters, which is a buoy that rides at the ocean surface and is usually weighted at some depth to negate the direct effects of wind on the buoy itself. Tracking this drifter (by satellite, radar, radio, sound, etc.) will give a description of the ocean current.

Following the pioneering development by John Swallow in the 1950s, neutrally buoyant floats have been a central element of global ocean circulation observations with highly temporal and spatial resolution [10].

3. ARGO PROFILERS DATA

The origins of Argo come from the World Ocean Circulation Experiment (WOCE) held in 1990–1997. This experiment was part of the World Climate Research Programme (WCRP) and its mission was to collect an unprecedented set of observations in the deep ocean. The main focus of WOCE was the necessity to collect data on ocean currents at about 1000 m throughout the oceans. In order to do this Russ Davis from Scripps Institution of Oceanography in California and Doug Webb of Webb Research Corporation developed the Autonomous Lagrangian Circulation Explorer (ALACE) [11,12]. The floats ALACE use the principle of neutral buoyancy developed by John Swallow in the mid-1950s to follow the currents at a particular pressure level [13]. Each of the floats ALACE rose to the surface in regular intervals and its position was detected by a satellite. The scientist realized that, while rising to the surface, the floats could measure the salinity and the temperature of the ocean's water. Until the end of WOCE most of the floats were provided with salinity/temperature sensors.

In the 1998 Dean Roemmich of Scripps Institution of Oceanography and Ray Schmitt of Woods Hole Oceanographic Institution explored the potential of using profiling floats for monitoring the ocean. The name ARGO comes from the abbreviation Array for Real-time Geostrophic Oceanography (ARGO**)**. For the first time the physical state of the upper layer of the ocean is systematically measured and the advantage of Argo is that it is not confined to major ship expeditions that vary with seasons like other observing networks are.

In 2000 the deployment of floats has started and until 2007 the original goal of 3000 floats is achieved [14]. The global array of 3000 floats was distributed roughly every 3 degrees (300 km). The 3° by 3° array satisfies both the requirement for sampling global anomalies in temperature and heat storage and also provides reasonable signal-to-error characteristics for sampling large-scale oceanic variability corresponding to the global altimetric data [15]. The latest picture of the Argo array (Figure 2) shows that the coverage of the ocean is well distributed, except for some parts of the southern seas.

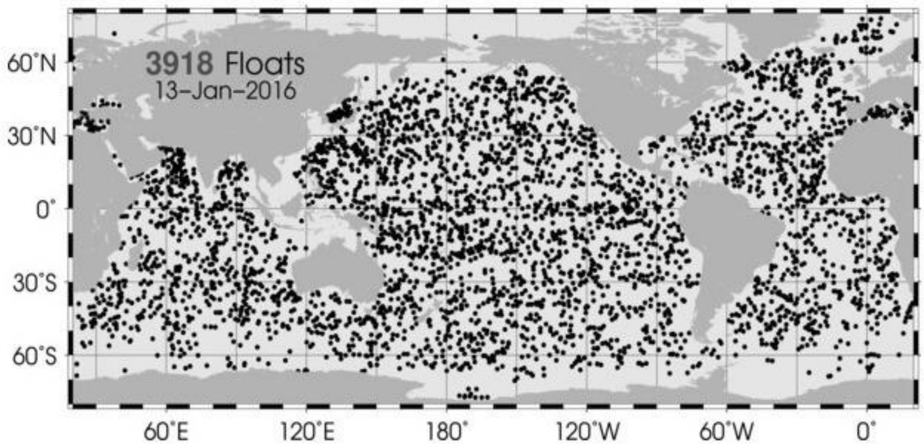
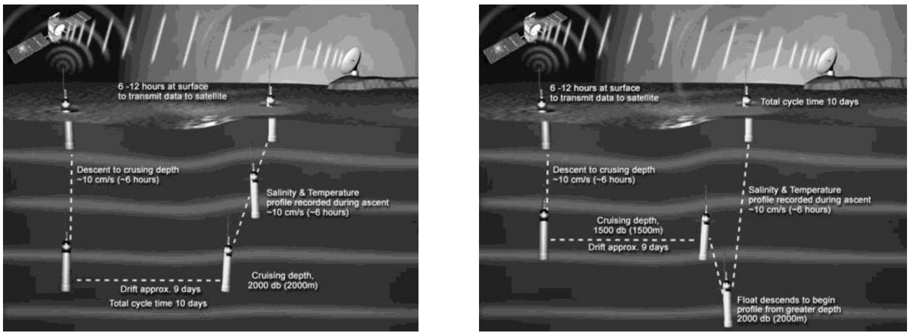


Fig.2 Latest picture of Argo array

The profiling floats are powered by batteries and spend most of their lifetime at depths where they are stabilized by being neutrally buoyant (parking depth). Currently the most commonly used Argo profiling floats are 3 types. All work similarly, but differ in the characteristics of the design. During a given interval, programmed in advance, the floats pump fluid into an external bladder and rise to the surface for about 6 hours while measuring salinity, temperature and other characteristics, if equipped with appropriate sensors. When they are on the surface, satellites determine their position and receive the collected data. The bladder then deflates and the float returns to its original density and sinks to drift until the cycle is repeated. Floats are designed to make about 150 such cycles and after that the battery dies.

Generally, there are two standard operational missions (Figure 3): the first one is simple operational mission and the other one is a park and profile mission. In the simple operational mission the float descents to a certain depth (usually 2000 m) and then it starts the salinity and temperature profile. In the park and profile mission the float descends to its parking depth, recommended 1000 m, drifts at this depth for some time then descends to 2000 m and starts ascending while measuring temperature and salinity [16].

The Argo data are widely used for reconstruction of termohaline 3D fields in the ocean. But yet another very useful application is to derive the map of the deep ocean currents. The simplest way to estimate the deep displacement is to use the first Argos fix from the present cycle and the last Argos fix from the previous cycle. The simplest method assumes a linear movement between the two points; other more complex methods take into account the inertial movement. This was done by [17] for their YoMaHa'07 displacement/velocity file. This dataset contains data from 4284 floats which provided 296974 estimates of velocity at a float's parking depth in the period 1997 to 2007.



a b

Fig. 3. a) Simple operational mission; b) Park and profile mission

4. BLACK SEA RESULTS

The Argo autonomous profiling floats operate in the Black sea since 2002 but in more consistent way they have been deployed after 2010. Since then 22 floats were deployed, in the frames of different programs, from which 9 are still operating (Table 1). Six years of continuous measurements with Argo accumulated sufficient amount of data to make possible analysis of the Black sea deep circulation.

For calculating the Lagrangian velocity of displacement, we assume that the movement is linear and we use:

$$v_n = \frac{x_n - x_{n-1}}{\Delta t} ,$$

where Δt = 5 days is the time between the communicated measurements and $x_{n,n\text{-}1}$ are the two consecutive positions of the float.

Table 1. Argo floats in the Black sea 2010–2015

Float N	Number of profiles	Parking Depth [m]	Start Date	End date
1901200	234	200	08/12/09	22/02/13
6900803	168	750	19/03/11	01/07/13
6900804	168	750	19/03/11	01/07/13
6900805	351	750	18/03/11	still working
6900807	76	200	28/11/14	still working
6901828	65	200	30/09/13	23/08/14
6901831	107	200	18/07/14	still working
6901832	96	350	12/09/14	still working
6901834	8	350	27/11/15	still working
6901895	176	750	02/08/13	still working

6901896	85	200	04/08/13	05/10/14
6901899	37	500	02/05/14	10/11/14
6901900	122	200	02/05/14	still working
6901959	210	200	08/06/12	21/04/15
6901960	26	350	09/06/12	14/10/12
6901961	210	200	06/11/12	19/09/15
6901962	214	200	17/08/12	20/07/15
7900590	135	750	29/08/13	02/07/15
7900591	112	200	16/12/13	still working
7900592	79	200	15/12/13	25/10/14
7900593	63	1000	29/06/14	15/04/15
7900594	39	1000	29/06/15	still working

The high temporal resolution of the data (float cycling period of 5 days generally) allows to use their deep displacement as an indicator of the deep sea currents at their parking depth (varying from 200 m to 1000 m). Fig. 4 shows the positions of the available floats which are used in this study. It is seen that the whole basin is covered by observations excluding the shallow northwestern shelf part. Furthermore, in this figure a distinction between the seasons is made to prove that each season is well represented (this is usually not the case in the oceanographic ship measurements when the cold part of the year is much less monitored). The seasons are defined as follows: winter is the mean value for the months January, February and March; spring – April, May and June, and so on.

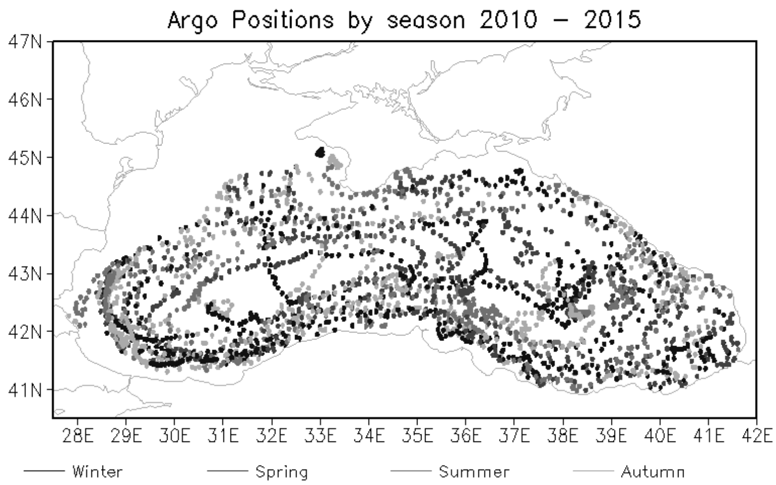
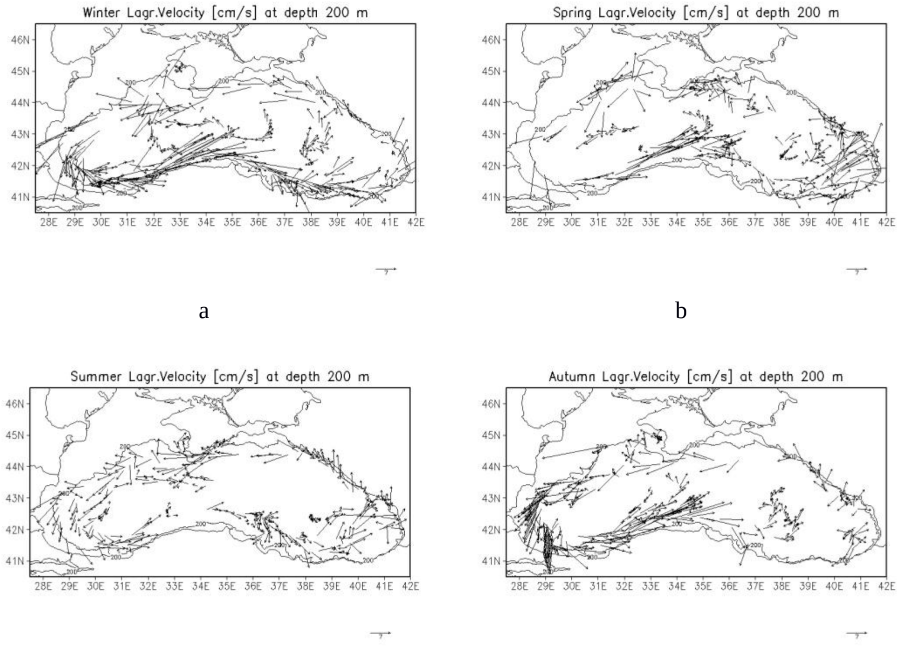


Fig. 4 Argo positions coloured by season in the period 2010–2015

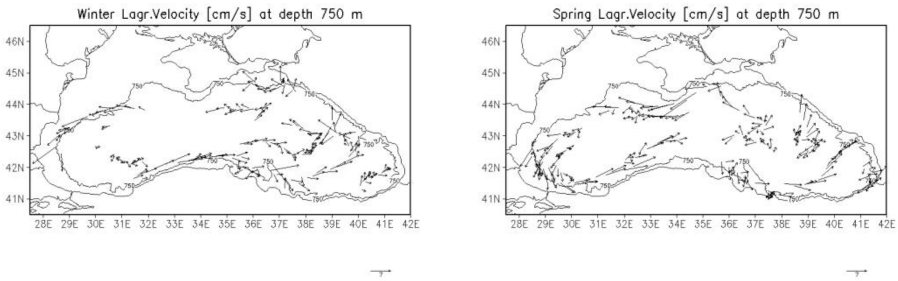
Most of the floats drift at parking depth 200 m (11 floats), those drifting at 750 m are much less (5 floats), 3 floats drift at 350 m and 2 – at 1000 m.



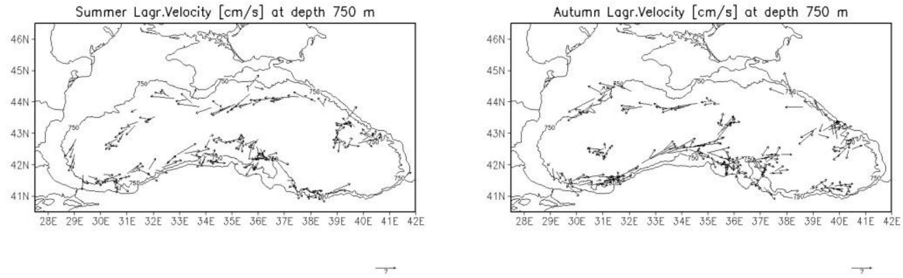
c d

Fig. 5. Lagrange speed [cm s^{-1}] at depth 200 m in: a) winter, b) spring, c) summer, d) autumn

In Fig. 5, the speed of displacement of the floats, drifting at parking depth 200 m, is presented, and as in the previous figure the distinction between seasons is made (a to d). This is done the same way for the floats with parking depth 750m (Fig. 6a–d). For the floats drifting at 350 m and 1000 m all 4 seasons are shown in one figure, as the figures are based by only 2–3 floats measurements (Fig. 7a and 7b).

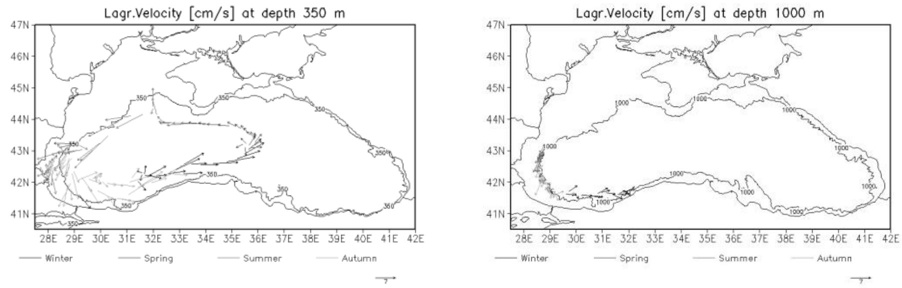


a b



c d

Fig. 6. Lagrange speed [cm s^{-1}] at depth 750 m in: a) winter, b) spring, c) summer, d) autumn



a b

Fig. 7. Lagrange speed [cm/s] at depth: a) 350 m, b) 1000 m

The deep circulation as a rule follows the deep Rim current branch, as the Argo floats are being captured by this current. The largest speeds are observed along the South coast especially in the Sakarya and Sinop – Kizilirmak areas. At 200 m in winter (Fig. 5a) in those areas the currents' speed exceeds 30 cm s^{-1}. Another region with higher velocity is the Crimean region, where in winter speeds up to 15–20 cm s^{-1} can be observed. In general during the summer the currents are weaker than in the other seasons. Even in the Sakarya – Sinop-Kiziliramak area, the speeds are rarely higher than 10 cm s^{-1}. However, this is not so evident at depth 750 m and 1000 m, where the seasonal variability is less pronounced and during whole year the speed is similar.

Overall the currents are stronger closer to the shore and weaker in the open sea. In the inner parts of the Black sea the speed is no higher than 5 cm s^{-1}.

As a rule, the speed decreases with the depth. We can notice this by comparing Fig. 5, 6 and 7. At 750 meters (Fig. 6a–d) close to the shore, where the currents typically are the strongest, the speed of displacement of the float is around 10 cm/s. At 1000 m (Fig. 7b) the currents are between 1 and 5 cm s^{-1}.

Another interesting question is if there is a significant inter-annual variability of the deep currents. This is difficult to retrieve as the number and positions of the floats vary in time so the years are not exactly comparable to each other. We show the simple average Lagrange speed for the 6-years period 2010–2015 at the depths 200 and 750 m (Fig. 8) because at 350 and 1000 m we don't have enough data. From the plot it is seen that at 200 m the circulation was definitely stronger in 2010. After a slowdown in 2011, a smooth acceleration of the currents until 2014 could be noticed (Fig. 8, upper plot).

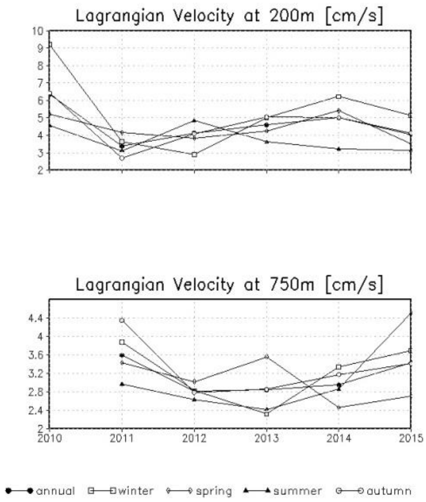


Fig. 8. Annual mean currents speed in the period 2010–2015

At 750 m (Fig. 8, lower plot) the strongest currents were in 2011. After that year, another noticeable increase, especially in the summer, is observed in 2015. From this short period one could speculate that the deeper layer (750 m) variations are delayed from the upper layer (200 m) by one year. Interesting fact is that summer and winter circulation tend to be opposite: when the winter currents intensify, then the summer currents weaken.

The explanation of what is observed is yet to be discussed. The currents in the Black Sea are dependent on the atmospheric circulation, fresh water fluxes, deep water formation processes and thermohaline structure so there is a complicated chain of interconnected processes. In order to find the correlations many different sources of data should be used and this could be subject to future work. Nevertheless, the present paper is a valuable contribution to our knowledge on the deep Black Sea circulation which at present is very limited.

4. CONCLUSIONS

In this study the possibility to retrieve the deep circulation in the Black Sea from the displacement of the autonomous Argo floats is investigated. The main features of the Black Sea known from the literature are discussed in the introduction section. The deep currents are one of the most difficult oceanographic element to determine from observations as the measurements are limited both in space and time. The Black Sea Argo program has been initiated in 2002 and since then 29 Argo autonomous profilers have been deployed generating ~3600 profiles of the thermohaline properties of the sea in the 2000 m water column. Apart from the valuable measurements of the water column properties, the floats' movement with the currents at their parking depth could give information about the deep sea circulation. In fact what could be measured is the Lagrange speed of displacement as we know only the starting and ending positions without information about the movement in between. In this study the data from 21 Argo floats in the period 2010–2015 are used to calculate the Lagrange speed at 4 different depths: 200, 350, 750 and 1000 m. The results are analysed separately for seasonal and inter-annually variations. The main results could be summarized as: 1) The deep circulation is similar to the surface circulation and the main cyclonic Rim current engage the whole 0–1000 m layer; 2) The largest speeds (~30 cm s^{-1} at 200 m) are observed along the South coast especially in the Sakarya and Sinop – Kizilirmak areas in winter; another place of intense horizontal movement is around Crimean Peninsula; 3) Overall the currents are stronger closer to the shore and weaker in the open sea; 4) The speed generally decreases with the depth; 5) The seasonal variations of the currents are more significant closer to the surface and decrease with depth; 6) There is an inter-annual variability observed at all 4 levels investigated.

The explanation of what is observed is yet to be discussed. Nevertheless, the present paper is a valuable contribution to our knowledge on the deep Black Sea circulation which at present is very limited.

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