World Applied Sciences Journal 13 (8): 1938-1947, 2011
ISSN 1818-4952

Seasonal Influences of Boundary Conditions in Coastal Water Quality Variations (Case Study: Northern Zone of Persian Gulf)

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Abstract: Persian Gulf, as an important biological aquatic basin in Middle East, joints via Hormuz Strait to Oman Sea and Indian Ocean. Tide, wind, precipitation, solar radiation and evaporation are main phenomena regarding the oscillation trend of water quality variation in mentioned basin. Moreover, the flow entrance from Arvand River to Persian Gulf influences aforesaid phenomenon, extensively. This research bases on Mt. Mitchell statistics collected in NOAA research vessel observation through the Persian Gulf, Strait of Hormuz and Gulf of Oman. Investigating the variation of shallow water conditions in aforesaid aquatic basin; we analyzed the regional observations and measurements in comparison with the outputs of a numerical model which has been developed based on Navier Stokes partial differential equations. The results argue that baroclinicity and stratification of fluid column are two important events occur and change in Persian Gulf, seasonally. Based on our obtained results, creation of turbulence; and consequently, diffusion of internal waves originate from both occurrence of thermocline through the water environment and variation of this event in space and time. Just the same, this study focuses on effective parameters and elements in creation of thermocline and the related influences of flow entrance from Arvand River. According to the results, we are convinced about creation and existence of more baroclinicity and turbulence in north-eastern coasts of this aquatic basin in comparison with deeper parts; and this event originates from effects of internal flow from Arvand River, related bed stresses and situation and direction of wind sources.

Key words: Persian Gulf · Arvand River · Summer thermocline · Baroclinicity · Internal waves

INTRODUCTION

It is undeniable that atmosphere plays an important role in water circulation of each aquatic environment and variation of the related physical parameters [1]. Approximately 15 to 50 percent of needed energy for oceans water turbulence leads to tide waves. In other words, we can say that friction between mentioned tide waves in shallow waters and topology of seabed near the sea shores; plus, the effects of tide wave spread in deeper surfaces of fluid between two layers along fluid column; and also strike of tide waves with seabed ridges lead to creation of water turbulence, mixture and circulation, especially in baroclinic fluids. Theoretically, tide waves spread with the velocity of 200 meter per second through the shallow waters [2]. Furthermore, some climatic features are in direct relation with physical properties in oceans and seas. As the interest continues to grow in climate variability, however, questions about the thermocline arise, naturally. Thermocline is the dominant feature of temperature distribution [3].

Indian Ocean as the third largest aquatic basin of the world involves roughly 20 percent of whole surface water of the Earth. Also, Persian Gulf as a part of the aforesaid basin limited among Northern 24 and 30 and Eastern 47 and 57 geographical degrees with the maximum dimensions of approximately 990 kilometers length and 370 kilometers width and average depth of 36 meters; also, it occupies a surface area of about 239000 square kilometers [4]. All in all, direct observations of the

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circulation within Persian Gulf are scarce. Just the same, the NOAA research vessel Mt. Mitchell had been operated in Persian Gulf, Strait of Hormuz and Gulf of Oman, from February 1992 to June 1993. Continuous shipboard measurements of meteorological and oceanographic variables were recorded. During this cruises, currents measured by vector-averaging current meters at 10 and 30 meters depth on northern mooring of Persian Gulf [5]. This Gulf is semi-enclosed shallow water which situates in Middle East, where evaporation greatly exceeds precipitation and river runoff entrance. In addition to its large contribution in the heat budget; evaporation plays an important role in maintaining the water circulation of the Gulf. Furthermore, tide forcing as a result of Newton gravitational force of moon against the earth and monsoons from south-west of Persian Gulf, set up mixture and turbulence through water column in this basin [6]. In the condition of interface between two layers along fluid column, internal waves move and transmit the Turbulent Kinetic Energy (TKE) to under surface layers of water [7].

Needless to mention that most of the previous researches and experiences in this aquatic basin focus on Strait of Hormuz where main body of the Persian Gulf water is separated from Oman Sea. High salinity water of Persian Gulf flows into Oman Sea and spreads through 200-350 meter depth within Oman Sea in the northeast of Indian Ocean [8]. When salinity stratification is included, mixed layer buoyancy flux results in such a small-scale deep convection [9]. Johns modelled the mass transport through the Strait of Hormuz and expressed the existence of water circulation due to water exchange [10]. In 2009, Sadri Nasab mentioned that a seasonal thermocline is evident with a surface to bottom temperature difference of around 12 centigrade degree in summer; also, in the northern part of the Gulf when the wind direction is parallel to the coast with a speed of greater than 9m/s, upwelling could occur [11]. Based on seasonal cycles in solar heating, wind and evaporation and on cross-sections across the Strait, Chao suggested that inflow through the Strait of Hormuz peaked at 0.17 Sv in March and decreased to 0.03 Sv in August to September [12]. Johns and Olson observed a dramatic shift in the temperature-salinity (T-S) properties of water flowing through the Strait of Hormuz at most depths in July and a more gradual reversal in properties between November and January [10]. Paradoxically, the densest water forms during the months of peak rainfall [13]. Temperature and salinity fields were analyzed in the Strait of Hormuz and the results showed that in summer the upper layer is highly stratified and the dense saline outflow layer enters the Oman sea, unimpeded and appears as a coastal trapped layer intact, due to less mixing as a result of stronger stratification near the top interface [4]. However in winter the upper layer entering the Gulf is highly mixed with some temperature inversion around the Strait of Hormuz. Kampf and Sadri Nasab employed a three-dimensional hydrodynamic model to study the circulation and water mass properties of the Persian Gulf. Their findings suggested that the Persian Gulf experiences a distinct seasonal cycle in which a gulf wide cyclonic overturning circulation establishes in spring and summer, but this disintegrates into mesoscale eddies in autumn and winter. Establishment of the gulf-wide circulation coincides with establishment of thermal stratification and strengthening of the baroclinic exchange circulation through the Strait of Hormuz. The densest water in the Persian Gulf forms during winter in shallow waters along the coast of United Arab Emirates (southern shallows) and around Bahrain. This is associated with atmospheric cooling of extremely saline water masses in shallow water. Air-sea interaction, coastal circulation and primary production exhibit an annual cycle in the eastern part of this aquatic basin [11]. During June to September, strong south-westerly winds (4 to 9 m/s) promote sea surface cooling through surface heat loss and vertical mixing in the central parts of this sea. Swift and Bower claimed that Seasonal variable incursion of Indian Ocean Surface Water (IOSW) into the Gulf peaks in spring to summer. This timing may be due to seasonal changes in sea surface slope driven by variations in evaporation rate [14]. Bower determined the density and thus the depth of Gulf overflow water by source characteristics as it flows through the Strait of Hormuz and by subsequent mixing processes on the continental shelf and slope off Oman and Iran [15].

This paper aims to study these aforesaid phenomena among Persian Gulf and in particular through the northeastern zone of this basin with utilization of related temperature, density and salinity statistics which have been collected on the basis of Mt. Mitchell cruise; also, solution of Navier Stoks equations for shallow water conditions with the usage of numerical modeling technique.

MATERIALS AND METHODS

First of all, to have a comprehensive dominance, we decided to study the main effective boundary conditions that Persian Gulf is faced to.

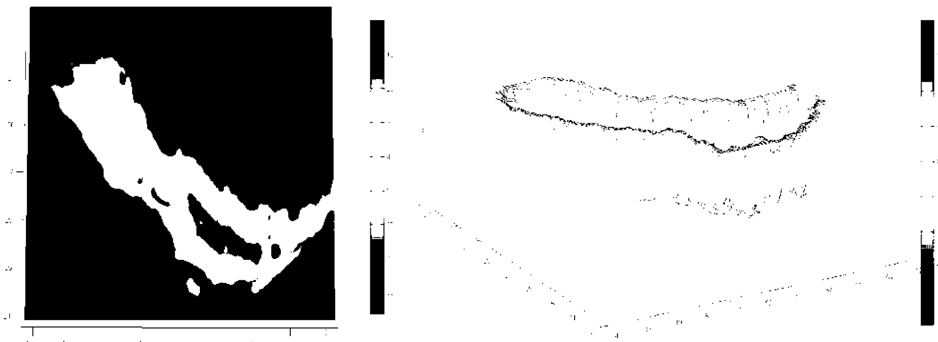

Fig. 1: Two and three dimensional smoothed bed topography models of Persian Gulf

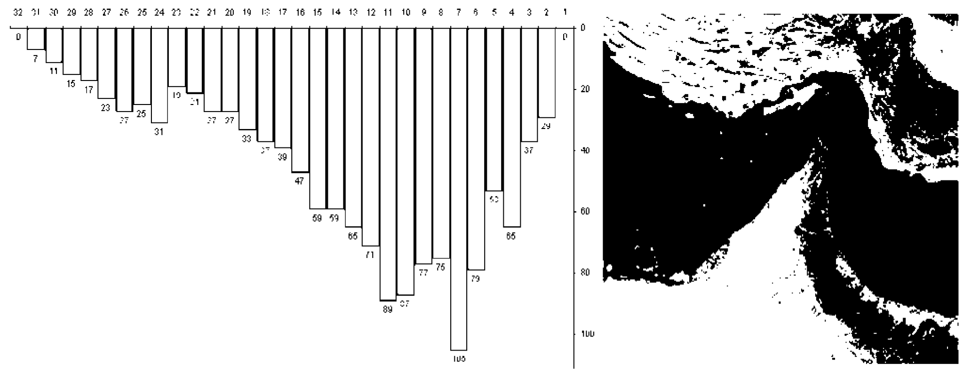

Fig. 2: Cross section profile and plan of Hormuz Strait

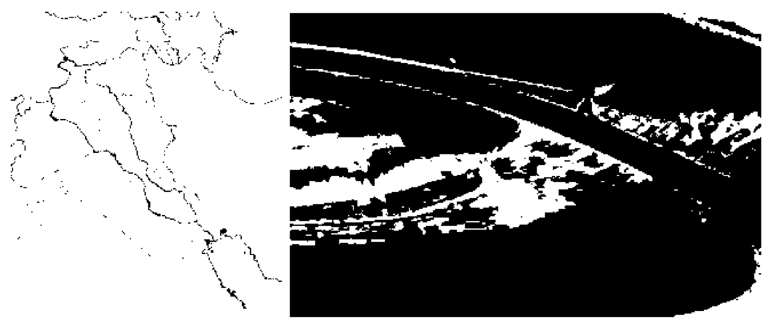

Fig. 3: Arvand River basin and related delta in the northern coast of Parsian Gulf

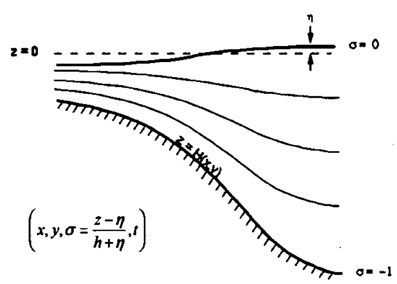

Fig. 5: Sigma Coordinate System

Our investigations argue that the effects of inflate topography of this seabed on the conditions of water flow is undeniable. Consequently, we improved and smoothed both two and three dimensional models with the utilization of ETOPO2 depth statistics of Iranian National Centre of Oceanography. Figure 1 illustrated topography of Persian Gulf after smoothing.

Furthermore, the cross section profile of Hormuz Strait as the eastern boundary condition of this aquatic basin with 195 kilometers distance width and 7689500 square kilometers area represented in the following graph.

Moreover, Arvand River on the northwest of Persian Gulf drains a zone with approximately 948375 square kilometers area through its direction and provides nearly 82 cubic kilometers water discharge, annually. Figure 3 illustrates this mentioned area.

Table 1: Range and frequency period of four main tidal harmonics of Persian Gulf [8]

Phase (degree)	Amplitude of Oscillation (meter)	Period (hour)	Kind of tidal harmonic
214.980	1.1	12.42	M2
192.200	63.26	25.82	O1
248.900	0.4416	12.00	S2
288.300	0.3378	23.93	K1

To approach to the conclusive aim of this research; Shallow Waters Equations have been solved with the utilization of numerical methods to model the water quality parameters of our studied aquatic basin. In this way, we used Navier Stokes Partial Differential Equations in baroclinicity modeling of Persian Gulf with the usage of Sigma Coordinate System. In this system h and η lead to topography of seabed and deviation of water level in comparison with mean water level of free seas, respectively; also, σ changes from zero in z=η to -1 in z=h and local depth defines as below:

Difficulty of Shallow Water Analysis Originates from Two Main Issues: Firstly, the orbital motion induced by surface gravity waves and generates an oscillating boundary layer with thickness of nearly 10 centimetres. It is embedded in the thicker boundary layer which generated by low-frequency currents. Secondly, this fact accepted that the geometry of the seabed is not known a priori [16]. Equation1 refers U(t), as the time dependant velocity, to the tidal currents amplitude:

$$U(t) = V + U_0 \, Sin\omega t \qquad (1)$$

Where U_0 is initial tidal currents velocity and ω belongs to the current frequency.

Furthermore, tidal amphidromic points are places though the aquatic basin where the frequency of tidal waves is nearly zero. This phenomenon originates from interplay effects of two or more tidal waves, tidal waves and their reactions from seashore and influence of coriolis forces. In this way, range and frequency period of four main tidal harmonics of Persian Gulf represents in Table 1, below.

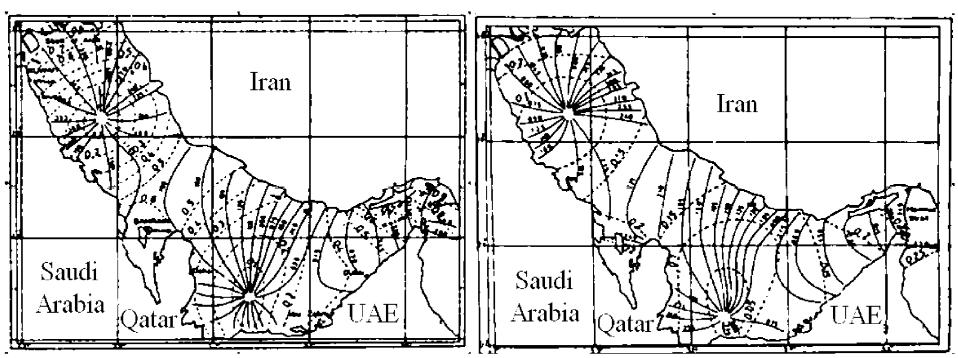

Fig. 6: Main components of M2 and S2 tidal harmonics of Persian Gulf

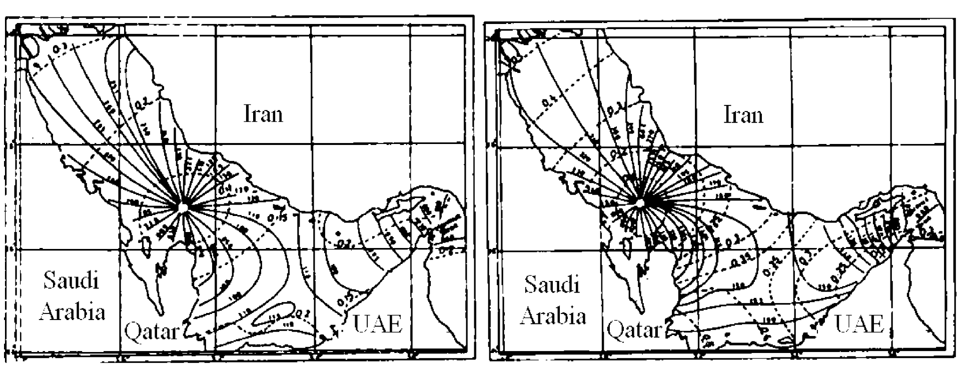

Fig. 7: Main components of O1 and K1 tidal harmonics of Persian Gulf

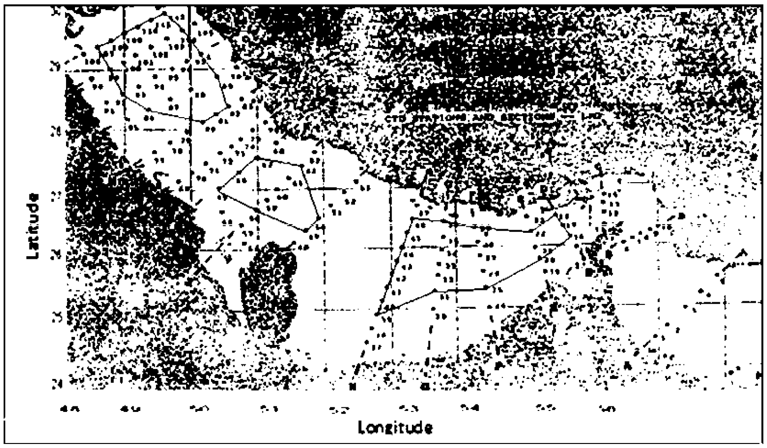

Fig. 8: Mt. Mitchell stations of cruise measurements and three important zones of thermocline creation among the north of Persian Gulf

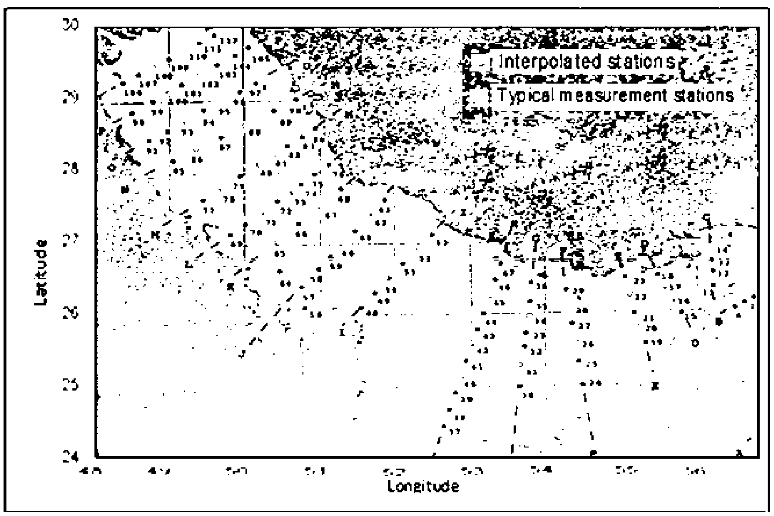

Fig. 9: Whole utilized stations (containing measured and interpolated ones)

One amphidromic point related to daily tides in the middle of Persian Gulf beside Bahrain and two ones related to half daily tides in northwest and south of the same basin are illustrated in following graphs.

Internal waves are able to provide and transmit the energy, which is essential for aquatic circulation and mixture. Moreover, in coastal areas it is distinguished that changes in fluid temperature column causes existence and diffusion of internal waves. Based on variation of mean temperature degree; Figure 8 illustrates three most important zones in Persian Gulf which involve summer thermocline.

Moreover; we interpolated temperature and salinity statistics for all stations of this basin with the usage of Cressman method based on collected measurements of aforesaid typical stations in Persian Gulf based on measured statistics of Mt. Michel observations during summer of 1994 to winter 1995. Meanwhile, Figure 9 illustrates the location of typical measurement stations plus stations of interpolated data.

To terminate the project, we compared aforesaid diagrams of temperature and salinity with the results of our three dimensional shallow water equations solution in 11 layers of water column with the usage of Boussinesq Approximation and Arakawa-C method [6]; also, definition of three meters costal depth around the studied aquatic basin with the volume of 138600 cubic meters (dimensions of 126meters length 100 meters wide and 11 meters depth) as the boundary conditions, in summer 1993. In this way, we utilized statistics of mean solar radiation factor, evaporation, wind, entrance of water discharge from Arvand River on the north-west of Persian Gulf and water exchange with Oman See among the Strait of Hormuz.

RESULTS AND DISCUSSION

After temperature profile drawing in 112 stations of Mt. Mitchell cruise measurements (Figure 8); three important zones of thermocline creation among the north of Persian Gulf, deep middle part of this basin and beside the Strait of Hormuz have been accepted. Figure 10 shows the changes in mean temperature degree, water salinity and density of mentioned zones.

Based on the graph of temperature changes among north-eastern zone of Persian Gulf (Figure 10.g), it could be seen that a noticeable temperature descend to the point of less than approximately 19 centigrade degree in the depth of roughly 19 meters from the water surfaces of this zone occurs which could be seen neither beside the Strait of Hormuz (Figure 10.i); nor, whole parts of its extra studied aquatic basin. In other words, as it obviously illustrates in Figure10.g, instead of gentle descending trend of water temperature from surface to the depths of 10 meters in northern zone of Persian Gulf (nearly 2 centigrade degrees), cold soft water discharge of Arvand River with the depth of approximately 1.5 meters and low salinity causes a sharp temperature decrease from roughly 22 to 18 centigrade degrees between the depths of 10 to 19 meters.

Just the same, Figure 11 illustrates variation of temperature and salinity with changes of depth during summer and winter seasons in stations of number 16, 52, 80, 97, 103 and 109 as some typical Mt. Michel measured stations inside our studied basin. Considering the graphs, we could say that in spite of existence of an obvious steady trend of temperature change with depth in all of mentioned stations during winter season, a noticeable break in the same diagrams during summer season could be seen.

As it could be obviously seen in the below curves related to winter season, variations of temperature with depth through the water column are not considerable while a negative vertical gradient of temperature with depth changes (Figure 11.a to Figure 11.h). It could be due to wave activities and eddy current motions takes place in under surface layers during summer which represents summer thermocline formation, so seasonal thermocline could be formed in whole of water in Persian Gulf during summer. Just the same, variation in salinity with depth happens as a result of thermocline formation (Figure 11.i to Figure 11.m). This is particularly marked in summer profiles. Of course, in the Strait of Hormuz as a result of water exchange with the Oman Sea, thermocline forms in winter, too.

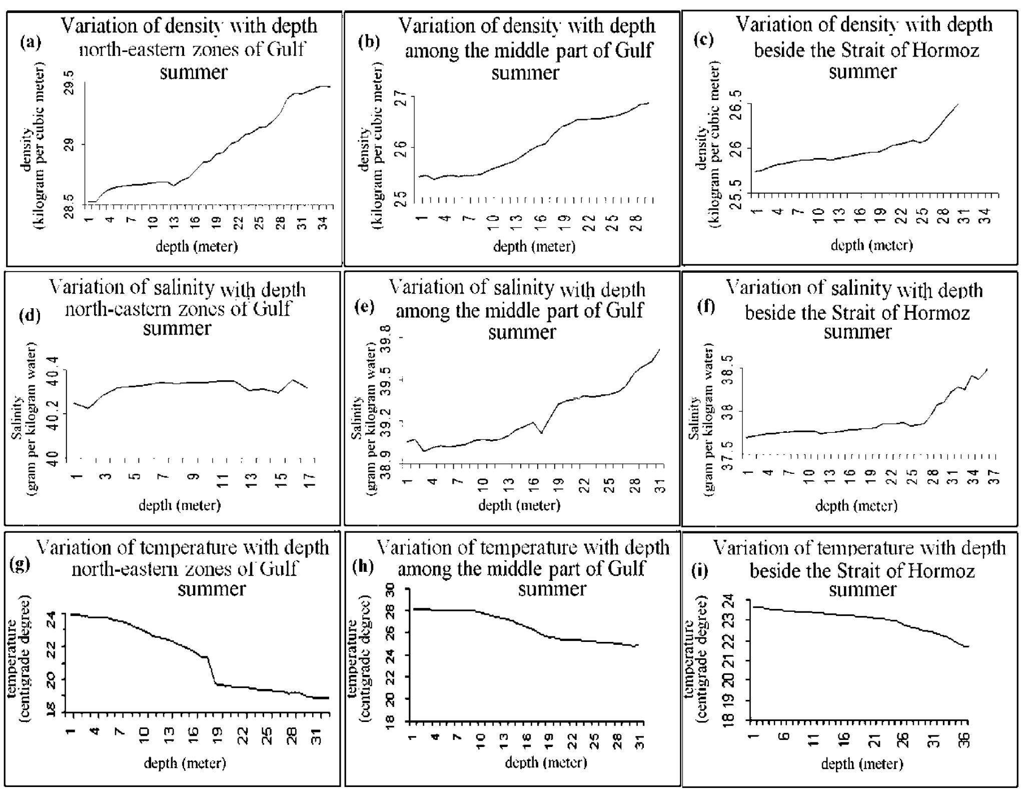

Fig. 10: Variation of temperature, salinity and density with depth in the three important termoclinic zones of Persian Gulf

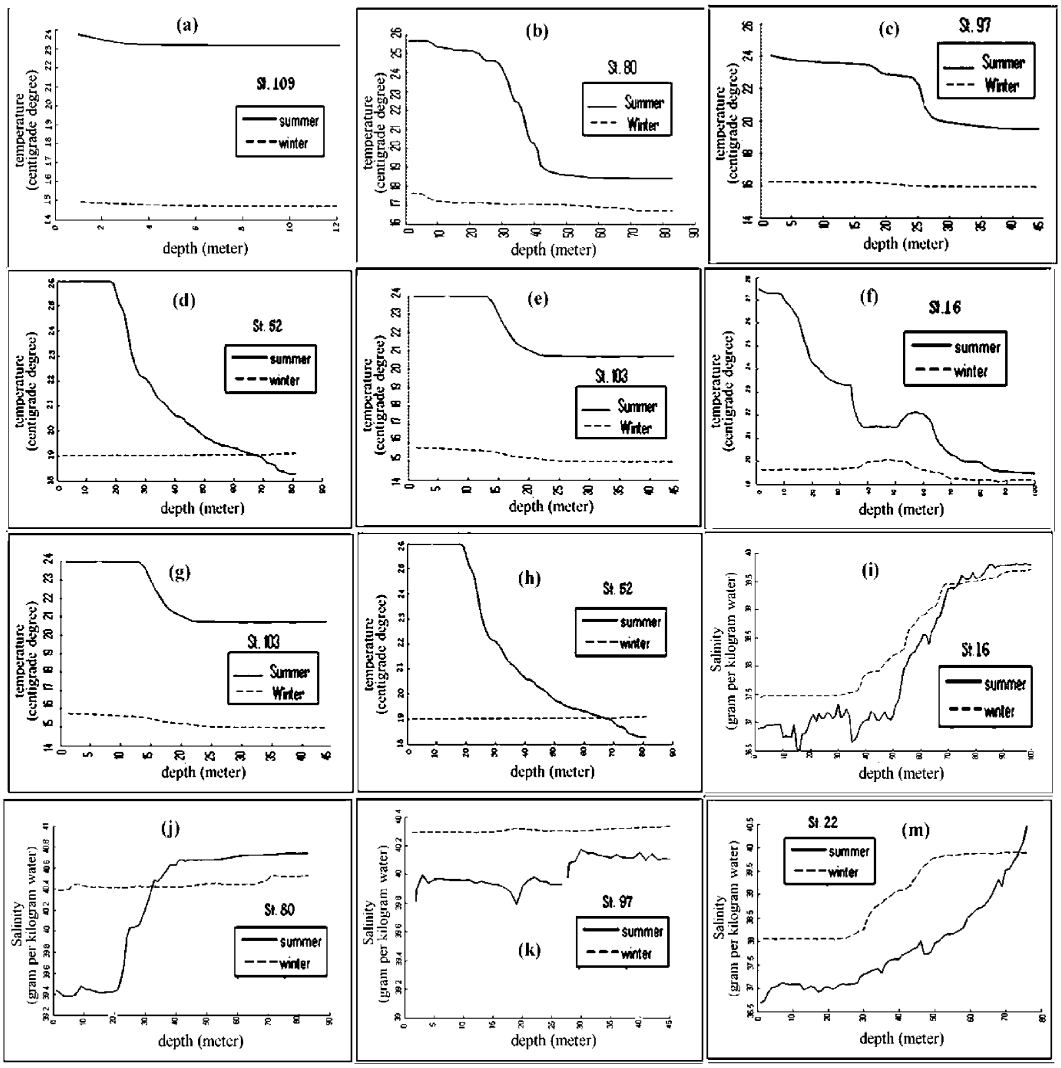

Fig. 11: Variation of temperature and salinity with depth during summer and winter seasons in typical measurement stations

Furthermore, we utilized the measured data of temperature, density and salinity in aforesaid typical stations plus interpolated ones though a direction between the outlet of Arvand River and Strait of Hormuz to make a comparison between winter and summer seasons about the existence of thermocline in Persian Gulf. Considering most of the factors dominating the Persian Gulf to happen turbulence and internal waves; temperature, density and salinity contours are drawn in parallel with a direction from outlet of Arvand River to the Strait of Hormuz in both winter and summer seasons. Figure.12 shows contours of temperature, density and salinity transacted along the axis of 15 to 106 stations.

All in all, comparing pictorial diagrams in Fgure 12, oscillation trend and variation of temperature, which leads to development of thermocline could be seen in summer. Although the gradient of temperature, density and salinity during winter season are not noticeable (all three right hand graphs); sharp variation of these issues during summer could be realized (left hand graphs). Looking at Figure 12.d, related to temperature changes during winter season we can obviously say that, apart from the Strait of Hormuz region with turbulence and more diffusion convection between the outflow and ambient water, especially at the upper boundary, there is almost no potential of vertical stratification in water column; so density roughly appears uniform (Figure 12.f). In addition, more evaporation and less depth of water level near the western coast of Persian Gulf; we can realize higher salinity in these regions (Figure 14.b and e).

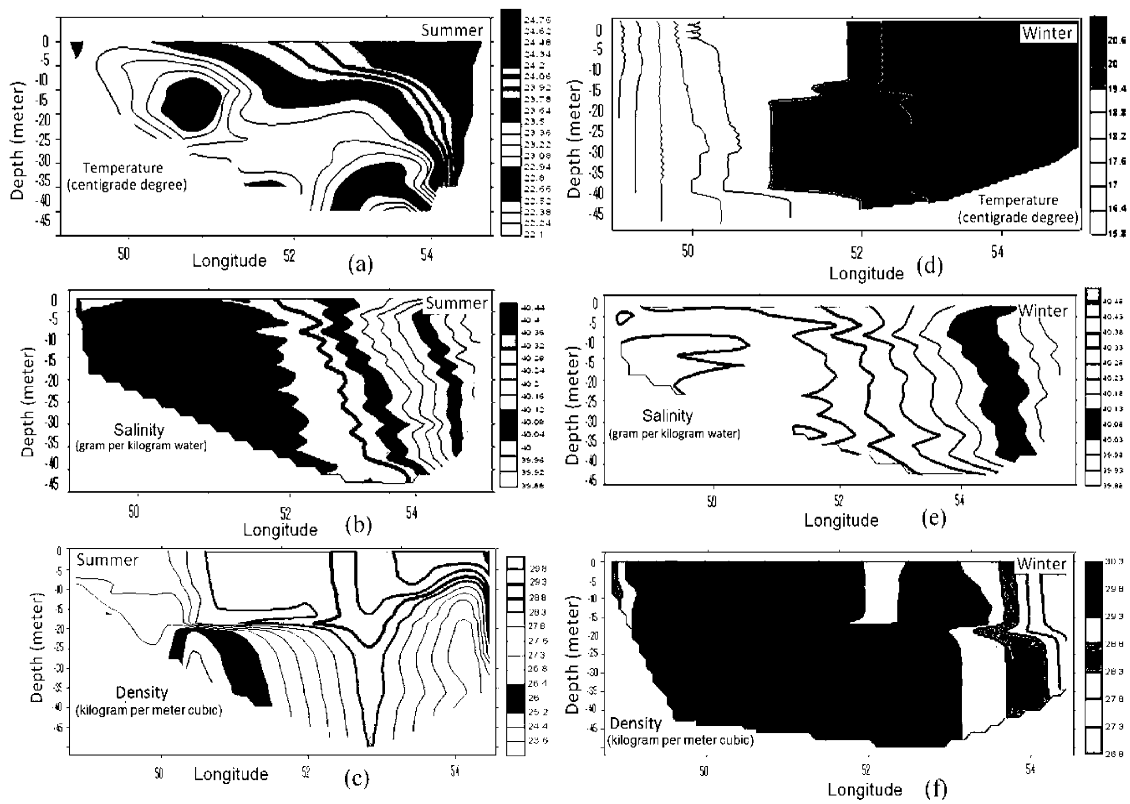

Fig. 12: Contours of temperature, density and salinity gradients during summer and winter seasons

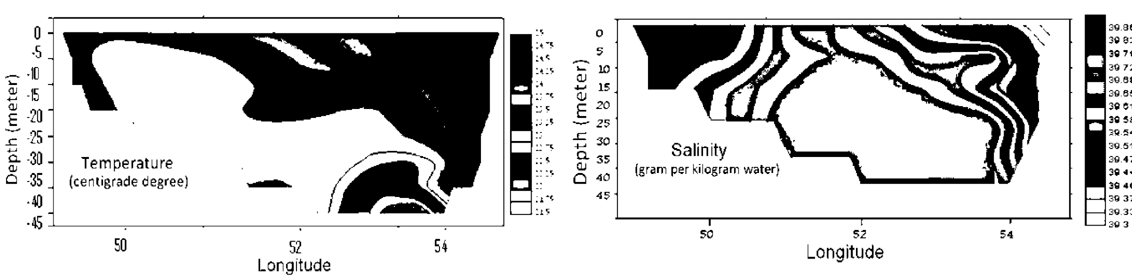

Fig. 13: Outputs of modeling (Containing variation of temperature and salinity gradient)

Just the same, in summer, lower temperature and salinity beside the north-western coast originates from entrance of cold soft water discharge from Arvand River during summer season. Consequently, existence of water column stratification and development of thermocline in this zone could be predictable. Also, the results of our shallow water modeling illustrates in the following graphs. As it can be clearly seen, variation of temperature and salinity gradient on the western zone, especially limited area between the depth of approximately -10 and -20 meters, during summer season is obvious. This issue completely supports the results of Figure 12 which explained before.

As it obviously illustrated in the temperature and salinity contours through longitudinal transects of Persian Gulf; thermocline formation can be predicted in summer in spite of winter in whole Persian Gulf water environment. Summer thermocline formation in Persian Gulf is a seasonal potential of turbulence and internal waves creation that is produced and propagated through the water. Moreover, numerical modeling of temperature variation from winter to summer shows that river currents of the Arvand River, wind stress and evaporation in the northern part of this zone have caused and developed thermocline. Thermocline forms in the Starit of Hormuz during whole year because of water exchange between the Persian Gulf and the Oman sea; while as time closes to summer, thermocline extends to north of the Gulf. Persian Gulf water in Arabian coasts (southern parts) is more salty rather than in Iranian coasts (northern parts) in summer and it is resulted from higher temperature, shallower water and the rate of evaporation in south of the Persian Gulf.

CONCLUSIONS

As we mentioned, Sadri-Nasab has been developed a numerical model of thermocline creation in Persian Gulf and based on his findings, this issue was influenced by temperature variations through water column [11]. Also, we could list phenomenon of ebb and tide, evaporation, wind, sun radiation plus continual water exchange with Omman See beside the Strait of Hormuz and entrance of water discharge from Arvand River as the factors and stresses which this aquatic basin is faced to. Moreover, recent climate studies have shown that atmosphere also plays an essential role in driving the circulation and maintaining the water properties at the sea surface [14]. In parallel, by this research our studies results that thermocline formation affected by Arvand River as the instability through the water column in the northern parts of Persian Gulf. Based on our investigations, we claim that the entry of fluid from Arvand River influences the water column stratification in the northwestern zone of Persian Gulf. Just the same, as density gradient causes internal waves creation in the gulf thoroughly; consequently, it leads to existence of turbulence which could be studied, seasonally.

To wrap it up, we can say that in comparison with winter thermocline formation in Persian Gulf which just could be seen among the Strait of Hormuz because of continual water exchange with Omman See, this occurrence could be seen the most among the northwest zone of Persian Gulf that is more influenced by Arvand River flow discharge during summer seasons.

As we mentioned, based on different measurements of temperature, salinity and density; and also, comparison and analysis of numerical modeling results of Persian Gulf, limited between north-west of this aquatic basin on the outlet of Arvand River and beside the Strait of Hormuz on the east; the conclusive results of this research confirmed the existence of more summer thermocline phenomenon in comparison with winter ones. Furthermore, these investigations indicated lower temperature degree on the north western of our studied basin. As far as we are convinced, Entrance of cold soft water discharge from Arvand River is the most important reasons regarding this mentioned occurrence. Variation of temperature gradient of approximately 12 centigrade in roughly 20 meters through the under surface water layers in northwestern zone of Gulf leads to summer thermocline event formation, as well. Moreover, our investigation and analysis argue that with the seasonal change in weather conditions from winter to summer, thermocline phenomenon develops from Strait of Hormuz as the eastern boundary of Persian Gulf to the near of Arvand River outlet on the west. Consequently, this event could be seen in whole northern part of this basin during summer season. In other word, we claim that existence of different stresses and forces during summer season lead to mixture and uniformity of upper layers of water along with descend of temperature degree in under surface layers which causes water column stratification, baroclinicity and summer thermocline phenomenon development especially among the northern zone of Persian Gulf. Finally, it is accepted that diffusion of internal waves and occurrence of turbulence and summer thermocline through the water environment in western part of this aquatic basin are thoroughly and deeply influenced by entrance of water discharge from Arvand River.

Formation of a shallow thermocline with upper mixing and displacements of the thermocline is associated with internal wave propagation which plays an important role in turbulence generation. The stratification as an important factor influencing local generation of internal waves in the coastal zones is subjected to seasonal variability. Gradients throughout temperature contours in parallel with the Persian Gulf axis indicates that thermocline can be formed in summer despite of winter; consequently, internal waves and turbulence could be happened. Thermocline only exists in the Strait of Hormuz in winter as a result of water exchange between Persian Gulf basin and Oman Sea, but it develops to western parts of the Gulf from winter to summer and summer thermocline exists in whole basin. Seasonal thermocline variations lead to internal waves propagation; consequently, it develops form the Strait of Hormuz to west from winter to summer and effects of summer propagation of these waves in Persian Gulf would be noticed.

Just the same, recent Iranian governmental watershed management strategies in Karoon River basin (upstream of Arvand River) with the construction of various structures, reservoir dams and diversion dams with the aim of providing water demand in the middle parts of Iran could decrease discharge in the outlet of Arvand River. This phenomenon could influence aforesaid trend of termoclin creation in north-western zone of Persiasn Gulf and lead to effective ecological and biological changes in Persian Gulf environment.

ACKNOWLEDGMENTS

Needles to mention that concept development and experiments design of this research; Also, data analysis and modeling of this research has been done as a cooperation of Ehsan Ranaee, Seyed Majid Mosaddad and Morteza Akbari. Furthermore, the authors wish to thank Islamic Azad University-Shooshtar branch; also, Young Researchers Club which not only supported and sponsored this research program; but also, associated with data observation and processing. Thanks are also due to the anonymous reviewers for many useful suggestions in improving the quality of this work.

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