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Seasonal variations of vertical structure in the deep waters of the Southern Caspian Sea

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Abstract

Seasonal variations of the vertical structure of the temperature and salinity in the Southern Caspian Sea were studied in this paper. The data were measured in one transect, and 9 stations during winter, spring and summer 2013-2014. Comparison of the estimated mixed layer depth using visual and threshold methods revealed that the threshold method underestimates the mixed layer depth. The depth of the mixed layer reaches its maximum in the winter during cooling and begins decreasing with starting the heating season. The temperature of the mixed layer varied in winter, spring and summer, between 10-12 ˚C, 16.5- 25 ˚C, and 25-25.5 ˚C, respectively. Bellow the mixed layer where the gradient of temperature is large, seasonal thermocline locates between 10-70m. The seasonal thermocline comes up with heating in the spring, and its slope reaches its maximum in the summer as the temperature rises. The temperature and salinity variations inside the deep layer, the deepest layer bellow the thermocline is not significant.

Keywords: South Caspian; Vertical structure; Mixed layer; Thermocline.

1. Introduction

The oceans cover more than 70% of the Earth's surface and are one of the largest solar power sources in the world. The thermal energy that lies in the oceans and seas is one of the richest renewable energy sources. One of the ways to use this energy source is Oceans Termal Energy Conversion motors (OTEC). These thermal motors use the difference in temperature between ocean surface and ocean depths and the difference in energy between these two depths for turning turbines and generating electricity (Kulkarni and Joshi, 2016). In addition, the

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changes in vertical water structure from surface to depth, which are affected by changes in physical properties such as temperature, salinity and density that are of great importance and have a direct impact on how the water flows. On the other hand, it affects directly on the biological and chemical properties of the sea. The mixed layer as a part of surface layer is interfaced with the air-sea surface interaction by wind, precipitation, evaporation, ice formation and ice melting and other factors, and as a result, the physical properties such as temperature, salinity and density in this layer are fairly uniform. The depth of mixed layer varies from about 10 to several hundred meters depending on the study area (Stewart, 2008). Due to the fact that the mixed layer and its depth have a lot of influences on the water surface processes, and the exchange of air-sea, bio-chemical interactions and so on are very important. For example, the depth of the mixed layer is directly related to the depth of the sound layer (Helber *et al*., 2007). Also, due to the effect of the mixed layer and its depth on the phytoplankton, the base of oceans food chain, this layer can be determined by the ocean's food chain.

A layer at the bottom of the mixed layer, in which temperature, salinity and density variations are high, and in the profiles of temperature, salinity and density, are respectively named thermocline, halocline and pycnocline. In general, the vertical column can be divided into three major areas: (1) the mixed layer, (2) thermocline, halocline and pycnocline for the profiles of temperature, salinity and density, and (3) the deep layer (Stewart, 2008).

The surface layer contains mixed layer and slope layer (thermocline, halocline and pycnocline), is directly affected by seasonal changes. The mixed layer, the interface between the sea and the atmosphere, plays an important role in climate change, because the transferring of heat, mass and momentum between the air and the sea, as well as inside the thermocline, are controlled by the turbulence inside the mixed layer. The mixed layer depth (MLD) and its variations are very important parameters in heat, mass, and gas exchange between the atmosphere and the ocean. The effects of the mixed layer on the deeper layers are controlled by the thermocline, halocline and pycnocline. The vertical structure of water, especially MLD, has been widely studied in seas and oceans around the world (Schneider and Muller, 1990; Polovina *et al*., 1995; Freeland *et al*., 1997). However, due to lack of field data in the Caspian Sea, especially seasonal data, little information is available on the water vertical structure in this area.

In this paper, first, the studied area in the South Caspian and data base is introduced, then the seasonal variations of the vertical structure of water and the depth of the mixed layer in a transect section are investigated from inshore to the offshore of Neka with about 700 meters depth in the southern Caspian Sea.

2. Materials and methods

2.1. Study area

The Caspian Sea with an approximate area of 400,000 km^2, 7500 km coastline, an average depth of 208m and maximum depth of 1025m, is the largest closed water basin in the world. The Caspian Sea, as the largest lake in the world, despite the secrecy and lack of direct connection with the seas, has unique features such as the magnitude, depth, physical and chemical characteristics that can be classified as a deep inland sea. The difference between the Caspian Sea and other inland seas is that the sea extends along its latitude with respect to its longitude (1000 km versus 200-400 km), which leads to extensive climate variation in the lake. The Caspian Sea is usually divided into three parts: north, middle, and south. The northern part with 80,000 km^2, an average depth of 6-5m, and a maximum depth of 20 meters is the shallowest section and has 24.3% of the total area of Caspian area. The climate of the southern part of Caspian Sea is subtropic, while the northern part completely freezes during the winter and the maximum thickness of ice reaches 40-50 centimeters in January. The middle Caspian has an area of about 140,000 km^2 and a very steep slope in the western part and a slow slope in the eastern part. The middle area ratio to the entire Caspian area is equal to 36.4. The average depth of the middle Caspian Sea is about 190 meters and its maximum depth is 788 meters. The southern Caspian Sea has an area of about 170,000 km^2, separated by an apsheron ridge from the middle section. Southern, southwest and part of the southeastern coasts of the Caspian Sea are surrounded by the Alborz Mountains. The maximum and average depth of water in the southern Caspian Sea is 1025m and 330m, respectively. The salinity of Caspian Sea due to being in the subtropical region is more than the northern and middle Caspian Sea (Kostianoy and Kosarev, 2005).

2.2. Field measurements

The data used in this study is temperature and salinity parameters measured by CTD in the 3 seasons, winter (March 6-7, 2013, phase 1), spring (May 10-11, 2014, phase 2) and summer July 14-16, 2014, Phase 3), which have been measured at 9 different stations. The specifications of the stations are shown in Table 1 and Figure 1.

Table 1. The geographical location and depth of different measuring stations

Station	Geographical location		Approximate depth (m)
	Longitude (E)	Latitude (N)	
St1	51° 20' 07.14"	38° 20' 01.98"	750
St2	51° 12' 49.32"	38° 20' 27.12"	725
St3	51° 27' 23.64"	38° 09' 56.82"	720
St4	51° 50' 28.98"	37° 58' 32.94"	630
St5	52° 09' 05.16"	37° 44' 26.46"	610
St6	52° 26' 17.94"	37° 31' 00.30"	560
St7	52° 44' 40.68"	37° 16' 51.96"	470
St8	53° 03' 15.36"	37° 02' 40.26"	270
St9	53° 09' 41.88"	36° 58' 47.58"	100

Figure 1. Study area and geographic location of the measurement stations

3. Results

3.1. Vertical structure of temperature and salinity

Based on observations from field measurements in winter, the temperature of the mixed layer varied between 10 °C and 12 °C, and with increasing depth, the temperature decreased in the thermocline (depth between 50-70 m), it reached to about 7 °C. The decreasing trend of the temperature in the deep layer, which is far from the seasonal variations is much slower, so at a distance of 400 meters (a depth between 300 and 700 meters) this change is about 0.5 °C and at a depth of about 600 meters reaches to 6 °C. The salinity variation in the mixed layer in the same season is between 12.54 and 12.44 (psu) and in the halocline layer the salinity trend decreases sharply from about 12.55 (psu) to a minimum of 12.35 (psu) at the halocline base. Afterward, the salinity in deep layer starts gradually to increase to the salinity of about 12.55 (psu) in depths of about 600 meters. In the spring, measurements indicate that the temperature of the mixed layer varies between 16.5 °C and 21 °C and decreases dramatically in the thermocline with depth increasing, so that in the seasonal thermocline bed (depth from 10 to 30 m) reaches to about 10-11°C. In summer, with decreasing MLD and increasing water temperature, the thickness of the thermocline increases, so that the water temperature decreases from about 27 °C to about 7 °C at a depth of 70 m. The temperature of mixed layer in summer varies between 27.7 °C and 24.7 °C, and also the salinity in this layer varied between 12.71 and 12.31 (psu) and reached 12.70 (psu) at depth of 70 meters. Surface layer salinity in the southern Caspian Sea is usually affected by rivers' entrances, rainfall, wind and water flow, and in some ice-melting areas.

3.2. Mixed layer and its depth estimation

As already mentioned, the mixed layer is a part of surface layer in the sea and the ocean, in which the physical properties of sea water such as temperature, salinity and density is relatively constant due to the interaction with the atmosphere. Since the interaction between ocean and atmosphere in this layer (including the exchange of energy, mass, gas, etc.), in the long time will have a significant impact on the weather and climate (de Boyer Montégut *et al*., 2004). The depth and temperature of the mixed layer varies daily and seasonally. Any process that leads to stratification, such as air temperature increasing and melting ice, can reduce the depth of MLD. On the other hand, processes those disrupt layering and increase mixing such as blowing wind, decreasing air temperature, and ice formation lead to MLD deepening.

There are several methods for estimating MLDs, including visual method and multiple computational methods. In this research, two visual and threshold methods have been used as a computational method for estimating MLD. At first, data on temperature and salinity were interpolated with intervals of 1 meter, and then the depth of MLD have been visually estimated and compared with the estimated MLD by the threshold method. In order to estimate the MLD visually, we consider the MLD in a depth where for example the temperature is relatively stable from the surface to the desired depth, and the temperature variations inside this layer are negligible compared to the changes in the total vertical structure. It should be noted that in profiles where the layering is intense and we do not see a layer in which the physical parameters are relatively constant, we put the MLD equal to NaN (Not a Number). Figure 2 shows the profile of temperature at different stations in three seasons of winter, spring, and summer. The depth of mixed layer in winter is at its peak at station 3, and in spring and summer it reaches its minimum, so that the minimum MLD value is observed in spring at station 6. Figure 3 shows the seasonal variations of the temperature profile at station 4. The seasonal variations of the mixed layer and the seasonal thermocline, are more evident in this figure. Looking more closely into Figures 2 and 3, it seems that there is a thermocline at a depth of 50 to 70 meters, which is generated with the onset of warm season in spring and its slope is sharply increased in the summer.

The threshold method is one of the most common methods for estimating the depth of the mixed layer. This method can be applied in the profiles of temperature, salinity, and density with different threshold values. According to this method, the mixed layer thickness is a depth where the difference in temperature, salinity, and density with corresponding values in the reference depth exceeds the threshold value (usually from 1 to 5 meters deep near the surface). The threshold value varies depending on the area under study, which is considered to be 0.1 °C for temperature (de Boyer Montégut *et al*., 2004). The depth of the mixed layer at different seasons using two visual and threshold methods have been given in Table 2. The average of all MLDs, regardless of the season using the visual and threshold methods, is 24 and 8 meters, respectively. The average depth of the mixed layer without separating the stations in winter, spring, and summer using the visual method is 53.8 and 10 meters, respectively, and using threshold method is 8.5 and 9 meters, respectively.

The calculated MLDs from the visual method are compared with the ones from threshold method in Figure 4. Large number of points around the red line for spring and summer data shows that for shallow MLDs observed in spring and summer, both methods estimate the MLD values close to each other. Looking more closely into data it is observed that even for shallow MLDs, there are some points for which the threshold method underestimates the MLD compared with visual method. As shown in the figure, MLDs in the winter were estimated by the visual method are much higher than the threshold method. Mean values of MLD using the threshold and visual methods have been estimated respectively 9 meters and 52 meters, which highlights this difference. In general, the accumulated points above the diagonal line indicate that the threshold method estimated the MLDs less than the visual method.

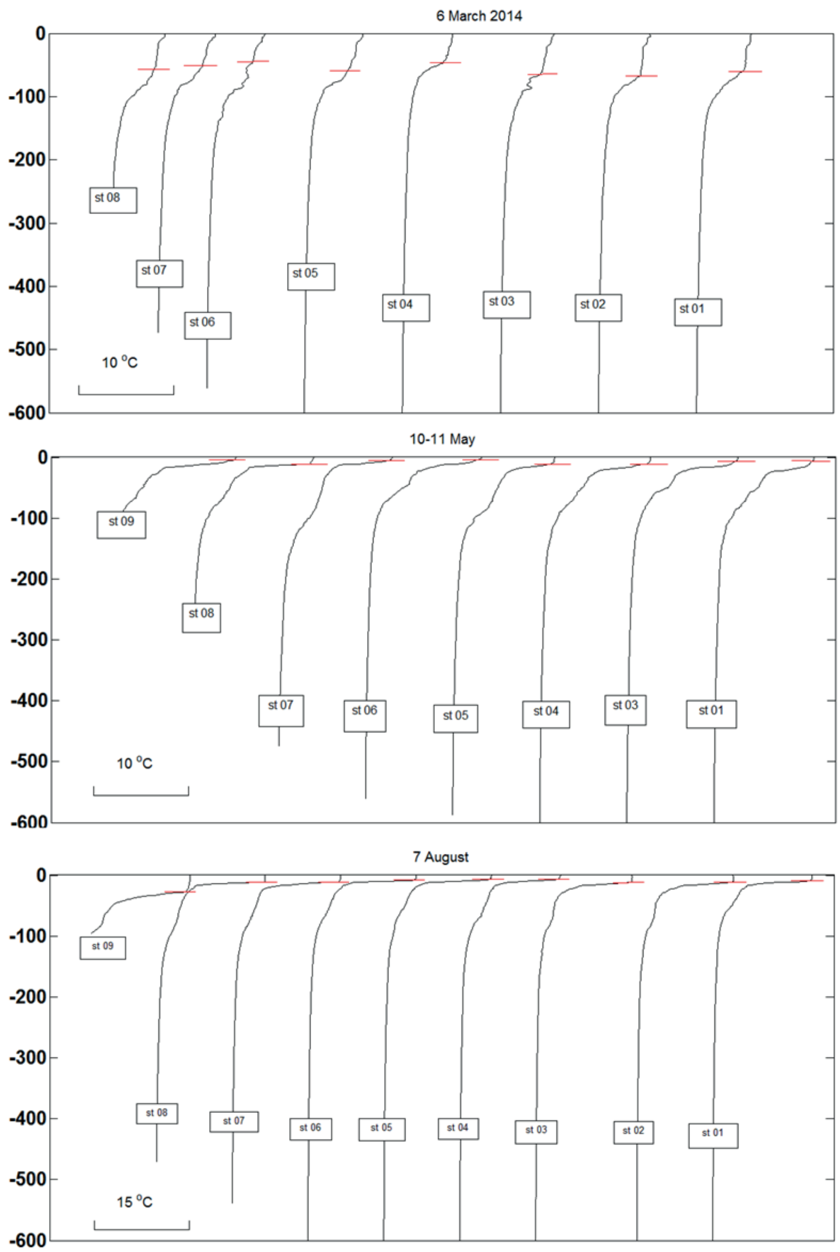

Figure 2. Temperature profile from CTD data collected in the three seasons of winter, spring and summer

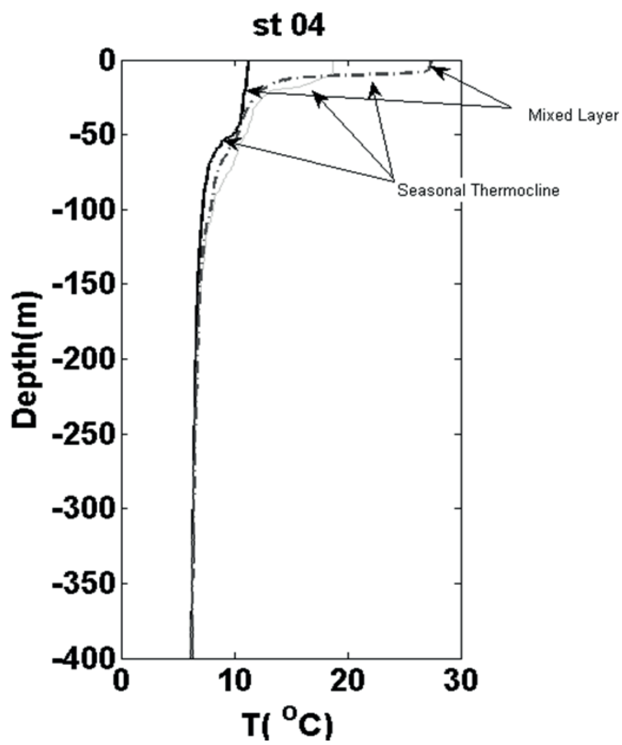

Figure 3. Seasonal changes in temperature profile at station 4

Table 2. MLD obtained from the visual (V) and threshold (T) methods in three seasons of winter, spring and summer

		Winter	Spring	Summer
St1	V	57	15	7
	T	17	6	8
St2	V	51	NaN	12
	T	7	NaN	11
St3	V	64	13	7
	T	6	5	4
St4	V	41	11	8
	T	8	9	6
St5	V	57	12	9
	T	8	4	7
St6	V	45	8	11
	T	4	4	9
St7	V	52	5	11
	T	7	3	12
St8	V	53	12	13
	T	8	4	9
St9	V	NaN	4	27
	T	NaN	3	16

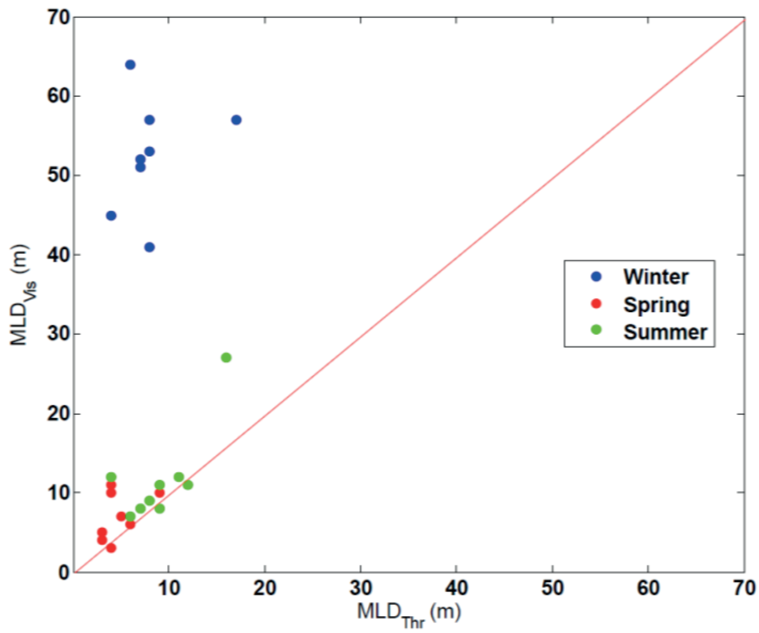

Figure 4. Comparison between MLDs obtained from visual estimation and calculated using threshold method for different seasons. The reddish red line represents the degree of proximity between these two measurements

Conclusion

Since the Caspian Sea is a closed sea, physical parameters such as temperature, salinity and density are affected by the outflow of rivers and atmospheric conditions. Seasonal variations such as heat flux, evaporation and precipitation directly affects the surface layer, including the mixed layer and thermocline, which forms the surface layer of about 70 meters. The data presented in this paper gives an initial understanding of how layering works in the deep part of the Southern Caspian. Mixed layer as part of the surface layer is very important because the depth of this layer impacts on various parameters such as gas exchange between sea and atmosphere, phytoplankton production, and sound channel depth. In this study, the depth of mixed layer has been estimated using two visual and threshold methods (with a threshold of 0.1 °C). According to the results, the threshold method underestimates the MLD compared with the visual method, especially in the cold season and for deep MLDs, which seems it is not an appropriate method for estimating MLD. The depth of mixed layer increases in winter with air temperature decreasing and cooling of the water surface layer as well as wind speed increasing.

It was expected that the MLDs start to decrease at the late of spring and reach the minimum in the summer, while based on the results, the minimum and maximum values of the MLD are respectively 3 and 11 meters and in the summer the minimum and maximum values are respectively recorded 7 and 27 meters. To analyze why the minimum MLD value unexpectedly happened in spring instead of summer, more temporal and spatial data along with atmospheric data are required.

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