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South Caspian vertical circulation during rapid sea level rise and fall

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ABSTRACT

The Caspian Sea as the largest land-locked water body is very sensitive to the environmental changes. The rise and fall of the Caspian Sea level has significant impact on the environment and coastal communities. Using extensive deep water measurements in the south Caspian Sea, we have examined the role of sea level changes on the vertical water exchange. While the deep water ventilation happened during sea level fall (70s of 20 century), coastal lagoon expansion and marine stagnant circulation state were the major impacts during rapid sea level rise (1980-1995). The marine environment however benefits the rapid sea level fall. During sea level fall, vertical circulation penetrates deeper and faster which distributes oxygen and nutrient more effectively in the water column. It provides the condition for enhanced bio-productivity. However, the current global warming could prevent the impact of lowstand to faster circulation. The present rapid sea level fall displays new impacts on the marine environment, reflecting as hypoxia.

Keywords: Deep water circulation, Caspian water masses, water ventilation.

INTRODUCTION

The Caspian Sea encircled by five coastal states has experienced rapid sea level fluctuations during instrumental measurements (Kroonenberg *et al*. 2000; Arpe & Leroy 2007). The Caspian Sea level fluctuations in historical and geological time scale were much higher than that in the present time (Varushchenko *et al.* 1987; Rychagov, 1997; Naderi *et al*. 2013). The Caspian Sea as the largest closed-water body is very sensitive to the global and regional climate changes and variability. Therefore, it could play the role as microcosm or micro ocean in investigating the environmental changes (de Mora & Turner 2004). The Caspian Sea and its coastal environment encompasses valuable species, which have been adapted in this area since enclosing. During the last sea level rise since 1979 coastal inundation has happened in different extent based on the coastal slope. The role of rapid sea level rise and fall on the deep water circulation has been mentioned by the Soviet investigators since 1930s. The water level fluctuations in the Caspian Sea are controlled by the water influx mainly through Volga River and evaporation from the water surface. Sea level rise is associated with decreased salinity in the north Caspian Sea, while during sea level fall, opposite trend occurs. Deep water circulation is triggered by two main mechanisms: Winter convection and north Caspian freezing. The latter phenomenon occurs annually in that released salt incorporate to dense water formation in the northern part of the middle Caspian Sea. The higher the sea level, the lesser released salt and as a consequence, less dense water could penetrate in the lower depths. During sea level fall, the condition is prone to impose faster and deeper water mixing. This mechanism has strong ecological impact that archive even in the old bottom sediments. Trend of rising sea level stopped in 1995. Thereafter, general ascending trend prevailed and sharp fall happened in 2010 due to summer drought in the Volga basin (Lahijani *et*

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al. 2010; Arpe *et al*. 2012). Nowadays the Caspian Sea level is approximately 1.5 meter lower than that in 1995. Sea level fall could affect the circulation, marine and coastal ecology and navigation.
In this study, we investigate the impact of the past rise and current trend of sea level fall on the Caspian Sea circulation. The aim of this paper is to highlight new environmental consequences in the South Caspian Sea due to natural and anthropogenic pressures.

Geographical setting

Caspian basin

The Caspian Sea, a brackish water environment located at the border of Europe and Asia. The sea surface area is 3.8 x 10^5 km^2, approximately one-ninth if its catchment area (3.5 x 10^6 km^2). The catchment and the sea have meridional distribution, where the former is positioned from subpolar to sub-tropic regions. Morphologically the Caspian Sea is divided into three sub basins: north, middle and south parts. The water depth increases from a few meters in the northern sub basin to over 1025 m in the south one (Voropaev 1986). Fresh water influx enters into the sea from north, west and south coasts, whereas the east coast lacks a permanent river inflow (Lahijani *et al*. 2008). The north sub basin receives around 80% of riverine influx (Frolov 2005; Arpe *et al*. 2014). The surface seawater salinity increases from approximately 1 Practical Salinity Unit (PSU) in the north to 13 PSU in the south (Kostianoy & Kosarev 2005). Vertical change in salinity in deep waters is negligible. The surface seawater temperature also has ascending trend during winter time from the north to the south, while during summer time, the trend is reversed. The north sub basin experiences ice cover during cold seasons. During severe winters, the ice could penetrates into the coastal areas of the middle sub basin (Terziev 1992). There is a high gradient of temperature in vertical direction in deep waters of the middle and south sub basins where the water temperature is approximately 5 °C close to the bottom. Temperature gradient is responsible for seawater stratifications. Therefore, the sea water stratifies vertically in the middle and south sub basins.

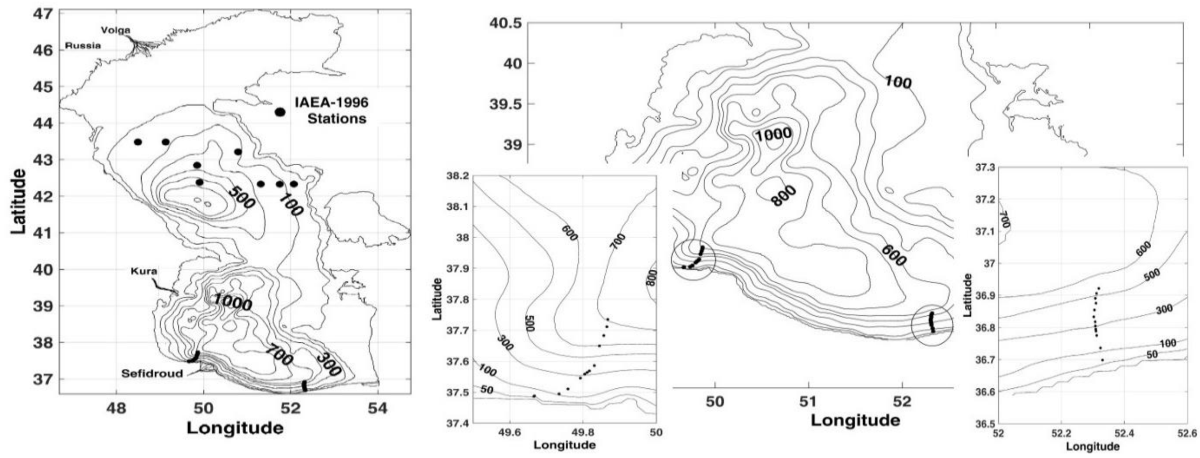

Fig. 1 the Caspian Sea physiography; Top left: Caspian Sea isobaths and the main rivers inflow to the basin, Top middle: IAEA-1996 stations in middle Caspian Sea, Top right: Southern Caspian Sea bathymetry; Bottom left and right: Anzali and Babolsar transects respectively; Stations are specified by dots.

Water strata depend on the inserted forcing. They include severity of winter freezing in the north Caspian sub basin, penetration depth of winter convection and the rate of evaporation in the east coast (Kosarev 1975; Kostianoy & Kosarev 2005). The former is strongly related to the Caspian Sea level changes. Sea level lowstand accelerates the vertical circulation and consequently enhances the mixing condition whereas during the highstand in which stagnant water condition dominates large extent of the sea (Sapozhnikov *et al*. 2010).

Sea level fluctuations

The Caspian Sea has experienced different sea level fluctuations since its isolation from the adjacent seas. Its level oscillated approximately 50 m in the Holocene, 10 m in the historical period and 3 m during the instrumental measurement (Varushchenko 1987; Rychagov 1994; Forte & Cowgill 2013; Naderi *et al.* 2013). The last sea level rise period occurred from 1979 to 1995. Thereafter, it has fluctuated with minor changes showing a general falling trend, with one sharp water level decrease in 2010 (Lahijani *et al*. 2010; Arpe *et al*. 2012). The current sea level

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is approximately 1.5 m lower than that in 1995. Riverine water influx into the basin, and the evaporation over the sea are two main water balance components and their relative changes determine the sea level variation. Direct water consumption in the catchment basin accounts for one meter decline in the sea level since 1960s, the start of vast anthropological activities such as major dam constructions (Frolov 2005). Climate forcing contributes in moisture transfer and evaporation regime over the Caspian Sea and its catchment are responsible for its level rise and fall. Long term climate prediction displays higher temperature for the sea and its catchment as well as variable precipitation patterns in its different parts (IPCC, 2013, 2014). Decreased precipitation will occur in the southern part of the catchment. However, higher latitudes will favor excess precipitation. They could stabilize the sea level in the current falling trend. More decline is expected in the case of higher water consumption.

Table 1. Specifications of data set.

No.	Stations	Data Type	First data set	Second data set	Third date set
1	Anzali transect	IDRONAUT multi probe data (CTD & DO, pH…	October 2016	September 2009	January 2008
2	Babolsar transect	IDRONAUT multi probe data (CTD & DO, pH…	October 2016	September 2009	January 2008
3	Noshahr transect *	IDRONAUT multi probe data (CTD & DO, pH…	November 2017	-	-
4	IAEA *	CTD by sampling	September 1996		
5	Kepco *	IDRONAUT multi probe data (CTD & DO, pH…	March 2014	May 2014	July 2014

* Not included in Figs.

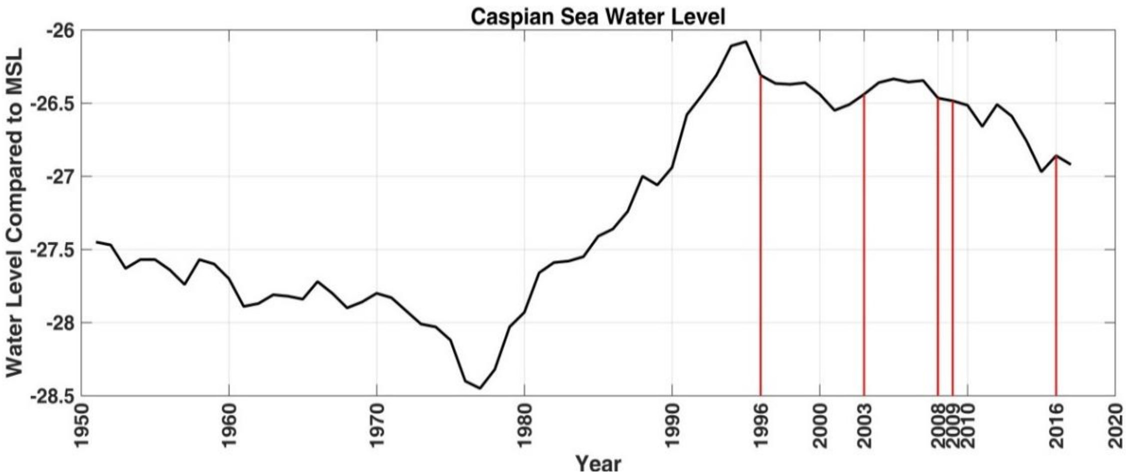

Fig. 2. Caspian Sea level variation. Date of cruises include deep water samplings and over 10 sampling stations are specified by red lines (IAEA: 1996; INIOAS: 2003, 2008, 2009, 2016).

Methodology

Water temperature, conductivity, pressure, dissolved oxygen, and pH measurements were conducted along three profiles around the Anzali, Babolsar, and Amirabad using an Ocean Seven 316 CTD probe (Fig. 1). The CTD passed calibration and laboratory procedures before each field operation. Coastal lagoon shrinking and desiccation was estimated by satellite image and a field campaign. There are several datasets from Caspian Sea acquired from 1995 so far, by Iran Ports and Martime Organization (PMO), Iran Meteorological Organization (IRIMO), Atomic Energy Organization of Iran (AEOI), Iran National Cartographic Center (NCC), Caspian Sea Ecological Research Center (CSERC), Universities and Iranian National Institute for Oceanography and Atmospheric Science (INIOAS). The last one (INIOAS) has more contribution and has performed most of deep water surveys while the other datasets covers coastal zones. Also other countries along the Caspian Sea borders have also performed data acquisitions among which Russia (formerly, Soviet Union) had the main role starting in situ measurements from early 19th century. Small portion of these data sets have been published throughout articles and books and main portion remains unpublished thus far. In this article, we analyzed the CTD data including temperature, conductivity and dissolved oxygen profiles from the southern Caspian Sea acquired by INIOAS, to assess the effect of rapid sea level rise and fall on the vertical circulation in the South Caspian Sea. These data were measured by an IDRONAUT OCEAN SEVEN multi parameter probe during INIOAS Caspian Sea Monitoring cruises in 2008, 2009 and 2016.

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The probe was calibrated in the lab before each measurement and descended from the sea surface to the bottom by speed up to 1 m/s. The QA/QC process were performed on all measured data. The stations were along two transects from the coastline to offshore deep waters around the Anzali and Babolsar cities located at the west and east coasts of the Southern Caspian Sea (Fig. 1).

RESULTS

The temperature profiles along the Anzali and Babolsar transects during late summer of 2009 and 2016 are illustrated in Fig. 3. As shown in this Fig., there is a strong thermocline in which a decreased 15˚C occurs in the top 30 meters. So that, the water temperature falls from 25˚C to 10˚C. Temperature near the sea bed is approximately 6˚C and remains constant throughout the year. The salinity profiles of 2009 in Fig. 4 show a relatively more fresh water layer compared to the surrounding in about 50 meters depth probably due to local rivers run off, but there is not any thermohaline in the water column. This run off appears as a band of high values in the dissolved oxygen profile in Anzali (Fig. 5). Except the coastal freshwater tongue, vertical and horizontal variation in salinity is negligible. Dissolved oxygen changes drastically from surface to bottom. Despite low water temperature from depth of 200 m which favors more solubility of oxygen, the water displays hypoxia condition. Temperature and dissolved oxygen have strong vertical stratification. However, the salinity stratification is not profound. The T-S diagrams for data from all stations in 2016, 2009 and 2008 are designated in Fig. 6 exhibiting that the two late summer T-S diagrams of 2016 and 2009 are different from winter diagram in 2008, where the latter displays water masses with negligible temperature gradient. In all diagrams two water masses are clearly distinguishable. The first one is a warm, well-mixed and oxygenated surface water mass with an average thickness of 200 m. The second one is a deep water mass that encompasses the whole water column beneath 200m. The deep water mass is cold and poor ventilated.

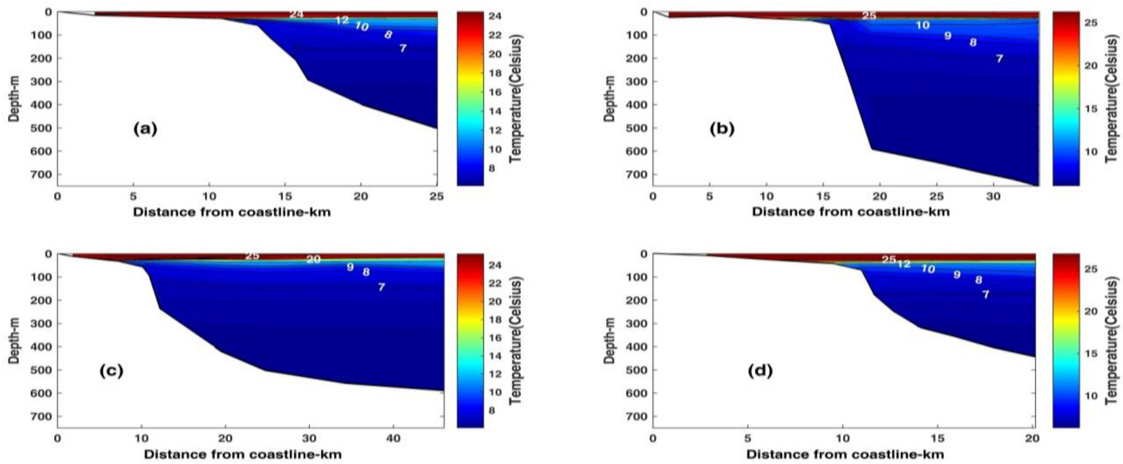

Fig. 3. Water Temperature; **a** and **b**: Anzali transect; **c** and **d**: Babolsar transect, in October 2016 and September 2009 respectively.

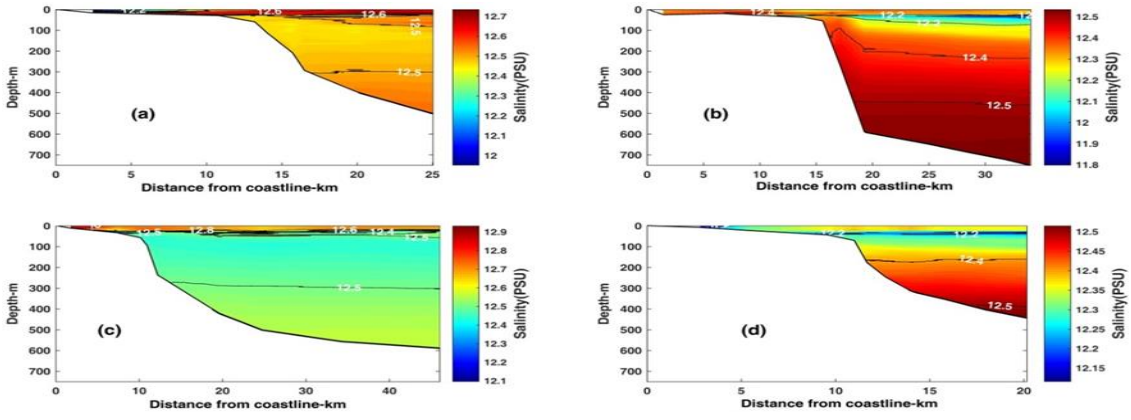

Fig. 4. Water Salinity; **a** and **b**: Anzali transect; **c** and **d**: Babolsar transect, in October 2016 and September 2009 respectively.

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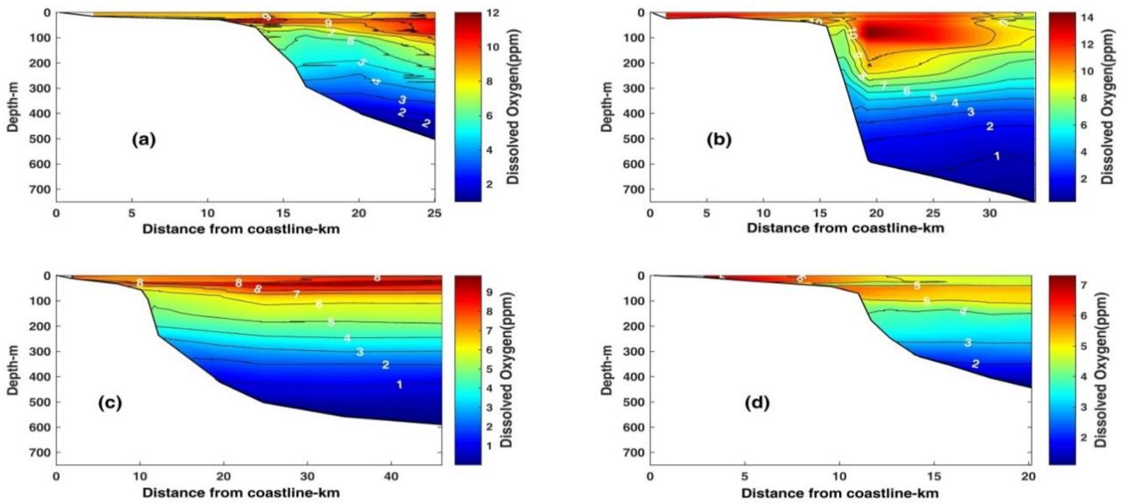

Fig. 5. Dissolved oxygen; **a** and **b**: Anzali transect; **c** and **d**: Babolsar transect, in October 2016 and September 2009 respectively.

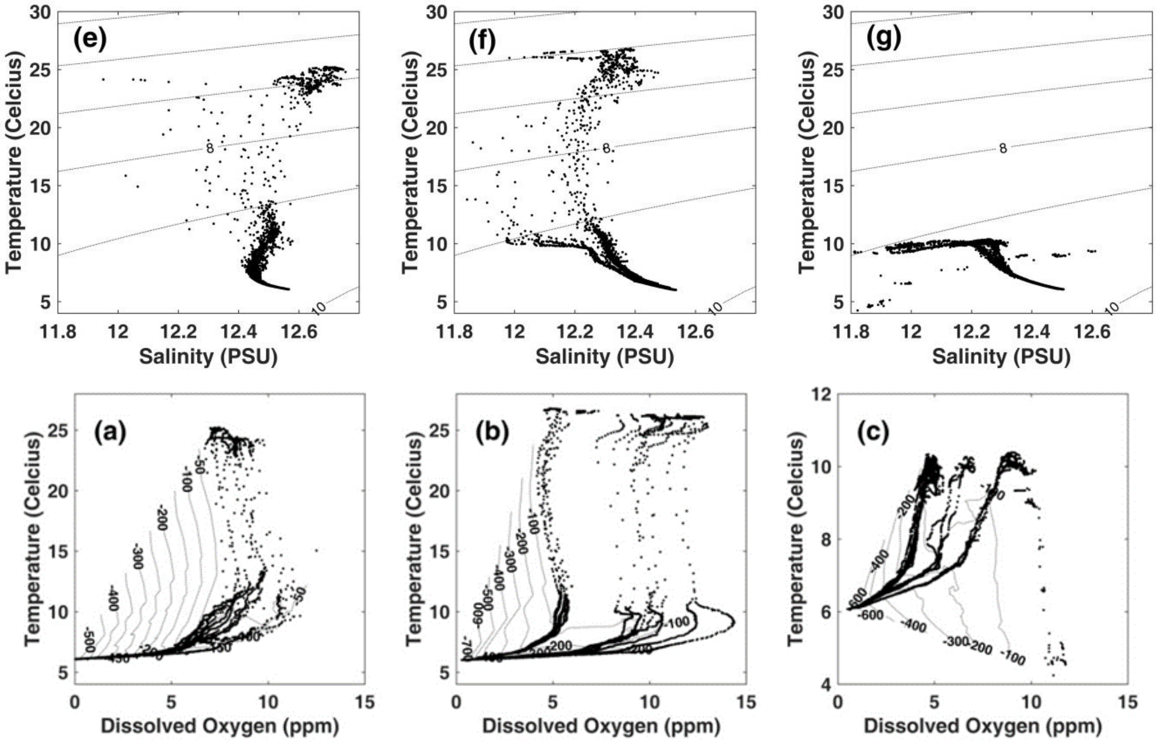

Fig. 6. T-DO and T-S Diagrams based on Anzali and Babolsar transects data; **a & e**: October 2016; **b & f**: September 2009; **c & g**: January 2008.

DISCUSSION

Vertical mixing

The Caspian Sea possesses different water masses with relatively distinctive physical and chemical specifications. Momentum and material exchanges among these water masses dispense material and energy within the Caspian environment from the surface to the bottom. Four water masses encompass the Caspian water column including the north, the surface middle and the surface south, the deep middle and the deep south Caspian water masses (Kostianov & Kosarev 2005; Ghaffari *et al.* 2010; Lahijani *et al*. 2019). The presented observations demonstrate presence of two water masses in the south Caspian sub basin. The winter convection and the north Caspian freezing are two main drivers for mixing of these two water masses, where the latter has vital role in vertical mixing of the Caspian Sea. Intensification and weakening of vertical mixing is attributed to the sea level fluctuations and hydrological processes in the north Caspian sub-basin (Kostianoy & Kosarev 2005). During the

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lowstand, salinity of the north Caspian water elevates (mainly in the area adjacent to the middle Caspian). It releases more salt during winter freezing than usual condition which makes dense water to sink into the deeper parts. This mechanism triggers the whole Caspian ventilation system that distributes nutrients and oxygen and also favours bio-productivity. Sea level rise in the Caspian Sea is also associated with high Volga discharge into the north Caspian Sea which in turn decreases the water salinity. During freezing period of winters in the north, less salt is incorporated to form dense water and as a result, it has not enough density to penetrate into deep part of the middle sub basin. The higher severity (sum of days with temperature below zero) of winter could accelerate circulation in the sea through both north Caspian freezing and convection (Terziav 1992). As observed in the past extreme sea level fall in 1970s, one could expect the similar condition in deep waters since 2010 with rapid sea level fall. However, the global warming which affects the air and water temperature in the region, has prevented acceleration of the vertical mixing.

Impact of Caspian Sea level changes and global warming on marine environment

The Caspian rapid sea level fall imposes various impacts on the coastal and marine environments which mainly include shoreline retreatment, wetland desiccation and modification in rate of deep water exchange. They could be weakened or deepened by the human intervention and the rate of global warming. The past observations and future projection display the rapid increased air temperature that could have significant impacts on marine environments (IPCC 2013 and 2014). The Caspian Sea deep water circulation has changed significantly during sea level fluctuation (Kostianoy & Kosarev 2005; Sapozhnikov *et al*. 2010, Saleh *et al.* 2018, Lahijani *et al.* 2019). The physiography of the Caspian Sea, riverine input, spatial and temporal distribution of salinity and temperature determine the formation of water masses and circulation processes (Terziev 1992). The water masses have relatively distinctive physical and chemical specifications, and exchanging among them dispense material and energy in the Caspian environment from surface to bottom. The shallow water north sub basin and huge freshwater influx of the Volga River shape a small water mass that is crucial for the sea circulation. This water mass has considerable annual variability in salinity and temperature (Terziev 1992). Upper layer of the middle and south sub basins have form a separate water mass that governs by the overall climate. Wind, wave, current and temperature cause mixing in this layer which has a thickness of approximately 100 m. The Apsheron Sill separates two deep sub basins: middle and south, and prevents free mixing between them. These two deep water masses are different due to physical and chemical characteristics. The former has a lower temperature and salinity and higher dissolved oxygen content compared to the latter. Various mechanisms cause water exchange among these water masses. Starting from the north, freshwaters of the Volga and Ural rivers enter into the sea mainly during spring flooding, and move southward using deeper path way of the western coasts. The Coriolis force and other river influxes supports such large scale movement (Ibraev *et al*. 2010). It moves counterclockwise like a long wave that can be detected by tide gauges as elevated water level up to 45 cm in July (Terziev 1992). The current salinity increases in the arid climate of the east coast and reaches to the north waters. The aforementioned mechanism and direct contact of the north Caspian water mass to the middle and south Caspian surface masses cause water exchange between them. Vertical exchange in the middle mass is caused partially by wind force forming a cyclonic gyre in the center as well as the upwelling along the east and west coast of the middle sub basin (Ibraev *et al.* 2010). Moreover, the intense evaporation along the east coast could form local warm, but saline and dense water penetrating into deeper parts. More extensive water exchange could happen between the water masses due to winter convection and north Caspian freezing. The first one mixes the water column vertically, extent of which depends on the severity, distribution, frequency and duration of the governing cold air masses. During mild winters, it penetrates down to around 200 m in the middle and 100 m in the south sub basins, that is not strong enough to tangle all water mass exchange. During severe winters, it reaches down to the middle Caspian bottom and to the depth of around 400 m in the south sub basin which enables vertical mixing of oxygen and other biochemical elements (Terziev 1992); (Ghaffari *et al*. 2010). The wind, evaporation and winter convection forced vertical mixing are not affected by the current sea level fluctuations. The Arctic type mixing occurs annually in the sea, encompassing whole Caspian water masses (Kostianoy & Kosarev 2005). The strength of this type of mixing is closely related to the severity of winter and the sea level. During sea level lowstand, mixing would be stronger and deeper.

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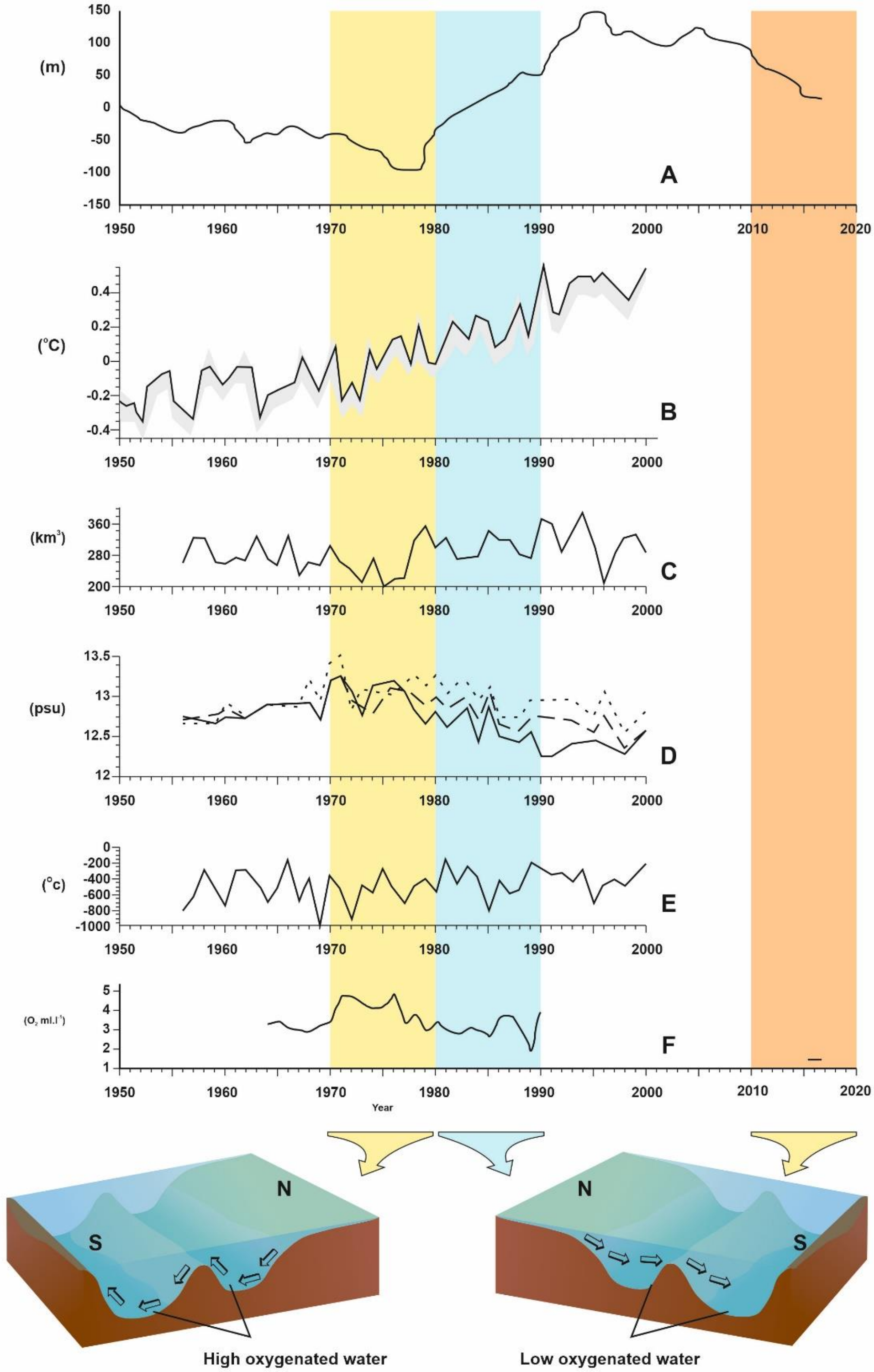

Fig. 7. Reconstruction of the Caspian water exchange using our data set and after Kostianoy & Kosarev (2005), Tuzhilkin *et al.* (2005) and Naderi *et al*. (2013). A: Caspian Sea water level curve; B: World surface air temperature; C: Annual river discharge into the Caspian Sea; D: Water salinity in surface (1), depth of 100 m (2), and 600 m (3) of the Middle Caspian Sea; E: Winter severity; F: Dissolved oxygen.

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In contrast, during the highstand, it fairly could touch deep water masses. The Caspian Sea level highstand and lowstand are correlated to the increase and decrease in the Volga River influx into the north Caspian sub basin. The salinity of the north Caspian water mass increases during sea level fall (decrease of the Volga discharge), and decreases during sea level rise (increase of the Volga discharge). In winter, freezing the north Caspian water mass, partially desalinizes the water and released salinity enters into the contact water of the middle Caspian which is saliniated by the water came from the south along the east coast. Near zero temperature and saline water getting denser close to =11-11.2 and sink deep down into the middle Caspian water mass. This part of the middle mass protrude into the south deep one. The density of middle Caspian Sea waters is shown in Fig. 8. During the freezing, salt releases from ice and makes the adjacent waters saltier. The depth of penetration is strongly controlled by the sea level. In the course of sea level rise, dense water formation is weak and could not sink into deep parts. During sea level fall, the north Caspian water mass is relatively saltier, so could release more salt during freezing, making the adjacent waters denser and also favors a deeper penetration (Fig. 7). High nutrient and oxygen bearing the north Caspian water mass triggers a circulation pattern that engages the whole Caspian Sea water. This mechanism enhances the biochemical condition for the marine productivity and favors fishery after a few years stabilizing the lowstand. The Caspian marine environment would benefit from the current sea level fall and the consequent accelerated circulation that could cause deep water ventilation and nutrient exchange. Arctic type circulation in the Caspian Sea starts from cold season. However, the mild cold seasons in the past years prevent the beneficiary condition of the sea level fall for mixing. The hypoxia in deep water mass of the south Caspian Sea would lead to the low productivity in the future.

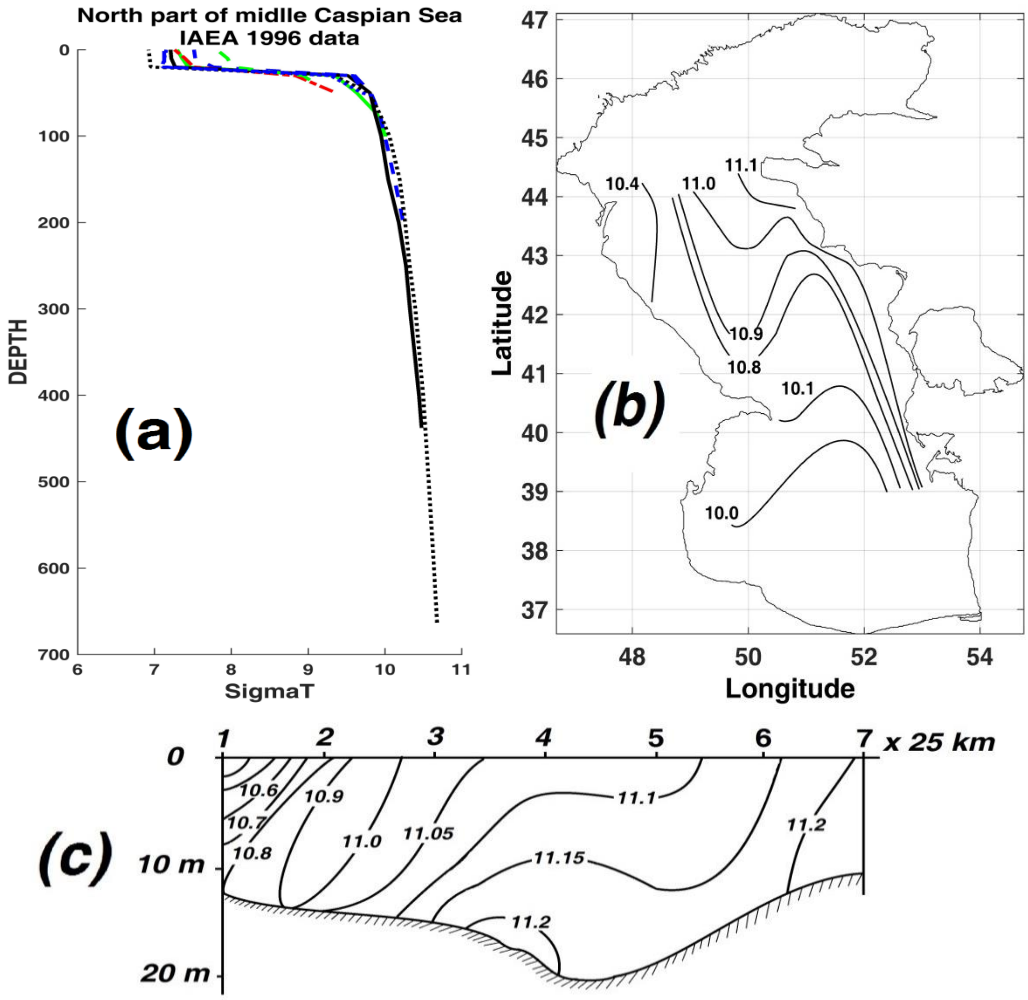

Fig. 8. a) Density profile of 8 stations in Middle Caspian Sea in early September, based on IAEA-1996 data b) Caspian Sea surface waters density-winter and c) Density contours of Chechen-Mangishlak cross-section- winter (Terziev 1992).

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CONCLUSION

The rapid sea-level fall in the Caspian Sea has the opposite marine and coastal environmental consequences. During past sea level fall, the marine environment has benefited from the acceleration in circulation and vertical mixing whereas the coastal area has faced environmental restriction. In the current condition, the sea level is falling rapidly. However, there is no sign of a faster mixing. In contrast, new measurements presented in this manuscript have revealed that the deep parts of the South Caspian sub basin contain a huge water column in hypoxia. The lower ventilation in deep water could worsen the environmental condition to maintain its normal bio-productivity and diversity.

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گردش آب خزر جنوبی در طی دوره‌های افزایش و کاهش شدید تراز آب

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چکیده

دریای خزر به عنوان بزرگترین بدنه‌ی آبی محصور در خشکی در برابر تغییرات محیطی بسیار حساس است. افزایش و کاهش تراز آب دریای خزر تأثیر چشمگیری بر محیط زیست و جوامع ساحلی دارد. با استفاده از اندازه گیری‌های گسترده در آب‌های عمیق در خزر جنوبی، نقش تغییرات تراز آب دریا در مبادله عمودی آب را بررسی کرده‌ایم. در حالی که تسریع در تهویه آب عمیق در هنگام کاهش تراز آب دریا (دهه هفتاد سده گذشته میلادی) اتفاق افتاد، اما گسترش در تالاب ساحلی و کاهش مبادله آب عمیق دریایی پیامد افزایش سریع تراز آب دریا (۱۹۸۰-۱۹۹۵) بود. به این ترتیب محیط دریایی خزر با کاهش سریع‌تر از آب دریا بهبود می‌یابد. در هنگام تراز پایین، گردش عمودی عمیق‌تر و سریع‌تر رخ می‌دهد و در نتیجه اکسیژن و مواد مغذی را به طور مؤثر در ستون آب توزیع می‌کند. این شرایط افزایش تولیدات زیستی را فراهم می‌کند. اما در سال‌های اخیر با گرم شدن کره زمین، مانع از تأثیرگذاری تراز پایین برای تسریع گردش عمودی آب شده است. تراز پایین آب دریا اکنون تأثیرات جدیدی را بر محیط دریایی نشان می‌دهد که به صورت کاهش اکسیژن در لایه‌های زیرسطحی یا هیپوکسی نمایان می‌شود.

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