Study of physical parameters of seawater in the Strait of Hormuz

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Abstract

This paper investigates the spatial and temporal changes in the physical parameters of seawater in the Strait of Hormuz. The data of temperature, salinity, and σ_t collected using CTD in three different seasons; winter 2012, spring, and summer 2013. Moreover, different water masses and layers were studied. The temporal variations in most stations showed that the whole water column was completely mixed in the winter, but in the summer, the surface layer was homogeneous, and in spring, it was in a transition state. The maximum values of σ_t variations in water column were 2, 4.25, and 5 kg/m^3 in winter, spring and summer, respectively. With the change of seasons, the volume of water outflow of the Strait of Hormuz varied. Therefore, in the spring water outflow from the Persian Gulf was traceable in the east of Hormuz Strait and the stations near Iran's coast. Based on this research, it seems that outflow from the Persian Gulf was more in this season. Studying the water masses in different parts of the Hormuz Strait showed that two distinct water masses in the eastern part were observable in all seasons. While, in the middle and western part of the Strait, two different water masses were observed only in the summer. Furthermore, in summer, three different layers were observed in the whole water column. Some fronts were formed in the interfaces between water masses that the strength of fronts was related to the salinity and temperature gradients.

Keywords: Field measurement; Salinity; Strait of Hormuz; Temperature; σ_t.

1. Introduction

Persian Gulf is a semi-enclosed shallow sea (average depth 35 m) that is connected to the northwest of Indian Ocean and the Oman Sea by the Strait of Hormuz. The Strait of Hormuz more or less is geographically located in the range of 26º 30´ N and 56º 30´ E. In addition, Iran is located in the northern part of the Strait, and the Oman and the United Arabic Emirates placed in the southern part of the Strait. The average width of the Strait is about 56 km and the greatest depth recorded for this

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strait is approximately 120 meters.

The narrowest part of the strait is about 39 km. The strait is the world's most important waterway of energy transfer that almost 20% of world energy consumption is transported through the strait (Sadrinasab, 2010). The Strait of Hormuz at the boundary between the northwest subtropical region and southeast tropical region of the Arabian Sea and the Indian Ocean where is affected by the monsoon. The prevailing wind in summer is southern wind, and in winter northwest wind (Reynolds, 1993). In addition, high-pressure system in winter and low-pressure system in summer are predominant in the region. The range of temperature changes in winter and summer are 18-20 ^{0}C and 32- 34^{0}C, respectively. The placement of the Persian Gulf in a dry region has caused considerable evaporation rate, minor precipitation, and limited water inlet. The evaporation rates reported by various studies are between 1.44-2.0 m/year (Privett, 1959; Reynolds, 1993; Bower *et al.*, 2000; Rezaei-Latifi and Hosseinibalam, 2015). Moreover, water inlet from the rivers and precipitation rates were reported 0.15-0.46 and 0.07-0.1 m/year, respectively (Hartmann *et al.*, 1971; Reynolds, 1993).

The shallow water and high evaporation rates has created salt and dense waters in Persian Gulf, thus, it is caused that the Persian Gulf acts as a reverse estuary. In this way, the high evaporation in the Persian Gulf is compensated by the low-salinity water inlet from the Oman Sea (Pous *et al.*, 2004).

Temperature and salinity are the physical parameters of the water that affect on the chemical and biological properties. Temperature and salinity contours in the Persian Gulf during the summer and winter represent different regimes in the year. In fact, Persian Gulf is one of the saltiest water bodies in the world. The Persian Gulf salinity in most parts is between 40-41 psu and in some restricted areas it even exceed of 50 psu. The high salinity of the Persian Gulf is due to dry climate, high evaporation rate, low fresh water input by rainfall, and limited rivers inflows (Yao, 2008).

Field measurement studies in the Strait of Hormuz are very few and just two studies have studied the physical and hydrodynamic properties in the region directly (Johns *et al.*, 2003). They investigated the parameters by deploying of mooring in the southern part of the Strait. In fact, these measurements were the first long-term fieldwork that occurred from December 1996 to March 1998. The salinity of outflow in the Persian Gulf and the southern part of the Strait ranged from 39.3 to 40.8 psu during a year, which the maximum amount of salinity observed in the winter.

Physical properties of the seawater, current speed and direction, and sea level fluctuations were measured in the October 1998 and early 1999 in the east part of the Strait (Pous *et al.*, 2004). Measuring of the water current was carried out with an Acoustic Doppler Current Profiler (ADCP) in the water column. Surface current was measured by using of the drifters. The water outflow from the Persian Gulf and water inflow to the Persian Gulf, and different water masses were studied.

Some other measurement studies in the area were conducted that are part of general studies in the Persian Gulf and Oman Sea (Emery, 1956; Brewer *et al.*, 1978; Brewer and Dyrssen, 1985; Reynolds, 1993). Furthermore, by using of numerical modelling, physical and hydrodynamic characteristics of seawater considered at the Strait of Hormuz (Yao, 2008; Thoppil and Hogan, 2009; Bidokhti and Ezam, 2009; Ezam *et al.*, 2010; Pous *et al.*, 2015).

In this paper, using of CTD data, physical properties of seawater, variations of temperature, salinity, σ_t, and different water masses are analyzed and investigated in the transects in western, middle, and eastern parts of the Strait for three seasons; winter 2012, spring, and summer 2013. In addition, the water exchange between Persian Gulf and Oman Sea based on the changes of physical characteristics of seawater is investigated.

2. Materials and methods

In this paper, temperature, salinity, σ_t, and different water masses are analyzed and investigated, which performed by field measurements in winter 2012, spring and summer 2013 at the Strait of Hormuz (Figure 1). The profiles of data are measured with 1-second time step using a CTD (Ocean Seven 316) probe (Idronaut, 2002). Only the downcast data of the CTD used (when CTD lowered) and the upcast data are not applied in this analysis. The CTD measurements data are low-pass filtered using a Butterworth filter with a cutoff frequency of 0.25 Hz. Finally, the CTD data are converted to the 1-meter resolution with the first-order linear interpolation method. The data analysis is performed in the MATLAB environment.

2.1. Study area

The study area is located within the Strait of Hormuz with the coordinates of 54.5-57.5 ºE and 25.0-27.5 ºN (Figure 1).

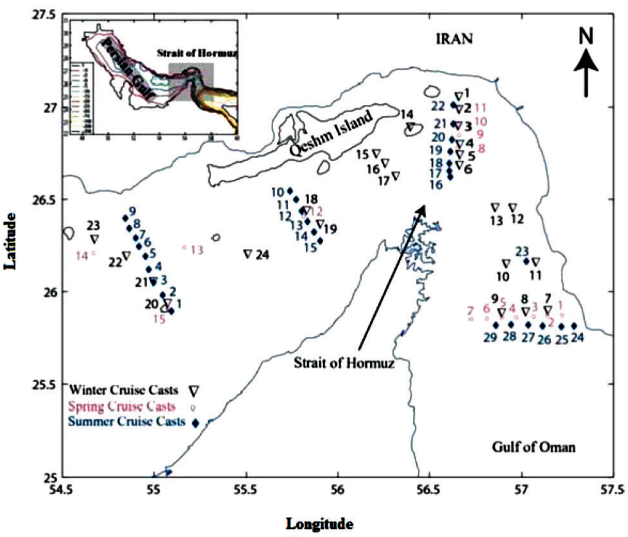

Figure 1. The study area within the Strait of Hormuz

Field measurements were taken at 68 stations in the Strait, where mostly distributed in internal waters and rarely exceed to maritime boundary (Figure 1). The measurements were performed in winter 2012, spring, and summer 2013. Table 1 shows the number of stations and the date of field measurements.

Table 1. Stations of physical parameters measurement with CTD

Number of stations	Date of measurements	Season
24	1/27/2013-2/1/2013	Winter
15	5/2/2013-5/6/2013	Spring
29	7/28/2013-7/31/2013	Summer

3. Results and Discussion

Figures 2 to 9 show the contours of the temperature (ºC) and salinity (psu), and σ_t (kg/m^3) of water for the seasons of winter, spring and summer in the study area. The contours of transects were drawn for three seasons in the east, center and west parts of the Strait of Hormuz. The approximate position of each station is available on the top of figures.

3.1. Physical parameters of seawater in winter, 2013

Figure 2 to Figure 4 show the contours of water temperature, salinity and σ_t in winter at the west of the Strait of Hormuz. The Figure 2(A) illustrates the contours of water temperature. Because of the cold wind blowing, the surface temperature was less than at the subsurface. Moreover, a thermal front was visible between the stations 21 and 22 and from 60-meter depth to the bottom. The temperature difference between the surface and the bottom was about 0.8 ^{0}C. In the middle of the Strait of Hormuz (Figure 3A) the water column was completely mixed from the surface to about 10-m depth. A thermal front was observed between the stations 4 and 5 and from 20 to 40 meters of depth. In addition, there was a weak front from depth of 40 meters to the bottom between the stations 2 to 4. The temperature difference between the surface and the bottom was about 0.9 ^{0}C. Water temperature increased from the north to the south in stations 1 to 6. The Figure 4(A) demonstrates the water temperature contours in the eastern part of the

Strait of Hormuz. The core of cold water located between 10 to 50 meters of depth. A warm core was also visible under the cold core and in the depths between 60 to 80 meters. Comparing the Figures 2(A), 3(A), and 4(A) reveals the temperature decreased from the east of the Strait to the west. Furthermore, a thermal front was traceable from a depth of 80 to 90 meters between the stations 7 and 8. The front was observable from the station 7 to 10 km off it.

The salinity contours are shown in the Figures 2(B), 3(B), and 4(B). In the west of the Strait of Hormuz (Figure 2B), the minimum value of salinity observed in the station 22. The water with lower salinity in the surface layer was due to water penetration from the Oman Sea to the area between stations 21 and 23, and was observable to a depth of about 20 meters. The maximum amount of salinity, about 39.6 psu, was near the sea bed. High salinity gradient was visible between the stations 21 and 23 and at a depth of about 50 meters. Figure 2(E) shows the salinity values in the middle of the Strait of Hormuz.

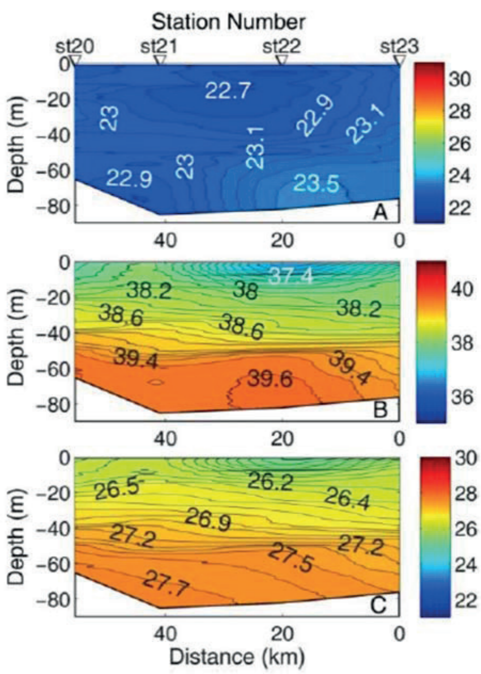

Figure 2. Physical characteristics of water within the west of the Strait of Hormuz in winter: (A) water temperature, (B) water salinity, and (C) σ_t

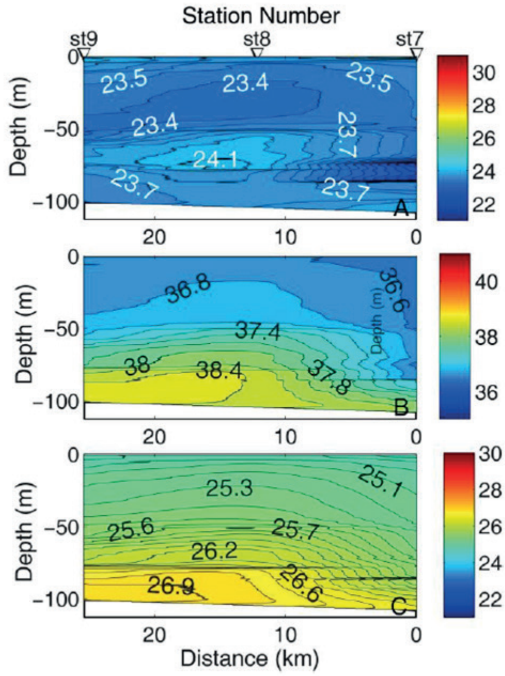

Figure 3. Physical characteristics of water in the middle of the Strait of Hormuz in winter: (A) water temperature, (B) water salinity, and (C) σ_t

Water salinity in the area was almost homogeneous and its variation is about 0.1 psu. The water penetration from the Oman Sea was traceable between the stations 1 and 2, and from the surface to a depth of about 20 meters. Moreover, in this area, salinity front was visible up to 10-meter depth. In the contour of the east of the Strait (Figure 4B), the penetration of water with high salinity was observed from the Persian Gulf and a depth of 80 meters to the bottom and between the stations 8 and 9. The salinity front has been formed in the interfaces of deep and surface layer. The front formed in 60 to 90 meters of depth, between stations 7 and 8. In this area, Persian Gulf water outflow with high salinity located under the water of the Oman Sea with low salinity.

Figures 2(C), 3(C), and 4(C) show the contours of σ_t in winter at the Strait of Hormuz. Water with low σ_t observed in the surface layer of the east of Strait (Figure 4C) and water with high σ_t was observable near to the bed and in the west of the Strait (Figure 2C). In the west of the strait, σ_t variations were mainly due to salinity changes. However, in one transect in the middle of the Strait, these variations were mainly due to temperature changes. In the east of the Strait, the variations of temperature and salinity had similar impact on σ_t changes, and in the depths with temperature or salinity gradient, the σ_t contours were closer together.

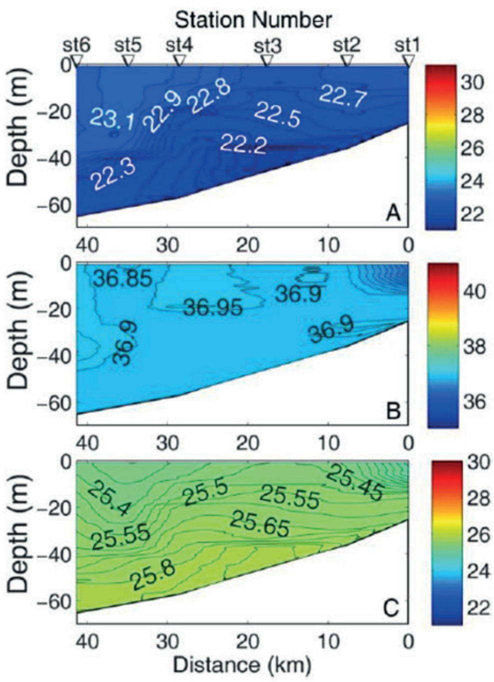

Figure 4. Physical characteristics of water in the east of the Strait of Hormuz in winter: (A) water temperature, (B) water salinity, and (C) σ_t

3.2. Physical parameters of seawater in the spring, 2013

Figures 5 and 6 illustrate the contours of the middle and eastern parts of the Strait of Hormuz during spring 2013. Unfortunately, in this period, there was not enough data in the west of the Strait. The temperature difference between surface and bottom of the vertical section in the middle of the Strait (Figure 5A) was about 2 ^{0}C. A thermal front observed between stations 8 and 9 from the surface to a depth of 40 meters. Vertical changes of temperature was about 5 ^{0}C in the east part of the Strait (Figure 6A). Cold-water cores in the stations 4 and 5 were evident in depth of 55 and 70 meters, respectively. A weak thermocline layer forms in each station. Figures 5(B) and 6(B) show the spatial variations of salinity in two sections; middle and east of the Strait. Salinity in surface layer was higher than depth layer in a cross section of the central part. Furthermore, the salinity expansion was evident from the north to the south, between stations 8 and 11. The reason can be due to increase of temperature and surface evaporation at the northern stations (shallow and near to coast). Penetration of salt water through the Persian Gulf between stations 2 and 7 is apparent in the eastern part of the Strait of Hormuz (Figure 6B). A front formed between two layers of water, one with high salinity under the water with low salinity, especially between stations 4 and 5. The water exchange between the Persian Gulf and Oman Sea was traceable in Figure 5(C) related to σ_t contours.

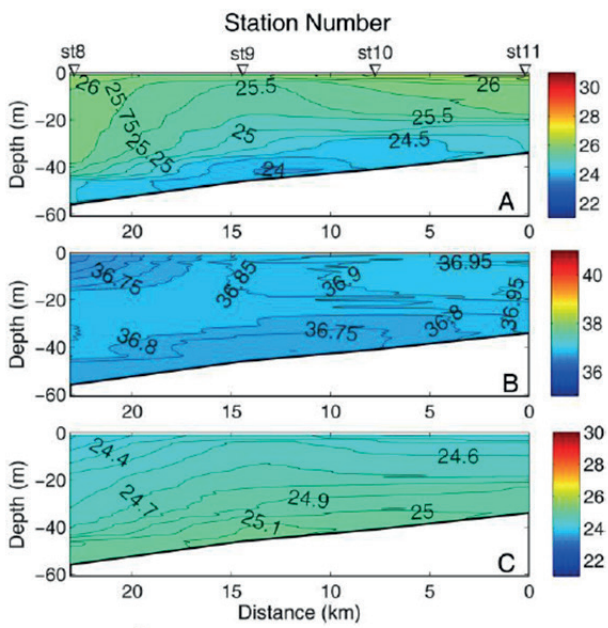

Figure 5. Physical characteristics of water in the middle of the Strait of Hormuz in spring: (A) water temperature, (B) water salinity, and (C) σ_t

At this section, the σ_t difference between surface and depth was about 4.25 kg/m^3. Low-density water entering from the Oman Sea to the Persian Gulf with σ_t less than 25.1 kg/m^3 was observable

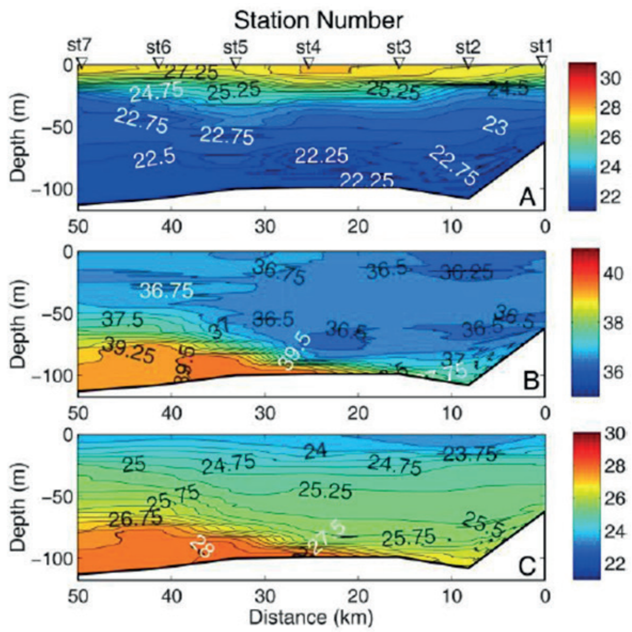

Figure 6. Physical characteristics of water in the east of the Strait of Hormuz in spring: (A) water temperature, (B) water salinity, and (C) σ_t

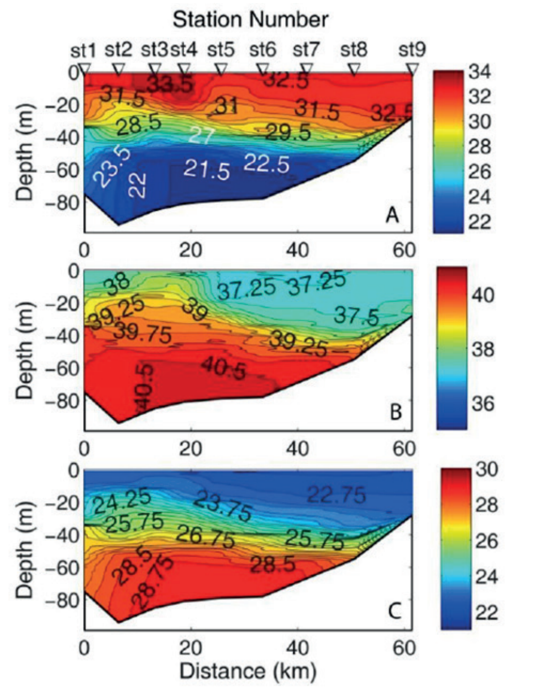

Figure 7. Physical characteristics of water in the west of the Strait of Hormuz in summer: (A) water temperature, (B) water salinity, and (C) σ_t

in the whole section of the middle of the Strait (Figure 5C). The water inflow from the Oman Sea to all middle stations was evident in winter and spring seasons. The σ_t in middle part was mostly influenced by temperature. In addition, temperature had impact on the σ_t in surface layer of eastern part of the Strait and salinity affected on it in the Persian Gulf water outflow (deep-water).

3.3. Physical parameters of seawater in summer 2013

Figures 7 to 9 illustrate the contours of cross sections of west, middle, and east parts of the Strait of Hormuz. The water was well homogeneous up to 10 meters in depth and in shallow waters was homogeneous up to 20 meters and its variation was about 0.5 ^{0}C (mixed layer). Water temperature reached to about 25 ^{0}C at a depth of 50 meters in the western part. A strong seasonal thermocline formed from station 1 to station 5 and from the depth of 15 meters to about 50 meters, but for stations near Iranian coast, the thermocline appeared from the depth of about 30 meters (Hartmann *et al.*, 1971; Pous *et al.*, 2004; Yao, 2008).

In addition, a thermal front has formed from 50 m to the bottom and between the stations 1 and 4 (Figures 7A, 8A, and 9A). Furthermore, another front observed between the stations 8 and 9 in the depth of 40-meter. In the middle part of the Strait, the water inflow from the Oman Sea has been nearly extended at all stations up to 40-m of depth and is completely homogeneous. The water outflow from the Persian Gulf was obvious between stations of 16 and 17 and from the depth of 50 meters to the bed. Moreover, a front formed between the stations 16 and 19 and on the border of water inflow and water outflow from the Persian Gulf. In the east of the Strait of Hormuz (Figure 9A), the surface water temperature was completely homogeneous and was mixed up to a depth of 25 m. The thermocline layer formed in a depth of about 25 m to 38 m. In addition, the temperature decreased in this layer was about 6 ^{0}C. The water column under the thermocline layer was stratified, and the water outflow from the Persian Gulf was traceable from a depth of about 90 meters between the stations 28 and 29. A front has been formed at interface of two water-masses between mentioned stations.

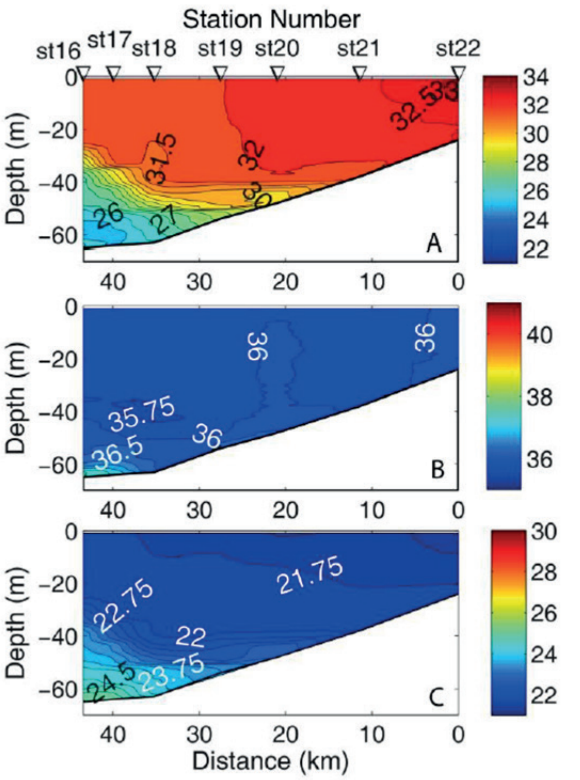

Figure 8. Physical characteristics of water in the middle of the Strait of Hormuz in summer: (A) water temperature, (B) water salinity, and (C) σ_t

Spatial variability of salinity in the summer between the Abu Musa Island and Iranian coast (Figure 7B) represented about 3 psu variation. The salinity has frequent variations in the region. There was a traceable front between the stations 4 and 5 up to a depth of 20-meter. There was also another front between the stations 5 and 6 extended from a depth of 20 to 40-m. While, the water column was well stratified between stations 1 to 4 and the surface layer is completely homogeneous in the stations 5 to 9. The maximum amount of water salinity was 40.5 psu. This quantity was related to the Persian Gulf water outflow and observed near the bottom. The water salinity in the middle of the area was fairly homogeneous and water column was stratified from 50-m depth to the bed, and between the stations 16 to 18. The high salinity was related to Persian Gulf water outflow. The Persian Gulf salt-water outflow was obvious between the stations of 27 and 29 at the east of the Strait of Hormuz from 90-m depth to the bottom (Figure 9B). The maximum amount of salinity was 38.7 psu and located close to the bottom. In addition, a salinity front has formed between the stations 26 and 28 from a depth of 95 meters to the bed.

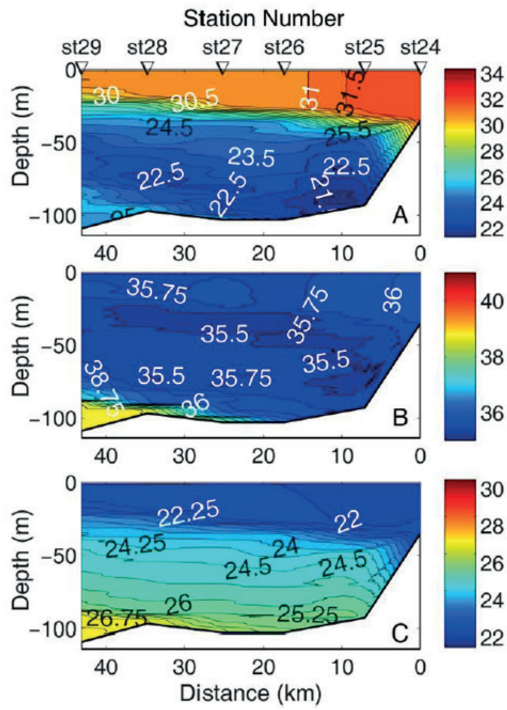

Figure 9. Physical characteristics of water in the east of the Strait of Hormuz in summer: (A) water temperature, (B) water salinity, and (C) σ_t

The σ_t variations were more conformity with temperature variations at the west of the Strait in summer (Figure 7C). It is notable that both temperature and salinity were effective on the σ_t. The σ_t in the deepest part of these areas was about 28.75 kg/m^3. Water temperature and water salinity in this depth were 21.5 ^{0}C and 40.5 psu, respectively. The Persian Gulf water outflow was more considerable in the middle part of the Strait (Figure 8C) due to the maximum value of σ_t than its surroundings waters. Water inflow into the Persian Gulf was observable at all stations except the stations 16 and 17. A front was observable on the boundary of inflow and outflow water in the Persian Gulf. Changes of σ_t was mainly due to changes of temperature in the east of the Strait of Hormuz (Figure 9C), and in the Persian Gulf water outflow its variations related to salinity changes. Water outflow from the Persian Gulf was traceable from a depth of about 90 meters to the bed between stations of 27 and 29. Furthermore, the comparison of the Persian Gulf water outflow in the eastern section of the Strait of Hormuz for three seasons represents that a maximum volume of water exchanges occurred in the spring (Figures 4C, 6C, and 9C).

3.4. The water masses around the Strait of Hormuz

Figure 10 shows temperature-salinity (T-S) diagrams for the CTD data of western, middle and eastern parts of the Strait of Hormuz. The whole water column was completely mixed in the western part of the Strait of Hormuz in winter (Figure 10A). Moreover, temperature changes were insignificant and salinity and σ_t changes were about 3 psu and 2.5 kg/m^3, respectively. One water mass was clear in this season. In spring, with increasing of the surface temperature, changes of salinity and temperature observed in the water column, simultaneously (Figure 10B). The changes of temperature and salinity were about 4.5 ºC and 3.5 psu, respectively. The σ_t variation was about 4.2 kg/m^3 and this large variation of σ_t was due to penetration of the Persian Gulf dense water in the western part.

In summer in some stations, the water column had two layers and two water masses were recognizable (Figure 10C). In the surface water mass both of temperature and salinity increased concurrently. The σ_t of this water mass was about 22.2-23.5 kg/m^3. In the deep-water mass, salinity values increased while temperature decreased. The amount of salinity changes in this water mass were from 38.8 psu to 40.5 psu and the temperature changes were from 32 ^{0}C to 21.4 ^{0}C. The σ_t variation in the western part in summer was 6.7 kg/m^3, which the maximum σ_t variation was observable in deep-water mass (about 4.8 kg/m^3). In some stations (northern stations near the coast of Iran), the water was one layer and one water mass was evident. In the middle stations of this part, the water body was transition from one water mass to two water masses.

Figures 10F, 10E, and 10D illustrate the T-S diagrams in the middle of the Strait of Hormuz in winter, spring, and summer seasons, respectively.

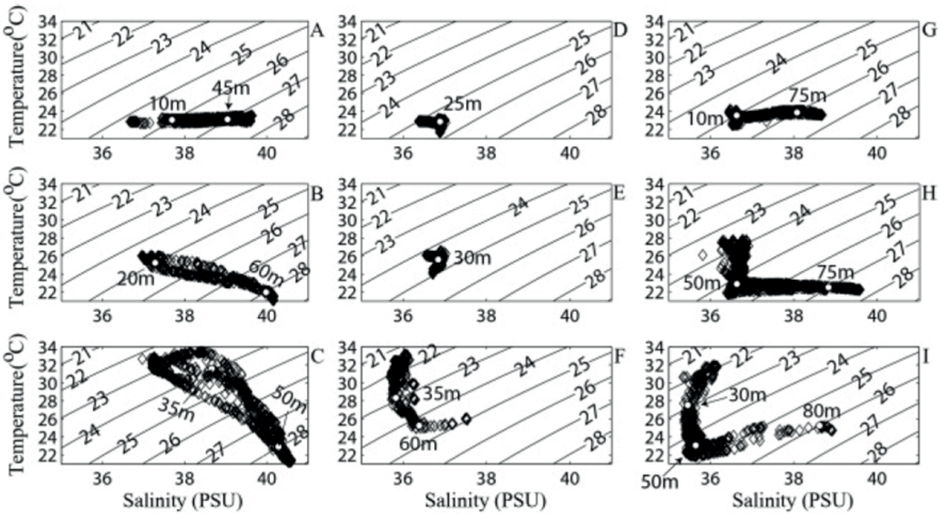

Figure 10. Different water masses in the range of the Strait of Hormuz: West of the Straits of Hormuz in the winter (A), spring (B), summer (C);) Middle of the Strait of Hormuz in winter (D), spring (E), summer (F); East of the Strait of Hormuz in the winter (G), spring (H), and summer (I). The white circles show some selected depths.

In the winter (Figure 10D), the changes of temperature and salinity were insignificant and changes of these parameters were 2.5 ºC and 0.5 psu, correspondingly. The σ_t changed in the range of 24.8 to 25.8 kg/m^3. In winter, two water masses were observable in the stations. In the surface water mass, with increasing the depth the salinity increased however temperature was constant. The deep-water mass was observable with decreasing in temperature and constant salinity. In the spring, despite of slight variations in σ_t (about 1 kg/m^3), there were two water masses in the middle part of the sampling stations. Surface water mass was observed with increasing salinity and constant temperature. This water mass was similar with observed in winter. The deep water mass was with decreasing in temperature and salinity with amount of 8.3 ºC and 4 psu, respectively. In summer, three distinct layers were traceable. The surface layer was associated with decreasing in temperature and salinity. These changes in temperature and salinity were about 6 ºC and 0.4 psu, correspondingly. In the middle layer with increase of the depth, the salinity increased and the temperature decreased and σ_t changed from 23.0 to 24.2 kg/m^3.

In the deep layer, both temperature and salinity increased with depth. The increase of temperature and salinity were about 0.4 ^{0}C and 1.6 psu, respectively. Surface evaporation cause water salinity increased at surface layer. In general, there were two water masses at this transect; deep dense water of the Persian Gulf and surface water mass with low salinity from the Oman Sea.

In the eastern part of the Strait of Hormuz two water masses were observable in the measured seasons (Figures 10G, 10H, 10I). The surface water mass specified with decrease of temperature and nearly constant salinity. However, the deep water mass (water outflow from the Persian Gulf) was recognized by increasing in salinity and relatively increasing in temperature. The water temperature increasing was considerable in summer (Figure 10I). In summer, the surface water mass consisted of two layers; the surface layer (affected by surface evaporation) and the middle layer. The maximum quantity of σ_t was observed in the spring. T-S diagrams show changes of surface water inflow from the Indian Ocean and the deep outflow of the Persian Gulf very well. These results also reported in numerical modeling studies (Kämpf and Sadrinasab, 2006) and observations (Johns *et al.*, 2003).

Conclusions

Physical parameters of seawater in the Strait of Hormuz are influenced of water inflow from the Oman Sea, and the dense water outflow from the Persian Gulf. Changes of these parameters depended on the temporal and special distribution completely. These dependences were clearly detectable by the contours of temperature, salinity, σ_t, and T-S diagrams. In winter, the measured temperature in different parts showed that the entire water column was completely mixed and the noticeable changes were just due to salinity (10A, 10D, 10G). These considerable changes represented the outflow of dense-water from the Persian Gulf. Furthermore, the σ_t differences in this season were mostly affected by salinity changes. The great temperature gradient caused the thermal fronts. In addition, the strong vertical gradient of temperature was a major factor in water temperature stratified. An approximate interface between water inflow from the Sea of Oman, and the water outflow of the Persian Gulf, was traceable between stations 7 and 8 at depth about 65 meters. Comparing the salinity and σ_t contours in western part of the Strait of Hormuz for three seasons showed the water mass boundary changed in different seasons from winter to summer, where the interface got distance from the Iranian coasts. It is also remarkable that with getting distance from Iranian coast, interface depth increased meaningfully. This result could indicate to extra evaporation in the summer. In addition, quantity of salinity for Persian Gulf dense water outflow was more in summer and its difference in similar stations was about 0.9 psu.

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